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THE EVAPORITES OF THE ORDOVICIAN BAUMANN FIORD FORMATION, ELLESMERE ISLAND, ARCTIC CANADA

Grant D. Mossop

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PREFACE

The Lower Ordovician carbonate-anhydrite Baumann Fiord Formation has for many years been recognized as an important stratigraphic marker in the lower Paleozoic sedimentary sequence of central Ellesmere Island. It is also important in understanding the structure of this part of the Canadian Arctic Archipelago because it was the site of an important zone of slippage during two major periods of deformation.

The Baumann Fiord region is mountainous and the formation is well exposed along fiord and valley walls. Permafrost conditions prevail in the area and as a result there is little or no development of surficial secondary gypsum to obscure textures and structures in the anhydrite, thus making the area suitable for the study of evaporites. Analogies with present-day Persian Gulf deposits suggests that the seaward equivalents of some Baumann Fiord rocks could serve as reservoirs for petroleum. However borehole information proving or disproving the existence of such rocks has yet to be obtained.

D.J. McLaren,
Director General,
Geological Survey of Canada.

Ottawa, December 1978

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Abstract

The Lower Ordovician Baumann Fiord Formation is a basin-margin evaporite sequence that forms part of the Franklinian Miogeosyncline-Arctic Platform sedimentary wedge. In the study-area on central Ellesmere Island, formation thickness ranges from about 200 m along the edge of the Precambrian craton to about 475 m at the basinward margin of the depositional wedge. The outcrop belt is about 110 km wide, extending more than 320 km along strike.

The fundamental genetic unit is the carbonate-anhydrite cycle. A typical cycle is 3.5 m thick and consists of a basal lagoonal lime mudstone facies, succeeded by an intertidal stromatolitic facies, in turn overlain by a supratidal anhydrite facies. Each of these regressive sequences is interpreted as a discrete sabkha cycle, analogous in all essential regards to the Recent Trucial Coast sabkha cycle. Some sections of the Baumann Fiord Formation on Ellesmere Island contain up to 120 superposed sabkha cycles.

Rhythmic successions of cycles were compounded during periods of steady and constant subsidence. Departures from conventional rhythmic cyclicity in any one vertical section may be explained in terms of temporal fluctuation in the rates of subsidence. Lateral changes in the character or thickness of individual cycles are explained as a function of spatial fluctuation in rates of subsidence. A regional stratigraphic synthesis, based on correlations between eight measured sections, reveals that, given appropriate subsidence differentials, the facies pattern in the formation as a whole can be explained in terms of sabkha model genesis.

Most of the original nodular anhydrite of the Baumann Fiord Formation underwent early-stage compactional flow to produce layered and laminar anhydrite. Deep burial, accompanied by pervasive recrystallization, further modified the textural character of some of the anhydrite, notably that of the seaward part of the sedimentary wedge. The Ellesmerian Orogeny (Middle Devonian to mid-Pennsylvanian) produced folding and, where deformation was intense, it caused remobilization and flow of the anhydrite. Subsequent thrust-faulting (Cretaceous-Tertiary Eurekan Orogeny) produced shear zones at various levels within the formation. During exhumation, the basal part of the formation locally underwent hydraulic fracturing. Water from the underlying strata moved up into the evaporites and hydrated the anhydrite to form secondary gypsum. The excess calcium sulphate liberated during this volume-for-volume replacement process precipitated in the fracture system, forming satin-spar veins.

The latest stages of exhumation of the formation have taken place during the permafrost regime of Pleistocence and Holocene times. Hydration by present-day meteoric water locally promotes gypsification of the outermost veneer of the exposures but, as a rule, it is unaltered anhydrite that outcrops.

Résumé

La formation de Baumann Fiord, d'âge ordovicien inférieur, est une succession évaporitique déposée sur la marge d'un bassin, et faisant partie du prisme sédimentaire du miogéosynclinal franklinien et de la plate-forme de l'Arctique. Dans la région étudiée, au centre de l'île Ellesmere, la puissance des formations varie entre environ 200 m le long du rebord du craton précambrien, et environ 475 m sur le rebord du prisme sédimentaire dirigé vers le bassin. La zone d'affleurement a environ 100 km de large et s'étend sur plus de 320 km le long de la direction principale des couches par rapport à l'horizontale.

L'unité génétique fondamentale est le cycle à carbonates et anhydrite. Un cycle typique a 3.5 m d'épaisseur et consiste en un faciès basal lagunaire à calcaire et mudstone, suivi d'un faciès stromatolitique intertidal, recouvert à son tour par un faciès supratidal à anhydrite. Chacune de ces séquences régressives est interprétée comme un cycle discret de sebkha, analogue dans ses grandes lignes au cycle de sebkha du "Recent Trucial Coast". Certaines sections de la formation de Baumann Fiord de l'Île Ellesmere contiennent jusqu'à 120 cycles de sebkha superposés.

Les successions rythmiques des cycles ont eu lieu pendant des périodes de subsidence régulière. On peut expliquer les irrégularités que peut présenter ce rythme dans une coupe verticale donnée par certaines fluctuations de la vitesse de subsidence. D'autre part, on peut expliquer les variations latérales de caractère ou de puissance des cycles individuels par des fluctuations de la vitesse de subsidence d'un endroit à l'autre. Une synthèse stratigraphique régionale, fondée sur des corrélations entre 8 sections mesurées indique que, en tenant compte des variations appropriées du rythme de subsidence, on peut expliquer la distribution des faciès de la formation prise dans son ensemble par la création d'un environnement de sebkha typique.

Une grande partie de l'anhydrite nodulaire originelle de la formation de Baumann Fiord a subi tout d'abord une phase de compactage et fluage, qui a engendré les stratifications et laminations d'anhydrite. L'enfouissement à grande profondeur, accompagné d'une recristallisation généralisée, a contribué à modifier davantage la texture d'une partie de l'anhydrite, en particulier sur le rebord du prisme sédimentaire dirigé vers la mer. L'orogenèse de l'Ellesmerien (Dévonien moyen à Pennsylvanien moyen) a engendré des plissements, et, là où la déformation a été intense, a donné lieu à la remobilisation et au fluage de l'anhydrite. Par la suite, des failles de chevauchement (orogenèse de l'Eureka du Crétacé et du Tertiaire) ont engendré des zones de cisaillement à divers niveaux de la formation. Pendant sa dénudation, la partie basale de la formation a subi localement une fracturation hydraulique. L'eau des couches sous-jacentes a migré dans les évaporites et hydraté l'anhydrite pour former du gypse secondaire. L'excès de sulfate de calcium libéré pendant ce processus de remplacement à volume égal s'est déposé dans le réseau de fractures, créant ainsi des veines de sélénite fibreuse.

Les dernières étapes d'exhumation de la formation ont eu lieu pendant le régime de pergélisol du Pléistocène et de l'Holocène. L'hydratation par les eaux météoriques actuelles provoque localement la gypsification d'une couche superficielle très mince des affleurements mais, en général, on rencontre en surface de l'anhydrite non altérée.

THE EVAPORITES OF THE ORDOVICIAN BAUMANN FIORD FORMATION, ELLESMERE ISLAND, ARCTIC CANADA

INTRODUCTION

The Baumann Fiord Formation is a Lower Ordovician carbonate-anhydrite sequence that crops out extensively on Ellesmere Island in the Canadian Arctic. A detailed stratigraphic and sedimentologic study of the formation was carried out under the auspices of the Geological Survey of Canada (Project 710007) and the results used as material for a doctoral thesis (Mossop, 1973a). Preliminary reports on the progress of the research are contained in Mossop (1972a, b, 1973b).

FIELD METHODS

Methods of organizing and carrying out geological fieldwork in the Canadian Arctic Islands are outlined in a short guide by Kerr (1974). For those unfamiliar with the problems involved, it is a useful introduction.

For the Baumann Fiord study, the weather station at Eureka, on Ellesmere Island (Fig. 1), was chosen as the base of operations for the two summers of fieldwork. In 1971, field camps were established at Sections 1 through 4. In 1972, camps were established at Sections 5 through 8 (Fig. 1). Transport in the field was provided by single-engined Otter aircraft and Bell 206 Jet Ranger Helicopter.

At each locality, examination of the Baumann Fiord Formation and the associated units was carried out by foot traverses. Where exposure warranted, it was possible to follow the formation for up to 15 km from camp in one or more directions. Much ground was examined in this way.

EXPOSURE CONDITIONS

Because of the paucity of vegetation on Ellesmere Island, and the mountain and fiord type topography, the Baumann Fiord rocks generally are well exposed. Furthermore, because of the prevailing permafrost conditions, there is little or no development of surficial secondary gypsum to obscure the anhydrite's textures and structures (Mossop, 1972a, 1973a, b; Mossop and Shearman, 1973). On the mountainsides, repeated summer thawing facilitates a measure of *in situ* hydration of anhydrite, locally giving rise to a white crust of powdery gypsum on the outcrops. The altered zone normally is less than 3 cm thick but, in valley areas where drainage is impeded, it may be as much as 1 m. The freshest anhydrite occurs in places where erosion rate exceeds hydration rate, notably in stream cuts and small landslips.

Talus cover is, in fact, the major handicap to the field geologist. Many slopes consist of series of coalesced talus fans, generated by downslope accumulation of frost-wedged bedrock (Fig. 2). The Baumann Fiord Formation, though essentially recessive in its weathering pattern, is usually spared from complete talus cover by the fact that the carbonate bands within the anhydrite are resistant enough to cause certain ridges to remain exposed above the talus (Fig. 2). The most continuous exposures are those occupying the buttresses between the talus-filled gullies.

PREVIOUS WORK

The first large-scale geological reconnaissance of the Canadian Arctic Islands was in 1955 when the Geological Survey of Canada conducted its Operation Franklin (Fortier *et al.*, 1963). Many parts of Ellesmere Island were mapped during the course of the operation and the stratigraphic framework for the region was established. Numerous maps and reports on the geology of specific areas of Ellesmere Island have since reached publication, as have the results of many regional stratigraphic studies and some detailed paleontological and sedimentological studies. A bibliography of papers on the Arctic written by officers of the Geological Survey of Canada has been compiled by Christie (1976). Works that have a direct bearing on the present study are referred to in appropriate sections of the text.

The comprehensive mapping program of central Ellesmere Island by the Geological Survey of Canada now is virtually complete and reliable geological maps for the whole of the study-area are available (Appendix A). Most of the maps, compiled using air photograph interpretation in conjunction with considerable surface section control, are on the scale of 1:250,000.

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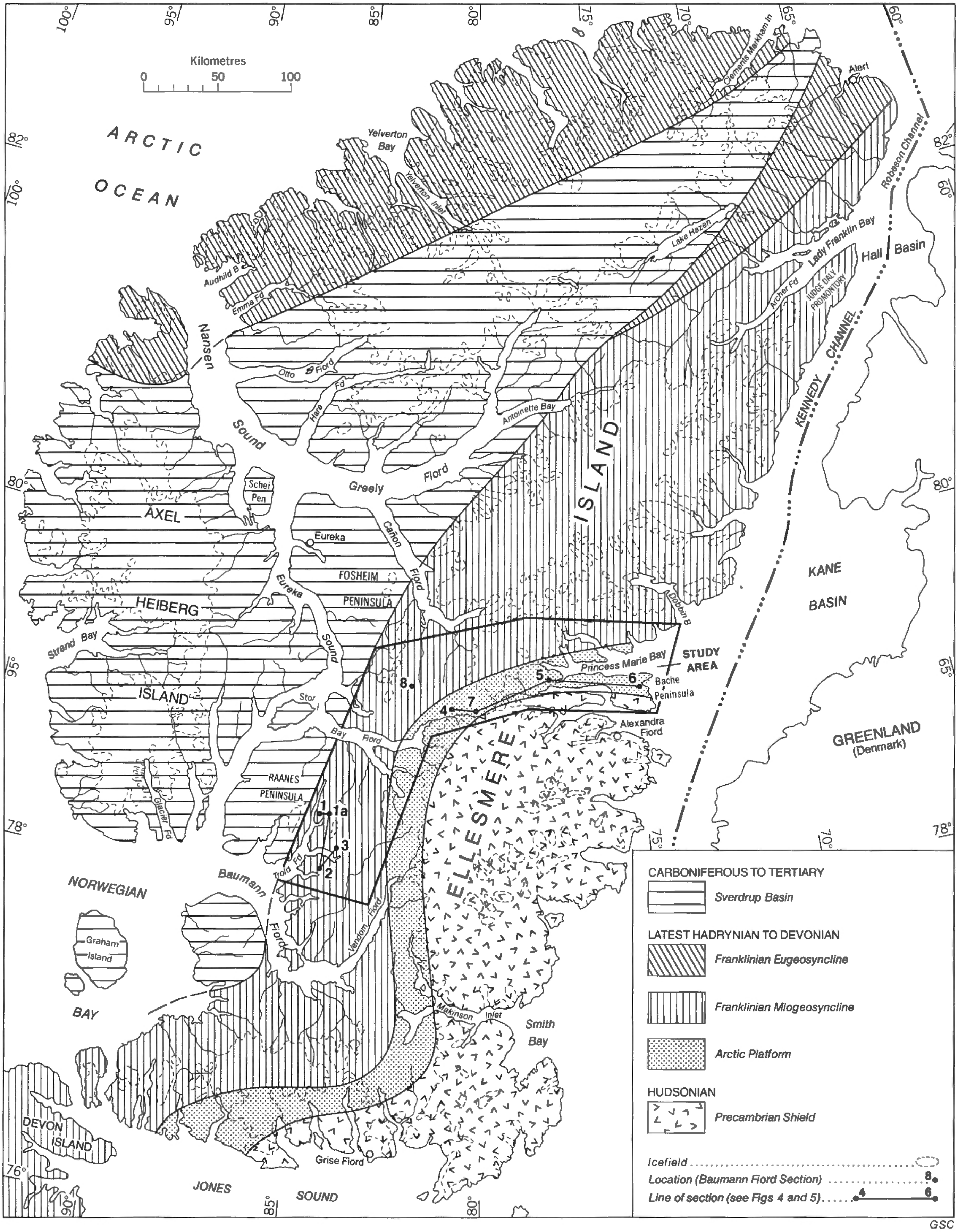


FIGURE 1. Index map of Ellesmere Island showing the major geological provinces in the region of the study-area. The Baumann Fiord Formation is part of the Arctic Platform-Franklinian Miogeosyncline sedimentary wedge.

The author thanks N.C. Wardlaw of the Geology Department, The University of Calgary, for the time and facilities to prepare this manuscript during my tenure of a post-doctoral fellowship in 1974.

J.Wm. Kerr, G.R. Davies and D.W. Morrow reviewed drafts of this manuscript. Their comments and suggestions proved very helpful.

STRATIGRAPHIC SETTING OF THE BAUMANN FIORD FORMATION

GENERAL GEOLOGY OF CENTRAL ELLESMERE ISLAND

Central Ellesmere Island is divided into four geological provinces (Thorsteinsson and Tozer, 1970): the Precambrian Shield, the Arctic Platform, the Franklinian Miogeosyncline, and the Sverdrup Basin (Fig. 1).

Crystalline rocks of the Precambrian Shield, which outcrop over a large part of southeastern Ellesmere Island (Fig. 1), have been dated as Hudsonian (1700 m.y.; Wanless, 1969). The Hudsonian rocks presumably extend beneath the Arctic Platform and the Franklinian Miogeosyncline to the north and west where they are interpreted as basement (Trettin *et al.*, 1972).

FIGURE 2. Exposures of recessive Baumann Fiord Formation (Ob) beneath the cliff-forming limestones of the Eleanor River Formation (Oe), Sanddola Creek, Bache Peninsula (Sec. 5), viewed from the east. Dark-toned talus, between the buttresses of Baumann Fiord Formation strata, comprises mainly limestone derived from the cliffs above. Light-toned talus comprises powdery 'weathering product' gypsum. The ice-capped dome in the centre of the photograph is about 8 km distant. Total thickness of the Baumann Fiord Formation at this locality is about 265 m. (GSC 203463).

The Arctic Platform and the Franklinian Miogeosyncline comprise sedimentary rock of late Precambrian to Late Devonian age and most formations are continuous from one province to the other. The two provinces are differentiated largely on the basis of thickness, the thin sequence of the Arctic Platform giving way to a much thicker sedimentary pile in the Franklinian Miogeosyncline (maximum 12 km thick; Thorsteinsson and Tozer, 1970). The line of demarcation between the two provinces marks the eastern limit of post-Franklinian tectonic influences; the Late Devonian to Early Carboniferous Ellesmerian Orogeny and the Tertiary Eurekan Orogeny (Trettin *et al.*, 1972). Deformation of the Franklinian Miogeosyncline produced the Central Ellesmere Fold Belt, which is dominated by folds of Ellesmerian origin. High-angle reverse faults and thrusts in the strata of the Franklinian Miogeosyncline are largely Eurekan in origin (Trettin *et al.*, 1972). In the Arctic Platform, equivalent strata are flat-lying or very gently dipping and are disrupted only by normal faults.

It should be emphasized that the Arctic Platform and the Franklinian Miogeosyncline together constitute a single sedimentary wedge, thin in the east where the strata onlap the Precambrian Shield and thickening westward and northward into the miogeosyncline. For some geologic periods (e.g., Cambrian) it is possible to isolate a flexure separating the two provinces, presumably marking the location of a hinge line (Trettin *et al.*, 1972). For the Ordovician, no such flexure exists (Kerr, 1967a). It is apparent that, for the Ordovician at least, the rocks of the Franklinian Miogeosyncline originated under depositional conditions similar to equivalent rocks in the Arctic Platform. The Baumann Fiord Formation, which constitutes part of the Arctic Platform-Franklinian Miogeosyncline sedimentary wedge, was examined in both belts in the course of the present study.

The Frankinian Miogeosyncline and the Arctic Platform consist mainly of carbonate rock and fine-grained clastic rock, with two major evaporite formations present as well. In general, the sequence is interpreted as being of shallow-marine shelf or bank origin (Kerr, 1967b, 1968). The present erosional limit of the sedimentary rocks along the edge of the Precambrian Shield may be only slightly west of the original depositional edge for most formations, the greater part of the present shield area having been positive during much of early Paleozoic time.

After the Ellesmerian Orogeny, a crustal depression developed over much of the area formerly occupied by the Franklinian Miogeosyncline. This depression, called the Sverdrup Basin (Fig. 1), was the site of almost continuous sedimentary deposition from Mississippian to early Tertiary time. The Eurekan Orogeny of Late Cretaceous to middle Tertiary time terminated the life of the Sverdrup Basin.

For a more comprehensive summary account of the geology of the Canadian Arctic Islands the reader is referred to Thorsteinsson and Tozer (1970). The tectonic history of the region has been comprehensively reviewed by Trettin *et al.* (1972).

STRATIGRAPHY AND STRUCTURE OF THE FRANKLINIAN MIOGEOSYNCLINE-ARCTIC PLATFORM SEDIMENTARY WEDGE

Table 1 shows stratigraphic columns for the Franklinian Miogeosyncline and the Arctic Platform in the central Ellesmere Island region. The column for the Franklinian Miogeosyncline applies in an area extending approximately from Baumann Fiord in the south to Cañon Fiord in the north (Fig. 1). The column for the Arctic Platform applies in the region of Bache Peninsula in the east and throughout the stable Arctic Platform belt.

Ordovician stratigraphic nomenclature for the Ellesmere Island sequence became somewhat confused in the early stages of mapping, partly due to a lack of reliable paleontological control and partly through a failure to recognize that there is not one but two major evaporite units, the Baumann Fiord Formation and the Bay Fiord Formation (Table 1). The discrepancies were resolved by Kerr (1967c) and the stratigraphic terminology used in this work is based upon his correlations.

The structural trend of the Franklinian Miogeosyncline is essentially north-northeast (Fig. 1) in the southern part of the study-area. Along the strike, component formations are generally of uniform thickness. Perpendicular to the strike, they thin markedly toward the east. In the eastern part of the study-area, the sequence trends east-northeast and thins toward the south, again roughly perpendicular to the strike. As a rule, then, the structural trend of the Franklinian Miogeosyncline in the study-area is parallel to the depositional strike of component formations (Fig. 1).

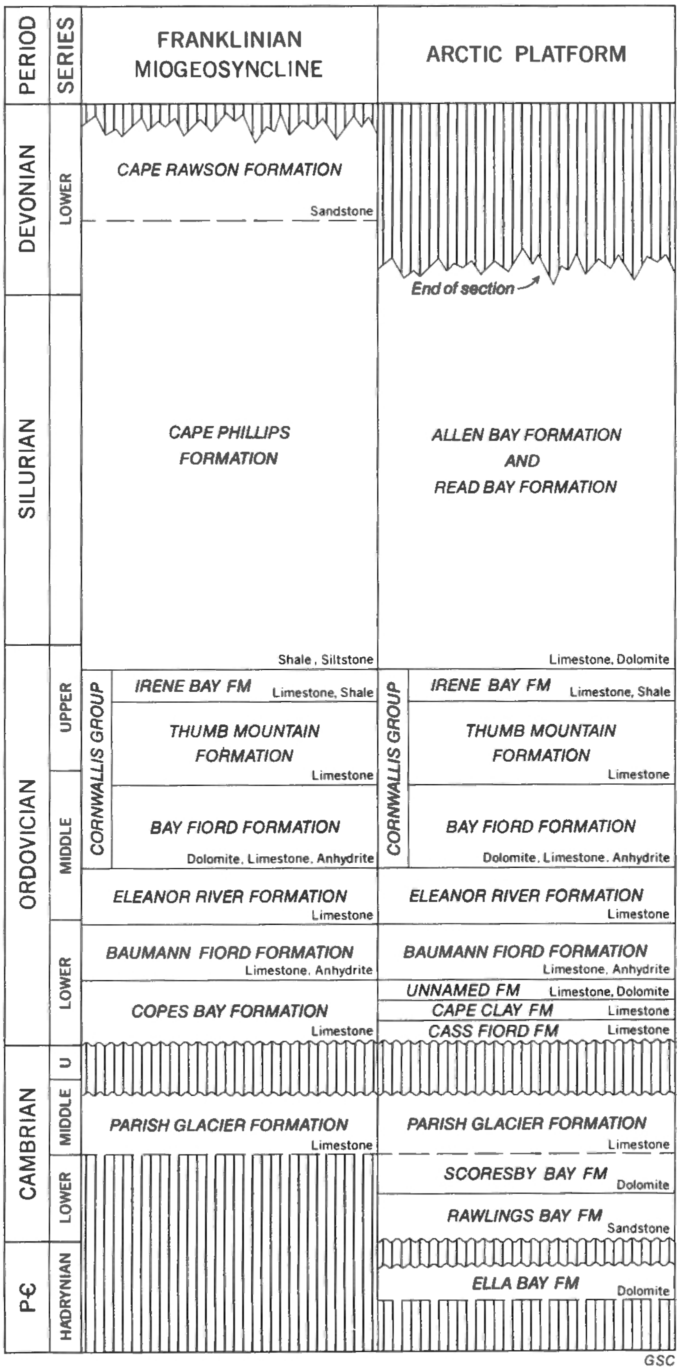
BAUMANN FIORD FORMATION STRATIGRAPHY

The type section of the Baumann Fiord Formation (Fig. 3), established by Kerr (1967c), is located on the east side of Trold Fiord, Ellesmere Island (Fig. 1, Sec. 1). At the type section and throughout the study-area as a whole, the formation lies conformably on resistant beds of the Copes Bay Formation and its equivalents (Table 1). The Copes Bay Formation consists of fine-grained, marine carbonate rock (Kerr, 1967c, 1968), mainly limestone and argillaceous limestone, but with thin anhydrite beds in the upper part. The Eleanor River Formation lies conformably on the Baumann Fiord Formation (Table 1). It comprises a sequence of slightly argillaceous, fine-grained limestones which have been interpreted as being of shallow-marine origin (Kerr, 1968). Because of erosional undercutting of the recessive Baumann Fiord Formation, the resistant Eleanor River Formation characteristically stands out as a prominent bluff or cliff (Fig. 3). In the Franklinian Miogeosyncline, the Baumann Fiord Formation is between 350 and 500 m thick (Fig. 1, Secs. 1, 1a, 2 and 3). It thins gradually toward the east and, in the Arctic Platform, thicknesses are about 250 m on the average (Fig. 1, Secs. 4, 5, 6 and 7).

For mapping purposes, the formaton is divided into three members (Kerr, 1968). The base of the lower A member is at the first recessive anhydrite-bearing stratum above the Copes Bay Formation limestone. It consists of rhythmically alternating bands of carbonate and anhydrite. The carbonate-anhydrite cycles are about 3.5 m thick with anhydrite generally predominating over carbonate by a ratio of two to one. The A member is about 350 m thick at the type section but thins to about 180 m in the Arctic Platform. Member B consists of a resistant limestone unit that ranges between 30 and 60 m. Its base is assigned to the first resistant carbonate beds above the recessive A member strata. The B member is a useful marker horizon throughout most of the study-area. The upper C member is essentially identical to member A in that it is characterized by a series of carbonate-anhydrite cycles.

TABLE 1.

Table of formations in the central Ellesmere Island region (adapted from Thorsteinsson and Tozer, 1970; Kerr, 1968; Christie, 1967). The column for the Franklinian Miogeosyncline refers primarily to the Trold Fiord region. The Arctic Platform column encompasses sections in the Sverdrup Pass-Bache Peninsula region.



PERIOD	SERIES		FRANKLINIAN MIOGEOSYNCLINE		ARCTIC PLATFORM
DEVONIAN	LOWER		CAPE RAWSON FORMATION Sandstone		End of section
SILURIAN			CAPE PHILLIPS FORMATION Shale, Siltstone		ALLEN BAY FORMATION AND READ BAY FORMATION Limestone, Dolomite
ORDOVICIAN	UPPER	CORNWALLIS GROUP	IRENE BAY FM Limestone, Shale	CORNWALLIS GROUP	IRENE BAY FM Limestone, Shale
			THUMB MOUNTAIN FORMATION Limestone		THUMB MOUNTAIN FORMATION Limestone
	MIDDLE		BAY FIORD FORMATION Dolomite, Limestone, Anhydrite		BAY FIORD FORMATION Dolomite, Limestone, Anhydrite
			ELEANOR RIVER FORMATION Limestone		ELEANOR RIVER FORMATION Limestone
	LOWER		BAUMANN FIORD FORMATION Limestone, Anhydrite		BAUMANN FIORD FORMATION Limestone, Anhydrite
			COPES BAY FORMATION Limestone		UNNAMED FM Limestone, Dolomite CAPE CLAY FM Limestone CASS FIORD FM Limestone
CAMBRIAN	U				
	MIDDLE		PARISH GLACIER FORMATION Limestone		PARISH GLACIER FORMATION Limestone
	LOWER				SCORESBY BAY FM Dolomite RAWLINGS BAY FM Sandstone
PЄ	HADRYNIAN				ELLA BAY FM Dolomite

GSC

Normally, the C member does not exceed 60 m in thickness. In those parts of the study-area where the C member is not present, the B member is included as part of the overlying Eleanor River Formation, to which it is similar lithologically.

The Baumann Fiord Formation was considered by Kerr (1967c, 1968) to be confined to the Lower Ordovician on the grounds that it is underlain by the Lower Ordovician Copes Bay Formation and overlain by the Lower to Middle Ordovician Eleanor River Formation. On Bache Peninsula, the B member of the Baumann Fiord Formation contains *Hystricurus* sp. (GSC locs. 47271, 47275; Christie, 1967), a trilobite genus which is thought to range from Tremadocian to early Arenigian (Twenhofel, 1954). Thus, the formation is considered to be entirely Early Ordovician in age, as indicated in Table 1.

Faunas collected during the present study from the B member in Section 7 (GSC loc. C-19559) were identified by B.S. Norford (pers. com., 1972) and dated as probably late Early Ordovician in age. The same section yielded conodonts which C.R. Barnes (pers. com., 1972) dated as late Early Ordovician (Barnes *et al.*, 1976). All new paleontological information gleaned in the course of the present study is tabulated in Appendix B.

MEASURED SECTIONS

The Baumann Fiord Formation was examined at eight separate localities (Fig. 1). Six sections are complete (Secs. 1a, 2, 3, 5, 6, 7), with the entire formation present and both the upper and lower contacts exposed. Two sections are nearly complete (Secs. 1, 4). In Section 8, the entire formation is present but extensive scree cover precluded compilation of a reasonable section.

FIGURE 3. Type section of the Baumann Fiord Formation, viewed from the northeast (Fig. 1, Sec. 1). Cliff-forming limestones of the Eleanor River Formation (Oe) constitute the crest of the ridge, underlain by the generally recessive Baumann Fiord Formation (Ob). B member limestones (B) are resistant relative to the enclosing anhydrite-carbonate members (A and C). The peak at right (6 km distant) is 950 m above the valley floor. (GSC 203463-A)

Figure 4 shows four sections in the Franklinian Miogeosyncline. The logs are arranged so as to delineate a cross-section that is perpendicular to the depositional and structural trend in the region. Figure 5 illustrates four sections in the Arctic Platform. These sections are close to the onlap edge of the sedimentary wedge and the line of section is approximately parallel to the regional depositional trend. In both Figures 4 and 5, the base of the B member serves as the horizontal datum on which the sections are placed. This datum was chosen because probably it is close to being a time line.

The left hand part of the section log columns (Figs. 4, 5) depicts gross lithology. Where accessory lithologies form 10 per cent or more of sections, these are noted in the right extremity of the columns. Sedimentary structures have not been included in the logs because of the small scale on which they normally are developed. Differentiation between anhydrite and gypsum is on the basis of inherent lithology and is not a reflection of degree of surficial hydration. Thicknesses shown reflect true stratigraphic thickness, not gross thickness, the latter being considerably greater in some places due to deformational modification.

TABLE 2

Thickness and exposure data for measured sections of the Baumann Fiord Formation

Section	Region	Thickness Present (m)	Thickness of Covered Intervals (m)	Exposed Thickness (m)	Percentage Exposed	Member	Member Thickness (m)	Thickness Covered (m)	Percentage Exposure	Percentage Carbonate
1	Trold Fiord	414+ (base obscured)	5	409	99	C	49	0	100	54
						B	44	0	100	100
						A	321+	5	98	31
1a	Trold Fiord	473	29	444	94	C	51	22	57	41
						B	43	0	100	100
						A	379	7	98	28
2	Flat Pebble Bay	364	20	344	95	n/a	-	-	-	-
						n/a	-	-	-	-
						A	364	20	95	47
3	Starfish Bay	312	38	274	88	n/a	-	-	-	-
						n/a	-	-	-	-
						A	312	38	88	35
4	Sverdrup Pass	204+ (base obscured)	10	194	95	C	63	10	84	28
						B	39	0	100	100
						A	102+	0	100	18
5	Sanddöla Creek	265	26	239	90	C	44	6	86	10
						B	33	0	100	100
						A	188	20	89	11
6	Bartlett Bay	232	133	99	42	C	35	24	31	16
						B	27	0	100	100
						A	170	109	36	16
7	Witch Mountain	278	31	247	89	C	57	15	74	11
						B	47	0	100	100
						A	174	16	91	18

Thickness and exposure data for the measured sections are compiled in Table 2. Exposure generally exceeds 90 per cent with the exception of Section 6 (42%) and Section 8 (not tabulated). Such exposure is not necessarily present in a single stream cut or scree buttress. Each illustrated section was compiled by combining the results of measurement in a number of laterally adjacent exposures, usually within about 1 km of one another.

Sections 1, 1a, 2 and 3, in the Franklinian Miogeosyncline, can be considered together (Fig. 4). These sections all lie well out in the miogeosyncline, Section 1 being some 80 km and Section 3 some 55 km west of the onlap edge of the sequence (Fig. 1). All the sections lie within the folded part of the Franklinian Miogeosyncline (Fig. 1). Folds in this region generally have amplitudes of 600 to 1000 m and wavelengths of 3 to 5 km. Locally, the deformation is more intense with overturned folds being common in certain confined horizons (Fig. 6).

Section 1 (Lat. 78°22'N, Long. 84°40'W) is the type section of the Baumann Fiord Formation (Kerr, 1967c). It is well exposed on the eastern slope of a mountain ridge that trends parallel to Trold Fiord (Fig. 3). The lowermost beds of the Baumann Fiord Formation and the underlying Copes Bay Formation are not exposed in the mountainside. A reverse fault near the base of the sequence produces a repeat of the sequence in the section log (levels 0-80 equivalent to levels 125-205, Fig. 4).

Section 1a (Lat. 78°22'N, Long. 84°25'W) is some 9 km east of Section 1. It is a complete section of the Baumann Fiord Formation, and the contacts with both the underlying and overlying formations are exposed. The section is not disturbed by any apparent faults or internal folds. Because Section 1a lies within the designated type area (Kerr, 1967c), it is recommended herein that this section serve as the principal reference section for the Baumann Fiord Formation.

Section 2 (Lat. 78°06'N, Long. 84°24'W) lies some 40 km south of Section 1a but, relative to the regional strike, it is only some 10 to 12 km farther east. The Baumann Fiord Formation at Section 2 contains a well-developed monocline (Fig. 7a), but is exposed in a relatively undeformed setting along a prominent ridge. Both Sections 2 and 3 lack evaporite development in the zone which elsewhere is designated as the C member. Consequently the B member, because it is lithologically indistinguishable from the Eleanor River Formation, is mapped as part of the latter.

In Section 3 (Lat. 78°13'N, Long. 84°05'W), which is closer to the craton than Section 2, the Baumann Fiord Formation is exposed at the end of a long mountain ridge (Fig. 7b). Although there is some talus cover near the base of the section, the contact with the underlying Copes Bay Formation is exposed.

FIGURE 6. Overturned folds in carbonate beds of the basal B member, of the Baumann Fiord Formation, Section 1. Folds here are confined to an 18 m stratigraphic interval. Regionally, the deformation is much less intense. (GSC 203463-B)

Certain relationships become apparent through comparative analysis of the four adjacent sections shown in Figure 4. First, it is clear that the formation as a whole thins eastward, toward the craton. Second, it is apparent that, while in many instances correlative units can be traced laterally from section to section, there are significant parts of each section in which the sequence is distinct from that of adjacent sections. The intertonguing of the carbonate and anhydrite lithofacies is complex and there is lateral variation both perpendicular to the depositional strike (compare Secs. 1 and 1a) and along the deposition strike (compare Secs. 1a and 2). Finally, it is clear that the C member in the region of Trold Fiord dies out toward the south, apparently along strike.

The four sections in the Arctic Platform (Fig. 5, Secs. 4, 7, 5, 6) all lie close to the onlap edge of the Franklinian Miogeosyncline-Arctic Platform sedimentary wedge. All the sections consist of strata that are flat-lying or very gently tilted, but otherwise undisturbed.

Section 4 (Lat. 79°15'N, Long. 80°40'W) is well exposed in the steep canyon walls of a deeply incised stream (Fig. 7c). Unfortunately, the lower part of the formation, and the contact with the underlying Copes Bay Formation, is buried beneath alluvium. The rocks near the base of the photographed section (Fig. 5) consist largely of secondary gypsum, not anhydrite, and these beds are ramified throughout with satin-spar gypsum veins.

Section 7 (Lat. 79°09'N, Long. 80°16'W) is about 8 km east of Section 4, within 3 km of the outcrop edge of the Precambrian Shield (Fig. 5). Baumann Fiord strata are exposed along the southern slope of Witch Mountain (Fig. 7d). In the 30 m zone above the Copes Bay contact there is extensive development of secondary gypsum, and satin-spar veins are present in abundance.

Section 5 (Lat. 79°15'N, Long. 78°08'W) is a complete section of the Baumann Fiord Formation that is well exposed along the steep slopes of the Sanddola Creek valley (Fig. 7e). This section contains some of the best exposed nodular anhydrite observed in the study-area. Secondary gypsum and satin-spar veins are in evidence in the basal part of the formation. Because this section exhibits most of the salient characteristics of the Baumann Fiord Formation in the Arctic Platform, it is recommended that Section 5 serve as a second reference section, to complement the Locality 1 sections.

Section 6 (Lat. 79°08'N, Long. 74°50'W) at Bartlett Bay is the most easterly section examined (Fig. 5), and it is unfortunate that only 42 per cent of this extremity of Baumann Fiord outcrop is exposed (Table 2). Talus obscures large parts of the sequence and the exposed strata commonly are weathered to gypsum to depths of up to 60 cm, making it difficult to procure fresh samples.

Comparison of the Arctic Platform sections (Fig. 5, Secs. 4, 7, 5, 6) shows the following relationships. First, there is a gradual thinning of the formation eastward, particularly in the B and C members (Fig. 5). The Baumann Fiord Formation near Section 6 possibly may be very close to the 'along-strike' extremity of its development, as evaporites at this level are unknown in Greenland (Troelsen, 1950). Second, there is much more sandy and argillaceous material in these sections than in those farther out in the miogeosyncline, suggesting a nearby clastic source area, presumably the Precambrian Shield. Finally, it is apparent that, as in the miogeosyncline, lateral variations in facies are pronounced at certain levels, making correlation between sections uncertain.

SEDIMENTOLOGY OF THE BAUMANN FIORD FORMATION

Although intertonguing of the Baumann Fiord carbonate and anhydrite lithofacies is rather intricate, in some places the formation as a whole can be viewed as a series of concordantly compounded carbonate-anhydrite cycles (Fig. 8). The cycles, which average 3.5 m in thickness, characteristically consist of a basal lime mudstone, an intermediate cryptalgal-stromatolite horizon and an upper anhydrite with accessory dolomite. Because these cycles constitute the fundamental genetic unit of the formation, an analysis of the depositional history of the single cycle leads directly to an understanding of the origin of the entire formation. The environmental model on which the following reconstruction is founded is that of sabkha genesis and diagenesis.

THE SABKHA

Sabkha evaporites

'Sabkha' is an Arabic word meaning 'flat salt-crusted desert' (Shearman, 1966). Any assemblage of evaporite minerals emplaced as a direct result of environmental conditions in such a desert setting may be legitimately termed a 'sabkha evaporite' deposit. Thus, the term 'sabkha', taken in its broadest sense, encompasses a great variety of evaporite deposits.

Coastal vs. continental sabkhas

Sabkha evaporites arise principally as a function of the extreme evaporitic conditions that prevail in sabkha desert environments. The waters from which the evaporites are derived may be largely of terrestrial origin, in which case the deposits are 'continental sabkha evaporites'. 'Coastal sabkha evaporites' stem from waters that are largely marine in origin. Since the initial discovery of the Trucial Coast sabkha and the introduction of the term 'sabkha' into the geologic literature (Shearman, 1963; Curtis *et al.*, 1963), the bulk of sabkha research has been concentrated on 'coastal sabkhas'. It is with the 'coastal sabkha' that this review is concerned. For simplicity, the term 'sabkha' is used herein to mean 'coastal sabkha', that is, a marine-derived sabkha.

The Trucial Coast sabkha

A review of the Recent Trucial Coast sabkha environment is appropriate here for two reasons: first to establish the character of the vertical sequence of lithofacies that develops in the sabkha setting, that is, a reference sequence to which the Baumann Fiord cycle may be compared; and second, to outline the known environmental parameters that control the genesis of the sequence, that is, a reference model on which the environmental reconstruction of the Baumann Fiord cycle may be based. This review encompasses only the most basic aspects of the Recent sabkha setting. For further

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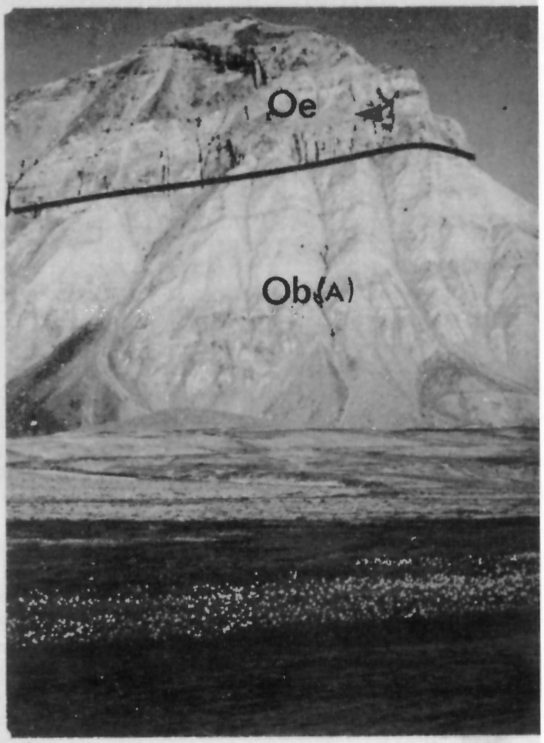

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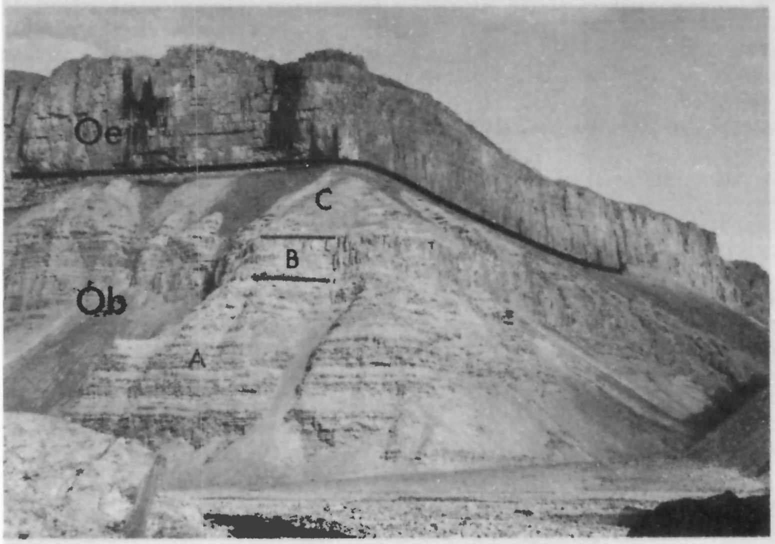

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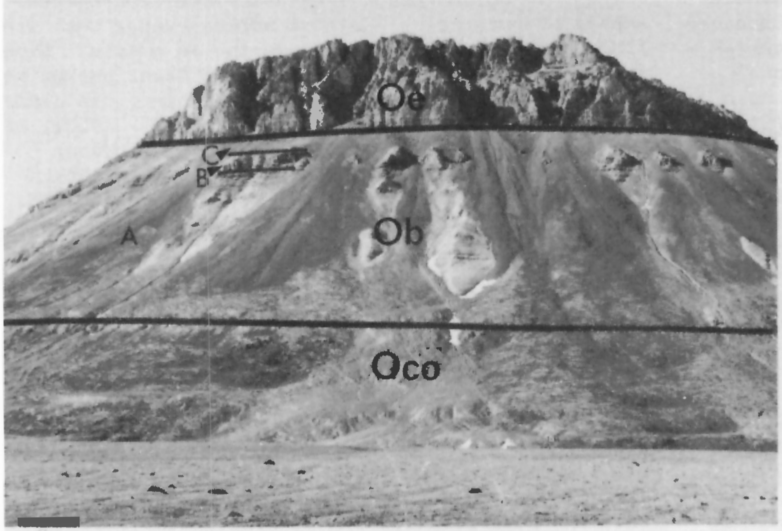

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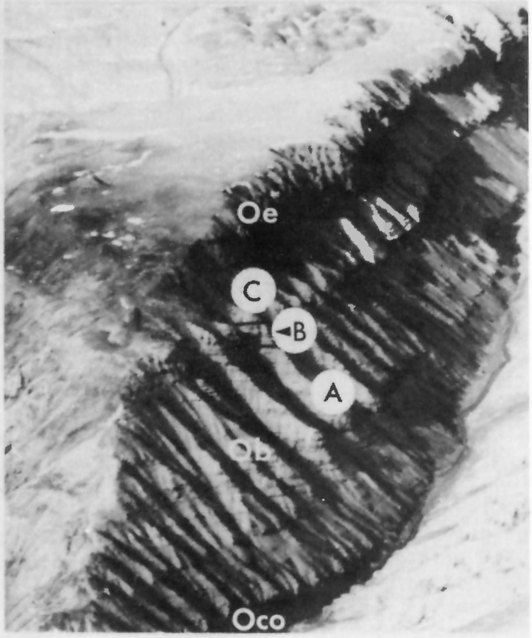

e

information on the Trucial Coast, and for a comprehensive bibliography of papers and theses pertaining to its carbonate and evaporite sediments, the reader is referred to Purser (1973), and to particular works by Bush, Butler, Cuff, Evans, Hsu, Kendall, Kinsman, Murray, Skipwith, Shearman, and Twyman.

The Trucial Coast of the Persian Gulf is an area of dominantly carbonate sedimentation. In the offshore region there is a complex of shoals, made up primarily of skeletal sands and oolites (*see* insert map, Fig. 9). Emergent parts of the shoals form a chain of islands that parallel the coast. Between the islands and the mainland lie shallow lagoons in which aragonite needle muds and pelleted muds are being generated. The broad coastal flat immediately adjacent to the lagoons is the sabkha proper. It extends for some 300 km along the coast and in places is as much as 30 km wide. The hinterland behind the sabkha is an area of arid continental sedimentation (Fig. 9).

Pits dug in the Abu Dhabi sabkha surface characteristically reveal the following vertical succession (Shearman, 1966): a basal marine facies, the uppermost part of which comprises subtidal carbonate muds of lagoonal origin; a thin intertidal algal mat facies; and a 1 m supratidal facies, the sabkha facies itself (Fig. 9). The sequence is clearly the record of a regressive cycle of sedimentation, each facies being diachronous in its development. In the last 3750 years, the system has undergone seaward progradation at a rate of about 1.6 km (1 mile) every 1000 years (Evans *et al.*, 1969).

The indigenous sediments of the supratidal facies consist predominantly of carbonates; in part wind-blown carbonate sand, derived principally from emergent offshore shoals, and in part aragonite mud derived from the lagoons. The latter is washed over the sabkha plain in the course of storms which periodically inundate the flats with marine flood waters. All the other mineral species present in the supratidal facies are of early diagenetic origin. These include replacive dolomite and magnesite, and displacive gypsum and anhydrite.

The mode of emplacement of these early diagenetic minerals is best considered by examining the sabkha's hydrologic system. Although there is considerable regional and seasonal fluctuation, the stable groundwater level in the sabkha is about coincident with the old buried algal mat, approximately 1 m below the sabkha surface (Fig. 9). The groundwaters, which are being continually concentrated by capillarity and/or evaporative pumping, are replenished in two ways: first, by gradual intra-sediment flow, fluxing inland from the

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FIGURE 7. Measured sections of the Baumann Fiord Formation:

a. Section 2, A member, viewed from the southeast. Note the monoclinal flexure in the Baumann Fiord strata at this locality (m). (GSC 161533)

b. Section 3, viewed from the west. The recessive weathering zone (r) in the otherwise resistant upper limestone contains no anhydrite and is mapped therefore as part of the Eleanor River Formation. Thus, only the A member of the Baumann Fiord Formation is defined at this locality. The peak is 800 m above the valley floor. (GSC 203264-K)

c. Section 4, viewed from the southwest. The basal part of the Baumann Fiord Formation and the Copes Bay Formation are buried by alluvium. The exposed thickness of the Baumann Fiord Formation is about 260 m. (GSC 161559)

d. Section 7, Witch Mountain, viewed from the southeast. The Copes Bay Formation here is more recessive than is usual. The Baumann Fiord Formation thickness is 295 m. (GSC 203264-J)

e. Section 5, Sanddola Creek, viewed from the air (*see* Fig. 2). The Baumann Fiord Formation is 265 m thick at this locality. (GSC 203264-L)

Oe	Eleanor River Formation
Ob	Baumann Fiord Formation
Oco	Copes Bay Formation (or equivalents).
C	C member
B	B member
A	A member

FIGURE 8. Baumann Fiord Formation carbonate-anhydrite cycles (Sec. 5). Each of the prominent, resistant bands is the carbonate component of a single cycle. The recessive bands are anhydritic. The cliff-forming strata at the top of the slope are the Eleanor River Formation limestones. The total thickness of the Baumann Fiord Formation at this locality is about 265 m. (GSC 203463-C)

lagoon; and, second, by downward seepage of the floodwaters that occasionally cover the sabkha surface. The former appears to be continually operative (Bush, 1973a, b), the marine-derived waters becoming increasingly concentrated as they progress farther and farther inland. This progressive concentration of the seawater produces a series of diagenetic minerals, some of which are direct precipitates and others the products of reactions between the brine and the earlier deposited sediment.

The first diagenetic mineral to form is gypsum. This grows displacively within the algal mats in the upper part of the present intertidal zone (Shearman, 1966). Accessory celestite ($SrSO_4$) is found also in the intertidal algal mat zone (Evans and Shearman, 1964). Additional displacive gypsum occurs in the supratidal sediment immediately inland from the high-tide mark (Fig. 9).

The fluxing brines that give rise to the gypsum crystals are concentrated relative to seawater by at least a factor of four. This order of relative concentration is a testament to the intensely evaporitic conditions that characterize the sabkha setting. By the time the seawater has been processed through the initial lagoonal, intertidal and nearshore supratidal environments, it is not only sufficently concentrated to precipitate gypsum, but also is modified markedly in its proportional concentration of dissolved substances. In particular, it is depleted in calcium, having precipitated two major calcium compounds in these early stages; namely, aragonite ($CaCO_3$) from the lagoonal waters, and aragonite and gypsum ($CaSO_4{:}2H_2O$) from the groundwaters of the intertidal and nearshore supratidal sediments. With the consequent increase in the Mg/Ca ratio of the brine, a considerable measure of dolomitization is promoted in the supratidal carbonate sediments (Fig. 9), and magnesite ($MgCO_3$) is present locally in the region proximal to high-water mark (Bush, 1973a, b).

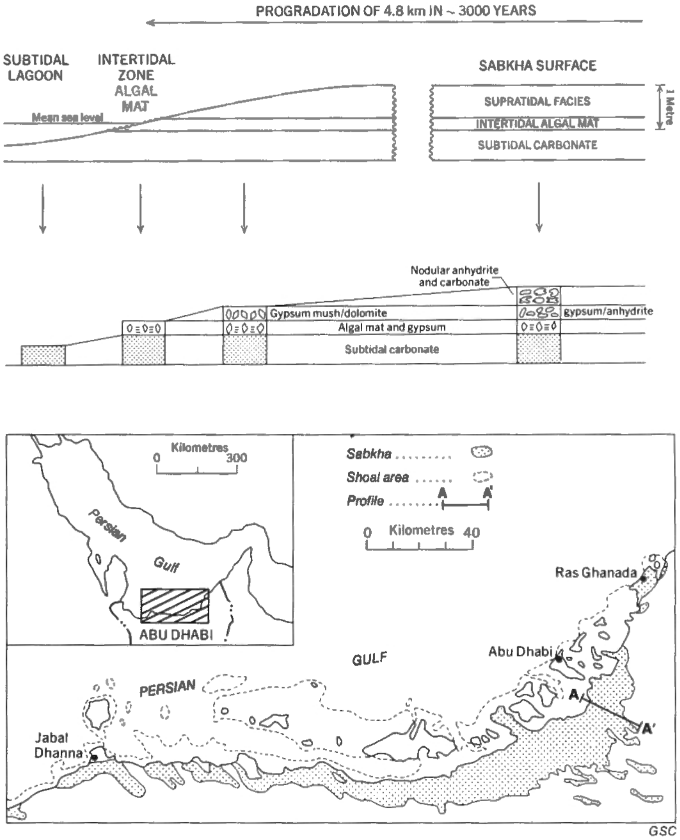

FIGURE 9. Schematic cross-section of the Trucial Coast sabkha complex, illustrating the form and distribution of early diagenetic evaporite minerals. The line of section is equivalent to A-A' on the Trucial Coast map. Map figured courtesy of P.R. Bush.

Anhydrite makes its first appearance in the supratidal sediments about 1 km inland from the normal high-water mark. It takes the form of either discrete nodules or bands of coalesced nodules. Growth of the nodules is by displacement of host carbonate, the calcium and sulphate being supplied by evaporative draw from the underlying groundwater brines. In some parts of the sabkha, anhydrite constitutes more than 50 per cent of the supratidal facies. Though many of the nodules appear to have originated as discrete entities, others clearly are derived from the alteration of pre-existing gypsum crystals (Holliday, 1968, 1973; Butler, 1970; Bush, 1973a, b). This alteration process results in the progressive loss of many of the earlier-formed 'algal mat' and 'gypsum mush' crystals (Fig. 9). In a general way, the predominance of anhydrite in the sabkha facies increases progressively toward the hinterland and, in parts of the sabkha far removed from the shoreline, it may be the sole calcium sulphate mineral present.

The Trucial Coast sabkha cycle thus can be viewed as the product of both depositional and diagenetic processes. The depositonal phase is manifest by progradational advance of the algal mats and the supratidal carbonates over the lagoonal sediments. This front is followed by a series of early diagenetic fronts, which lag behind the depositional front but which eventually result in a characteristic carbonate-anhydrite assemblage in the supratidal facies.

The sabkha cycle model

With continued research on the sediments of the Trucial Coast, it is becoming clear that there are many factors controlling sabkha deposition and diagensis and these are usually interrelated in an extremely complex manner. There remain many points of controversy regarding the nature of certain of the processes (*see* for example Hsu and Schneider, 1973; Bush, 1973a, b; Butler, 1969, 1970; Kinsman *et al.*, 1971; Holliday, 1973). However, the basic principles of sabkha development, as originally outlined by Shearman (1966) and Kinsman (1966, 1969), remain widely accepted as being sound. It is from this set of basic principles and associations that the 'sabkha cycle model' has evolved.

Although the Trucial Coast sabkha has provided the basis of the sabkha cycle model, the scope of the model has been delimited largely through analysis of ancient sabkha deposits. In the period since the Trucial Coast sabkha evaporites were first discovered, at least a dozen examples of fossil sabkha development have been documented (reviewed *in* Mossop, 1973b). The component cycles of these ancient sequences are all similar in their essential aspect: a shallowing-upward marine facies, commonly, but not universally, dominated by carbonates; grading upward into an intertidal facies, normally characterized by cryptalgal carbonates; overlain by a supratidal facies in which anhydrite is a principal component.

It is this sequence that forms the core of the sabkha cycle. Any set of strata that contains such a regressive succession may be justifiably termed a sabkha cycle. Apart from this requisite, however, there is no restriction on the variability that the sabkha cycle may embody. Some ancient sabkha cycles have an open-marine facies below the lagoonal carbonates, such as the Mississippian Madison Limestone cycle in Saskatchewan (Fuller and Porter, 1969). In others, the supratidal evaporites of some cycles are further overlain by continental red beds. The Windsorian cycles in Nova Scotia (Schenk, 1969) are an example. There are as many variations on the basic sabkha cycle theme as there are ancient examples.

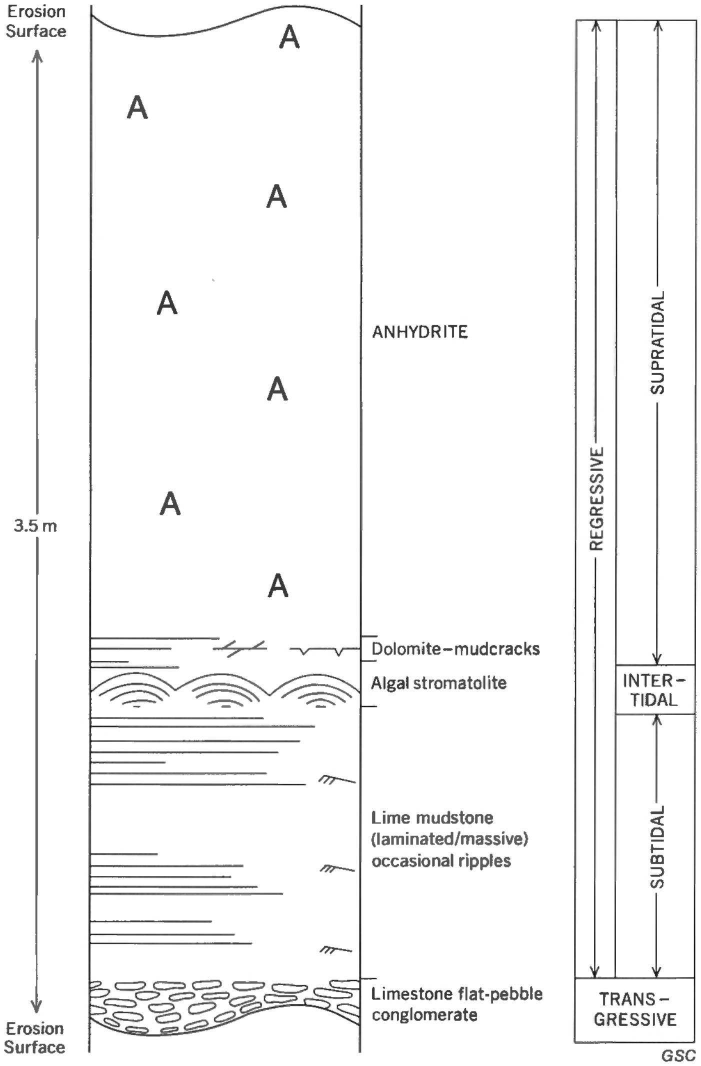

FIGURE 10. Schematic representation of a typical carbonate-anhydrite cycle of the Baumann Fiord Formation.

THE BAUMANN FIORD CYCLE

Figure 10 schematically depicts the vertical succession exhibited in a single Baumann Fiord cycle. Generally, these cycles average 3.5 m in thickness but there is significant regional variation. The cycle is made up of a basal limestone facies, dominated by lime mudstone, an intermediate cryptalgal facies, and an upper anhydrite-carbonate facies. It is argued that each of the components of this idealized cycle is justifiably explicable in terms of the sabkha cycle model.

Erosion surface

The erosion surface at the base of the cycle is characteristically sharp; the contact between the top of the underlying anhydrite and the base of the carbonate, although in places noticeably undulose, commonly is essentially concordant. The surface as such is, in places, marked by a thin film of dolomite.

It is probable that the erosion surface marks the passing of a marine transgression over the pre-existing supratidal flat, eroding and in part dissolving the uppermost reaches of the supratidal facies. That such a transgression would be accompanied by erosive action is demonstrated by the way in which storm-flooding of the Trucial Coast sabkha, a process that in many ways simulates that of rapid transgression, brings about erosion. In the wake of the Trucial Coast floods, the uppermost carbonate sediments of the supratidal flat are stripped away and much of the anhydrite that previously was some 8 to 10 cm below the surface is laid bare. In places, anhydrite nodules are eroded physically and in others they are partially dissolved by the relatively dilute seawater (Bush, 1973a). But, as noted previously, the Trucial Coast sequence does not in itself illustrate the implications of marine transgression, there being only a single cycle developed there to date. From the ancient sabkha cycles cited earlier, however, it appears that erosion of the top of a cycle is a natural by-product of rapid marine transgression.

Flat-pebble conglomerate

Immediately above the erosion surface there is a limestone flat-pebble conglomerate, normally 6 to 8 cm thick (Fig. 10). The conglomerate, normally grey to grey-brown in colour, consists of well-rounded flat pebbles, up to 5 cm across and with diameter to thickness ratios of about 4 to 1. The plane of flattening of the pebbles usually is parallel to bedding (Fig. 11a). Individual pebbles commonly are in direct contact with one or more adjacent pebbles, the whole set in a matrix of micrite. The pebbles, characteristically, are composed largely of homogeneous micrite, minor amounts of quartz silt (<5 %) being the only common impurity. More than 90 per cent of the pebbles are of this type. The remaining pebbles exhibit a great variety of internal lithologies, with constituents comprising skeletal fragments, pellets, intraclasts, lumps and ooliths, all set in a micritic matrix. In thin-section, these exotic pebbles stand out in striking contrast to the normal micrite pebbles (Fig. 11b). The matrix in which the pebbles occur consists dominantly of lime mudstone, usually structureless but in some places having a pelleted appearance. Minor amounts of skeletal detritus, with accompanying

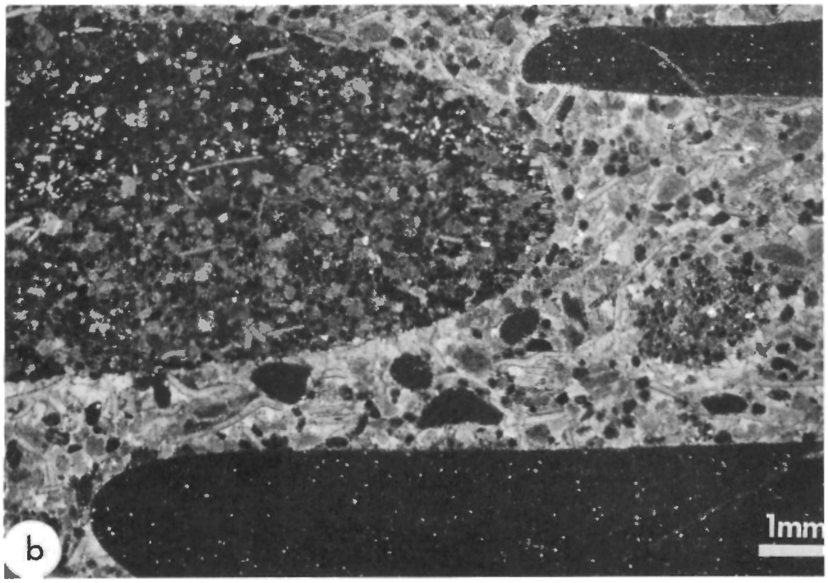

FIGURE 11.

a. Limestone flat-pebble conglomerate from the base of a Baumann Fiord cycle, viewed in plan. (GSC 203463-D)

b. Photomicrograph of limestone flat-pebble conglomerate, ordinary light. Micrite pebbles are in the bottom and upper right parts of photograph. Exotic, allochem-rich pebble is at left. This thin section shows an extraordinary abundance of allochems in the matrix. (GSC 203463-E)

intraclasts and other allochems, locally constitute a small fraction of the matrix. Dolomite is a common accesory constituent of the matrix (up to 35%). Blocky neomorphic calcite is a characteristic matrix cement.

Flat-pebble conglomerates of this type have been described in the Lower Ordovician Tribes Hill Formation of New York (Braun and Friedman, 1969). There, it is argued that the conglomerate originated as a result of reworking of desiccated mud-flat sediments. It seems reasonable to suggest that the Baumann Fiord flat-pebble conglomerate originated in a similar manner. Furthermore, it would seem that the deposition of a conglomerate of this type would be a natural by-product of rapid marine transgression over a pre-existing sabkha flat. Evidence to corroborate these suggestions is as follows.

First, there are ancient sabkha analogues. For example, Wood and Wolfe (1969) report that flat-pebble conglomerate is a characteristic feature of the zone immediately above the erosion surface in the Arab/Darb sabkha cycles. Similarly, some of the Purbeck sabkha cycles (Shearman, 1966) are characterized by carbonate conglomerate at the base and it is suggested (D.J. Shearman, pers. com., 1973) that these are the result of reworking of former supratidal carbonate sediments.

Second, there is a potential Recent analogue in a supratidal flat setting on Sugar Loaf Key, Florida (Shinn, 1968). There, 'washover' lime mud has been subjected to years of continuous desiccation and the mud polygons are undergoing gradual disaggregation to form flattened, pebble-size clasts (*see* Shinn, 1968, illustration, p. 615). The matrix in which the mud pebbles reside is selectively dolomitized (up to 25% dolomite). High-energy reworking of these sediments, either by marine transgression or spring-tide storm flooding, could produce a flat-pebble conglomerate lag deposit similar to that developed in the Baumann Fiord cycle.

Third, there is evidence from the Baumann Fiord conglomerate itself. The pebbles clearly have undergone some measure of transport, as shown by their well-rounded aspect. Those pebbles that consist of homogeneous micrite may have been derived from reworking of desiccated 'washover' lime mud on the supratidal flat proper; i.e., reworked essentially *in situ*. However, it is apparent that at least some of the pebbles, notably those with exotic lithologies, were derived from some distance away, their original environment of deposition being more readily attributable to more open marine conditions, i.e., toward the seaward edge of the sabkha complex, either in or immediately adjacent to the island shoals. Part of the pebble matrix, which includes sketetal detritus and other allochems, may stem from the same environment as that of the exotic pebbles. In summary it is clear that the character of the flat-pebble conglomerate is consistent with the thesis that it originated by reworking of former supratidal lime mud and that the transgression that brought about erosion of the top of the previous cycle was responsible also for the deposition of the flat-pebble conglomerate.

Lime mudstone

A sequence of lime mudstones that overlies the flat-pebble conglomerate shows a variety of sedimentary structures (Fig. 10). This lime mudstone facies is characterized by a paucity of fossils and the only accessory constituents are small amounts of quartz silt and clay (usually <5%) and disseminated organic remains. Much of the lime mudstone is essentially structureless, composed of very pure micrite[1] but containing as well some wisps of organic matter (Fig. 12). Laminated material also is composed of relatively pure micrite but some laminae are enriched slightly in quartz silt, whereas others are enriched in organic matter (Fig. 13). Sparse ripple marks, in places highlighted by partings of silt or pellet-rich lime mudstone, occur sporadically throughout the interval (Fig. 10).

The lime mudstone facies is interpreted to have been deposited in a shallow lagoonal environment comparable with the present-day Trucial Coast lagoon complex. However, the genesis of the aragonite needle mud in the Trucial Coast lagoons remains a point of conjecture. Kendall and Skipwith (1969) argue that there is a physiological control on precipitation with algal mucilage playing an important role in triggering aragonite nucleation (Bathurst, 1971, p. 205). Much of the organic matter in the Baumann Fiord lime mudstones may be of algal origin and the possibility exists that there is a causal link in the association.

Kinsman (1964, p. 178), on the other hand, concludes that "80-90 percent of the mid and inner [Trucial Coast] lagoon sediments must have been chemically precipated". This conclusion is based on a number of lines of evidence, the most pointed of which relates to the high strontium content of the muds (average 9390 ppm; Kinsman and Holland, 1969). No local biogenic source of high strontium aragonite is capable of supplying the required quantity of mud. Furthermore, the 9390 ppm value is consistent with that expected in aragonite precipitated in equilibrium with lagoon waters at the known temperatures (average 26-30°C; salinity 65°/₀₀ in the inner parts of the lagoon; Kinsman, 1964). Salinity and temperature in the Baumann Fiord lagoons may have been comparable to or even higher than those in the Trucial Coast, and it may be that much of the Baumann Fiord lime mudstone originated as a direct aragonite precipitate.

A major difference between the present-day lagoonal lime muds and the Baumann Fiord lime mudstones is the characteristic lack of pellets in the latter. Kinsman (1964) considers the ubiquitous pellets of the Trucial Coast lagoons to be fecal in origin, and there is no doubt that abundant lagoonal infauna and epifauna are capable of bringing about the observed degree of pelleting. Most of the Baumann Fiord lime mudstones lack skeletal material. There are no trace fossils and evidence of bioturbated is lacking. These features all point to there being, at best, a very restricted faunal community associated with the lime mudstone facies. Perhaps this is explained best by postulating that, in Early Ordovician time, deposit-feeding faunas were not evolved to the point where they could tolerate high-salinity conditions. Where pellets and skeletal remains are preserved (Fig. 14), it is possible sometimes to document local or temporal freshening of the lagoonal waters (e.g., associated fluviatile red beds; Mossop, 1973a, b). Other pelletal and skeletal detritus in the sequence, such as that associated with the basal conglomerate, is clearly allochthonous, and likely derived from the open-marine front.

Ripple structures and wavy lamination in the lime mudstone facies are somewhat of an anomaly. Mud-size sediment does not as a rule lend itself to current rippling, although rippled mud, commonly in association with pelleted mud, has been described in Recent sediments at scattered localites (Oertel, 1973). In some of the Baumann Fiord occurrences, small amounts of quartz silt or pelletal carbonate are present as distinct ripple crest laminae and it is these constituents that may have altered the mechanical properties of the sediment to an extent that allowed current rippling. In other places, no sand or silt size component is recognizable and the possibility exists that, under certain conditions, aragonite needle mud can undergo current rippling.

Taken as a whole, the lime mudstone facies of the Baumann Fiord cycle is seen as a shallow lagoonal deposit, now composed mainly of micrite but probably originally laid down as aragonite mud, some of which could have been a direct chemical precipitate. The deposit is essentially similar to the Trucial Coast lagoonal sediments and direct comparison of the two does not reveal any irreconcilable points of divergence. More important, all the characteristics of the Baumann Fiord lime mudstone facies are explicable in terms of shallow subtidal genesis and this is the single requisite for its interpretive identity with the model sabkha cycle.

Cryptalgalaminates and stromatolites

The top of the lime mudstone facies grades upward into a zone of 'algal-laminated' micrites, normally 20 to 30 cm thick. Delicate, co-planar lamination characterizes these micrites, the laminae being essentially planar although some show low-relief domal irregularities. Birdseye structure is common. The designation 'cryptalgalaminate' (Aitken, 1967) appears to suit the observed character of these rocks.

Cryptalgalaminate dominates this zone in some places but, commonly, more distinctive cryptalgal structures also are in evidence. The stromatolites assume a number of characteristic forms. In describing the different forms, the writer has chosen to employ the terminology defined by Aitken (1967), primarily because it accords most closely with historically established usage. The extremely precise and adaptable designations of the classification scheme set up by Logan *et al.* (1964)[2] are included in parentheses.

All the Baumann Fiord stromatolites have one aspect in common: they are composed almost entirely of micrite, with trace amounts of organic matter defining a delicately laminar internal structure. Three distinct groups are recognized, categorized on the basis of their external form (Mossop, 1973b): branching digitate stromatolites, polygonal stromatolites, and domal stromatolites.

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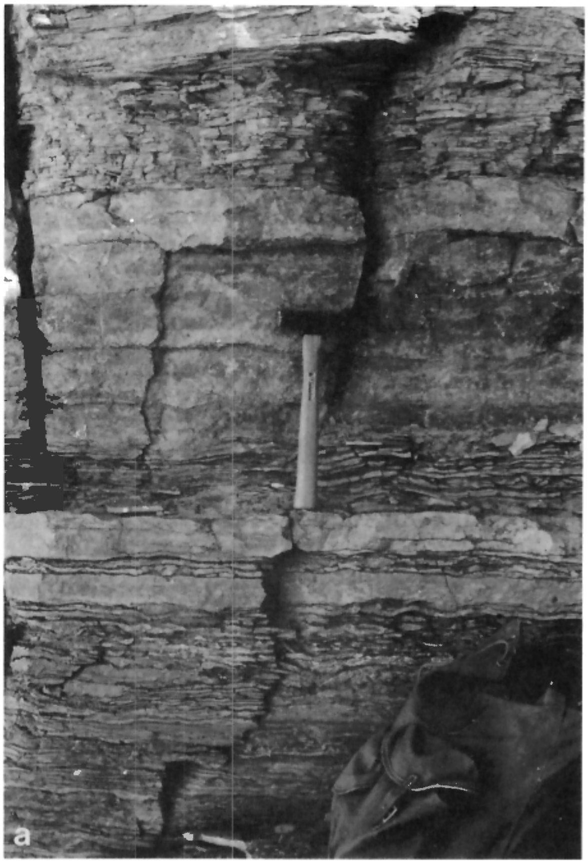
[1] The lime mudstone has undergone a measure of neomorphism, largely converting the micrite to microspar (>4 μm).

[2] Based on three basic geometric configurations: Vertically Stacked Hemispheroids (SH), Laterally Linked Hemispheroids (LLH), and Spheroidal Structures (SS).



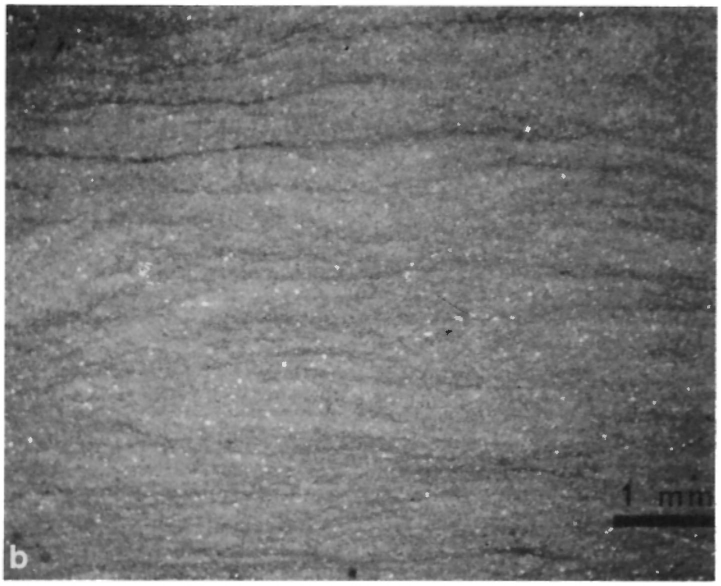


FIGURE 12.
  a. Bedded lime mudstone, interbedded with wavy-laminted to lenticular lime mudstone, in the basal part of an extraordinarily thick Baumann Fiord cycle. (GSC 203463-F)

  b. Photomicrograph of bedded lime mudstone, ordinary light. White grains of quartz silt are scattered throughout. Note the wisps of dark organic matter. (GSC 203463-G)

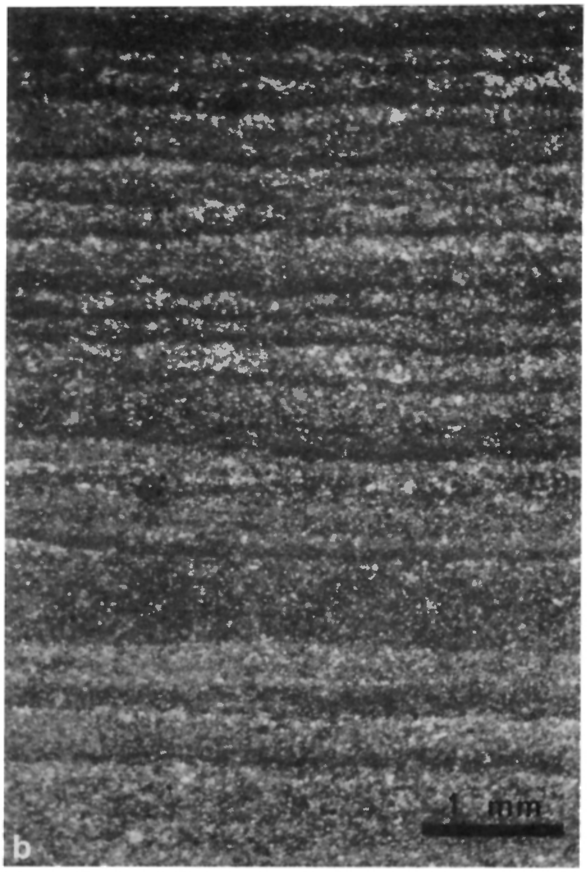


FIGURE 13.
  a. Laminar lime mudstone in the basal part of a Baumann Fiord cycle. White material on the outcrop surface is vein-filling calcite. (GSC 161536)

  b. Photomicrograph of laminated lime mudstone, ordinary light. Laminae are defined by dark organic material and by varying proportions of light-coloured quartz silt. (GSC 203463-H)

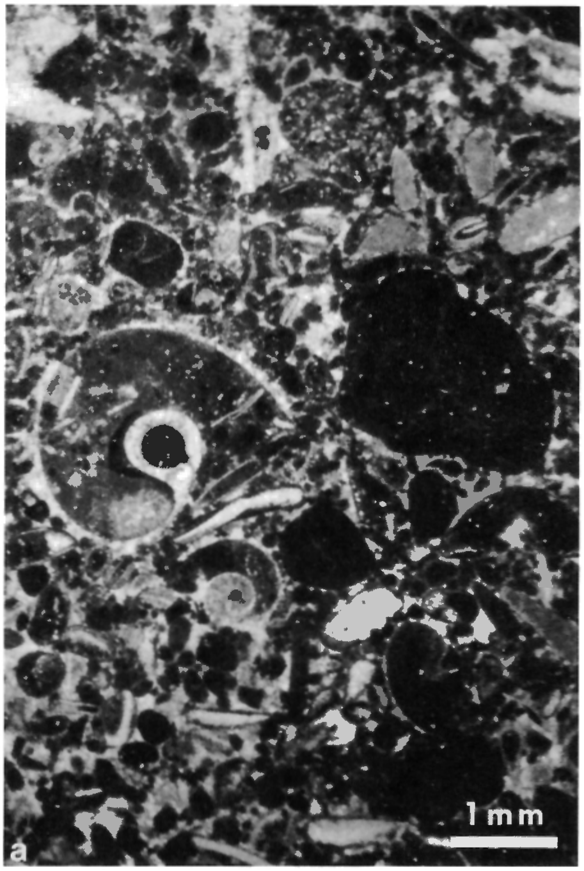
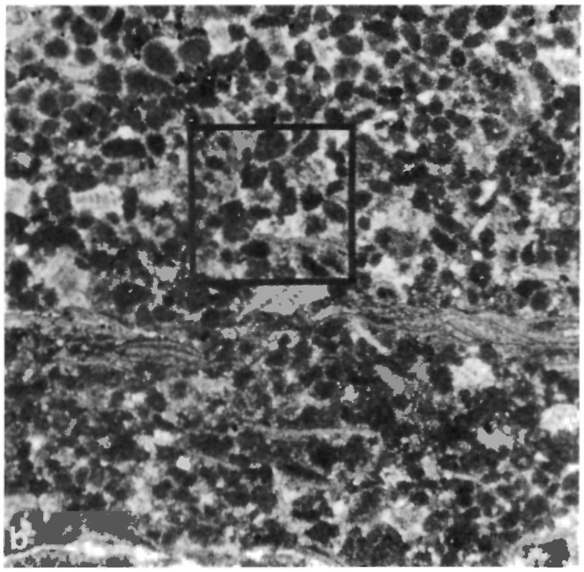


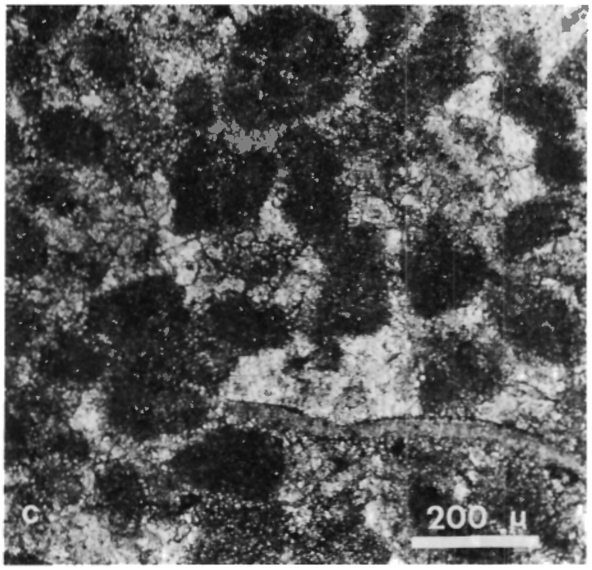
FIGURE 14.

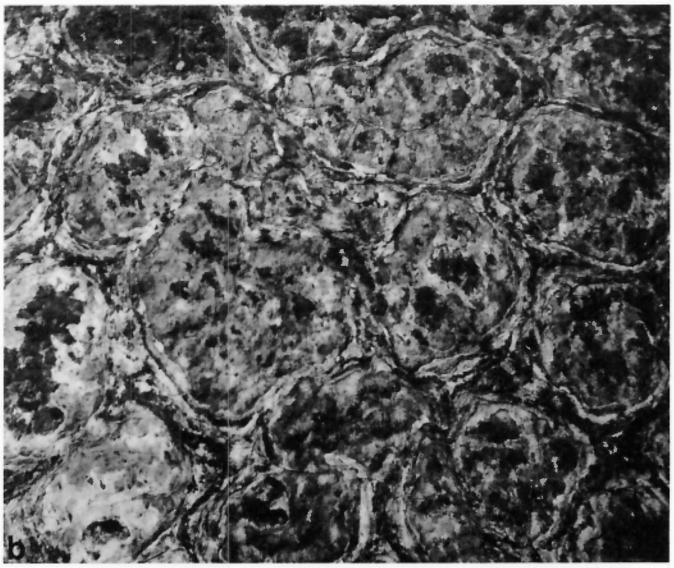
a. Photomicrograph of fossil-rich packstone from one of the rare fossil-rich horizons in the Baumann Fiord Formation, ordinary light. Constituents include skeletal fragments, pellets and coated grains. (GSC 203463-I)

b. Photomicrograph of pellet grainstone in beds associated with fossil-rich horizons, ordinary light. (GSC 203463-J)

c. Magnification of the area outlined in Figure 14b. (GSC 203463-K)







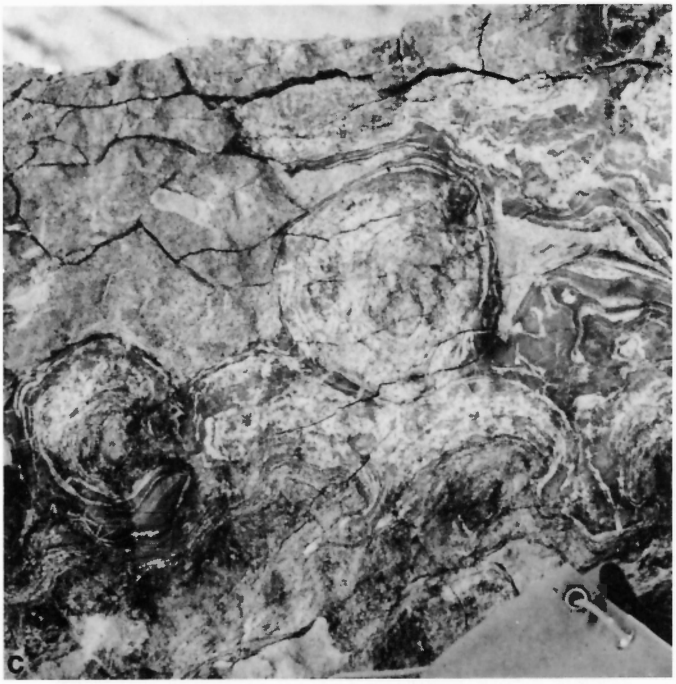


FIGURE 15.

a. Digitate stromatolites with convex internal lamination, cross-sectional view. The stromatolites weather dark and the matrix appears light coloured. (GSC 203463-L)

b. Polygonal stromatolites, viewed in plan. Polygons average 15 cm across. (GSC 161524)

c. Domal stromatolites, viewed in plan. Differential weathering of the tops of the domes reveals the concentric pattern of the internal lamination. (GSC 203463-M)

Digitate forms are the common and these exhibit the following characteristics (Fig. 15a):

- Individual 'fingers', which measure up to 2 cm across, are comprised of stacked hemispheroids (SH-V), with relief to 5 mm.
- The hemispheroidal laminae usually are very closely spaced (<1 mm apart).
- As a rule, the 'fingers' show a tendency to branch upward; i.e., single 'fingers' repeatedly bifurcate upward.
- The matrix in which the 'fingers' are imbedded normally is composed of dense micrite.
- Viewed in plan, it is not possible to discern any alignment or pattern amongst the 'fingers'.

Polygonal stromatolites (Fig. 15b):

- The polygons measure about 15 cm across and, though essentially linear along their edges, they normally are slightly rounded on the corners.
- The polygons average 5 cm in thickness and, viewed in cross-section, consist of closely spaced algal laminae that terminate abruptly along the usually slightly upturned edges of the polygon (SH-I; Kendall and Skipwith, 1969).
- Interstices between polygons commonly are filled with dense micrite.

Domal stromatolites (Fig. 15c):

- Individual domes, up to 30 cm high, consist of stacked hemispheroids (SH-V) with low internal relief (~2 cm), the lamination being delicate and closely spaced (1 mm).
- Discrete domes, usually about 10 cm across at their base, commonly increase in radius upward and may coalesce with adjacent domes (SH-V → LLH-C).
- In plan, the domes are circular to slightly eliptical and commonly are aligned in rows.

These three basic forms make up all of the stromatolites of the Baumann Fiord Formation (digitate, 65%; polygonal, 25%; domal, 10%). In any one place, a single form tends to dominate, but others are usually in evidence as well. The most characteristic associations are those in which cryptalgalaminate dominates the basal part of the zone, giving way to digitate stromatolites in the upper part. Where polygonal or domal forms occur, they are usually in the upper part of the zone, underlain by cryptalgalaminate or digitate stromatolites.

The most obvious Recent analogue to the Baumann Fiord stromatolites, at least from the point of view of evaporite-association, is that of the Trucial Coast. There, the algal mats are restricted largely to the intertidal zone (Kendall and Skipwith, 1968). Four mat types were recognized by Kendall and Skipwith (1968) and, of these, only their high intertidal 'polygonal zone' mats resemble structures developed in the Baumann Fiord Formation. Similar polygonal algal mats have been described in the high intertidal zone in other parts of the Persian Gulf (Illing *et al.*, 1965), the Bahamas (Black, 1933), and Florida (Ginsburg *et al.*, 1954). Although algal stromatolites resembling those developed in the other three Trucial Coast zones were not recognized in the Baumann Fiord cycles, some of the internal lamination of these present-day algal mats is similar to the cryptalgalaminate described in the ancient sequence.

Recent domal stromatolites have been reported in periodically exposed tidal flat settings in the Bahamas (Black, 1933), Florida (Ginsburg *et al.*, 1954), and Shark Bay, Western Australia (Logan, 1961; Logan *et al.*, 1974; Davies, 1970; Hoffman, 1971). Many of these present-day forms are strikingly similar to the Baumann Fiord domal stromatolites and it follows that the ancient examples may have formed under conditions similar to those of the Recent.

The origin of digitate forms is somewhat more problematical because Recent analogues are scarce. Hoffman (pers. com., 1972) reports digitate forms in a very shallow subtidal setting at Hamelin Pool, Shark Bay. It is not known, however, whether these actually are growing in this quiet subtidal setting or if they are relict from a previous period in which mean sea level was slightly lower. Logan *et al.* (1964) deduced that some digitate forms develop in the low intertidal zone. Aitken (1967) also assigned digitate stromatolites to the intertidal zone. The Baumann Fiord digitate stromatolites thus may have originated in the low intertidal zone but at least some of them may have grown in a shallow subtidal setting.

Garret (1970) demonstrated that, if certain living intertidal and supratidal algal mats are transplanted into the low intertidal or shallow sublittoral zone and there fenced off from the browsing cerithid gastropods that would normally devour them, they are capable of survival and even accretion. If, as maintained in the previous section, the Baumann Fiord lagoons were practically devoid of browsers due to prohibitively high salinities, then it seems possible that the algal mats may have spread into the sublittoral zone. Some of the cryptalgalaminates of the Baumann Fiord sequence may be of sublittoral origin.

It is interesting to note that, in the Baumann Fiord stromatolites, there is no definitive evidence of the former presence of interstitial gypsum, either in the form of observable gypsum pseudomorphs or otherwise. On the Trucial Coast, 'algal-mat' gypsum is restricted to the high intertidal zone, where evaporitive concentration of the seawater is sufficient to allow gypsum precipitation. In the Baumann Fiord setting, the lack of 'algal-mat' gypsum suggests that either the landward fluxing brines did not become sufficiently concentrated within the near-shore zone or that high intertidal algal mats were not developed extensively. A definitive solution to this problem is not possible at present.

In summary, the following reconstruction is proposed. Algal mats were able to spread over the shallowest sediments of the lime mudstone facies. These initial mats may have been either wholly or partially subtidal in origin and their propagation produced cryptalgalaminated fabrics and possibly some digitate stromatolite structures. Other digitate stromatolites along with polygonal and domal forms, structures that characteristically overlie the cryptalgalaminite, grew in the intertidal zone and were founded on the earlier formed algal mats.

Dolomite

The anhydrite facies of the Baumann Fiord cycle commonly rests directly on the top of the stromatolitic horizon. In some places, however, there is preserved a thin zone of carbonate material between the stromatolites and the anhydrite (Fig. 10). This zone, rarely more than 5 to 8 cm thick, consists of two components: a crudely laminated micrite and a microdolomite. The two are present in the ratio of 3:1 dolomite to calcite but they are mixed rarely in a uniform manner. Rather, the horizon is characteristically segregated into small lenses of relatively pure micrite residing in a mass of microdolomite. The dolomite is itself crudely laminated (Fig. 16b) and in some cases individual laminae can be followed from a micrite pocket into the adjacent dolomite. Desiccation cracks, rare elsewhere in the cycle, are preserved locally within this dolomite-micrite facies (Fig. 16a).

The original sediments of this facies are thought to have consisted of pure lime mud, washed over onto a supratidal flat by high spring tides or storms, and subsequently subject to desiccation-cracking due to prolonged exposure. This type of 'washover' lime mud is well known from the Trucial Coast sabkha and, as outlined previously, is extremely susceptible to dolomitization by the marine brines that subsequently pass through it (Bush, 1973a, b). It is not known why certain lenses in this washover facies were spared from dolomitization but permeability differences may have been an important factor, the slightly 'tighter' pockets having been by-passed by the fluxing brines.

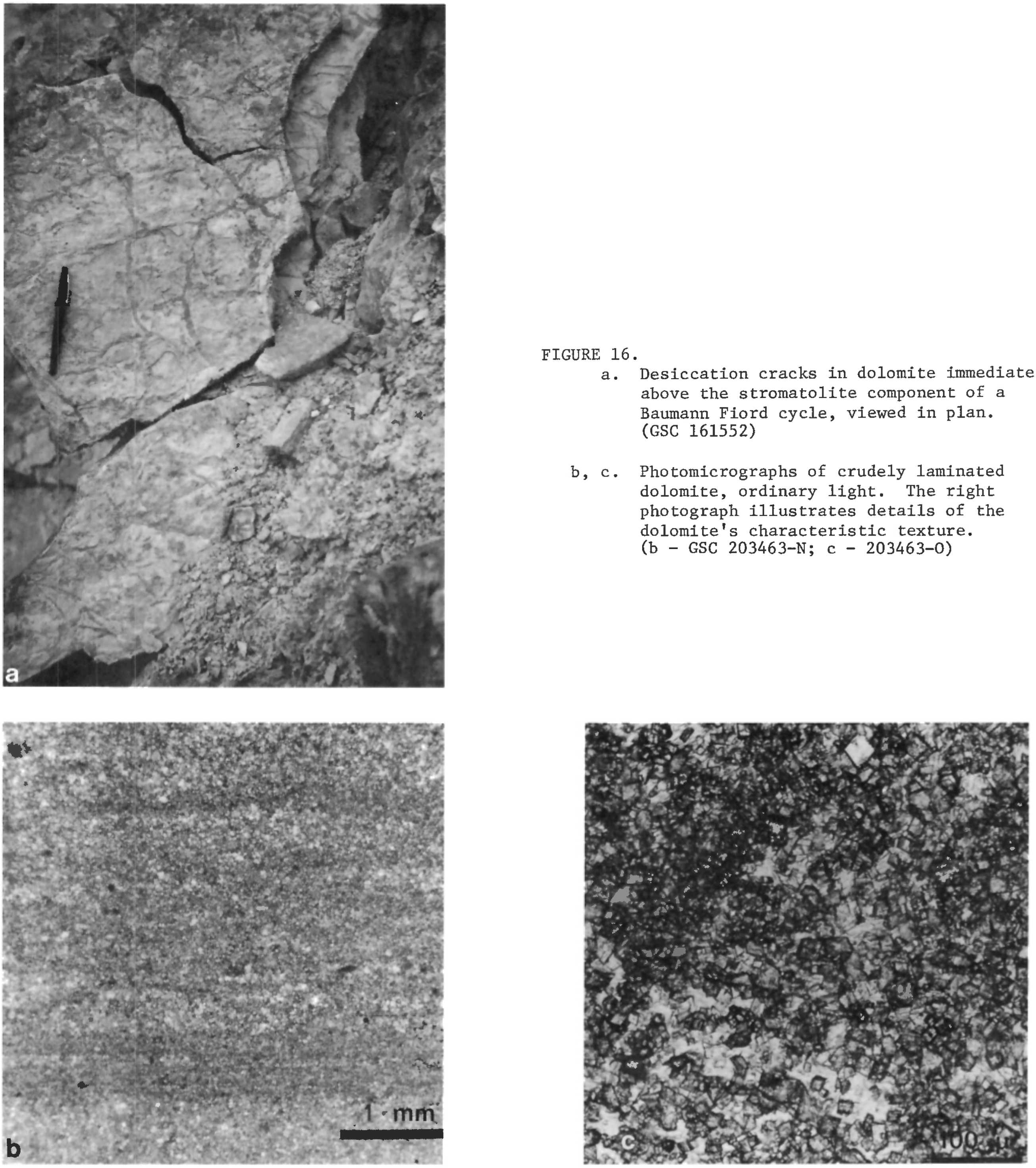


FIGURE 16.

a. Desiccation cracks in dolomite immediately above the stromatolite component of a Baumann Fiord cycle, viewed in plan. (GSC 161552)

b, c. Photomicrographs of crudely laminated dolomite, ordinary light. The right photograph illustrates details of the dolomite's characteristic texture. (b - GSC 203463-N; c - 203463-O)

Anhydrite

It would be misleading in the extreme to suggest that the anhydrites of the Baumann Fiord cycle are characteristically of the nodular form that typifies those of the Recent sabkha environment. In fact, most of the Baumann Fiord anhydrites have virtually none of the textural or morphological characteristics normally associated with anhydrites of supratidal origin. Rather, thinly layered or 'bedded' anhydrites are the norm, modes of occurrence practically unknown in the Recent. It is held, nevertheless, that the Baumann Fiord anhydrites originally were of typical nodular form but that they underwent extensive secondary modification including compactional and tectonic flow and, in some cases, metamorphic recrystallization, thereby extensively transforming and even obliterating their original aspect and form (*see* below).

In a few places, however, nodular structure in the anhydrite is preserved more or less intact and it is on these occurrences that the following discussion is based. In the field, these occurrences of anhydrite exhibit 'chicken-wire' structure (named as such by Forgotson, 1958), with closely spaced nodules, separated from one another by thin wisps of matrix material, either dolomite, micrite or organic matter (Fig. 17). In the classification scheme devised by Maiklem *et al.* (1969), this 'chicken-wire' structure is termed 'mosaic' or 'nodular mosaic' anhydrite. Close inspection of the nodules reveals that they are of the spherical to oblate form that is characteristic, though not diagnostic, of Recent sabkha anhydrite nodules. They are very densely packed and, in many specimens, matrix material constitutes less than 5 per cent of the bulk volume of the rock.

Anhydrite nodules in the Trucial Coast sabkha have been shown to grow by displacement of detrital carbonate (Shearman, 1966; Kinsman, 1966), the mechanical force of nodule growth being sufficient to push the host material aside. Thin sections of Recent anhydrite nodules from the Trucial Coast sabkha consist of lath-like cleavage flakes of anhydrite arranged in a decussate manner (Fig. 18a). The petrographic character of the Baumann Fiord nodular anhydrites (Fig. 18b) is, in all essential regards, identical with that of the Recent sabkha anhydrites. This petrographic identity cannot be taken as proof of genetic identity, however. Ancient nodular anhydrites with this type of petrographic character have been interpreted to have formed in a variety of environments, including shallow-marine or even 'deep' water settings (e.g. Wardlaw and Reinson, 1971; Wardlaw and Christie, 1975; Bebout and Maiklem, 1973; Davies and Ludlam, 1973; Davies and Nassichuk, 1975). There is indication, also, that certain ancient nodular anhydrites originated largely through replacive processes (as opposed to strictly displacive) in semi-indurated or fully lithified carbonate rocks (e.g. Corrigan, 1974; Bebout and Maiklem, 1973). In short, there does not seem to be any aspect of the structure or fabric of nodular anhydrite that can be considered diagnostic of a particular genetic setting. All that can be said about the Baumann Fiord nodular anhydrites is that their structure and fabric are consistent with a sabkha origin. The strongest argument in favour of a supratidal origin for the Baumann Fiord anhydrites is that they characteristically occur above carbonates of intertidal origin.

As a reconstruction of how the Baumann Fiord nodular anhydrites originated, the following sequence of depositional and early diagenetic events is postulated: above the intertidal zone algal mats, there was deposited some thickness of supratidal 'washover' lime muds. Subsequent dolomitization of these muds, due to reaction between the sediments and marine-derived brines, yielded the 'dolomite' facies. This dolomitized washover horizon is preserved only locally in the Baumann Fiord sequence and it is suggested that its lack of persistence is due to the disruption that early diagenetic growth of nodular anhydrite affected within it. The nodules grew displacively and jacked up the host carbonate, eventually yielding a nodular mosaic anhydrite deposit.

Discussion

The foregoing interpretive ideas regarding the Baumann Fiord cycle are largely substantiative in nature. They focus on establishing the applicability of the sabkha model in explaining the observed features of the Baumann Fiord cycle, rather than on attempting to discredit possible alternative interpretations. The model sabkha cycle, in its most fundamental form, comprises the following requisite elements: a basal shallow marine facies, followed upward by an intertidal facies, in turn overlain by a supratidal facies in which evaporites are a principal constituent. It is felt that the sequential components of the Baumann Fiord cycle accord completely with the requirements of the model sabkha cycle, save that the anhydrite facies does not exhibit, typically, the characteristic nodular structure and, even if it did, the structure could not be proven to be of supratidal origin. Apart from desiccation cracks in the host dolomite, which could be considered direct evidence of emergence, there are no unequivocal criteria on which a sabkha interpretation can be founded. A supratidal origin is favoured here largely because of the configuration of the associated carbonate facies. It is a configuration that, having progressed upward from subtidal to intertidal, points very strongly to a supratidal anhydrite cap to the sequence, completing a full regressive cycle.

FACIES RELATIONS IN THE BAUMANN FIORD FORMATION

In places, the Baumann Fiord Formation is made up of dozens of sequential repetitions of the basic cycle described above. However, at most localities, at least part of the sequence is not so straightforward. There are examples of extraordinarily thick carbonate development and of thick anhydrite development. Lateral intertonguing of anhydrite and carbonate lithofacies commonly is very intricate, as evidenced by the variability in the measured sections (Figs. 4, 5). If the sabkha concept of the formation's genesis is to retain credibility, these complexities must be explained.

In order to deal with the question of variability in the way Baumann Fiord cycles are compounded, it is first necessary to explore the mechanism by which sabkha cycles normally are stacked one upon another to form thick sequences. At the outset, it must be stated that the building up of thick sequences of cycles can take place only in a regime of net subsidence. Sabkha cycles are deposited essentially at sea level and for one cycle to be initiated above another requires that the first one subside below the sea level datum.

FIGURE 17. Mosaic anhydrite, preserved in a relatively undistorted state. The 'chicken-wire' between the nodules here consists of dark-coloured dolomite and some organic matter. (GSC 203463-P)

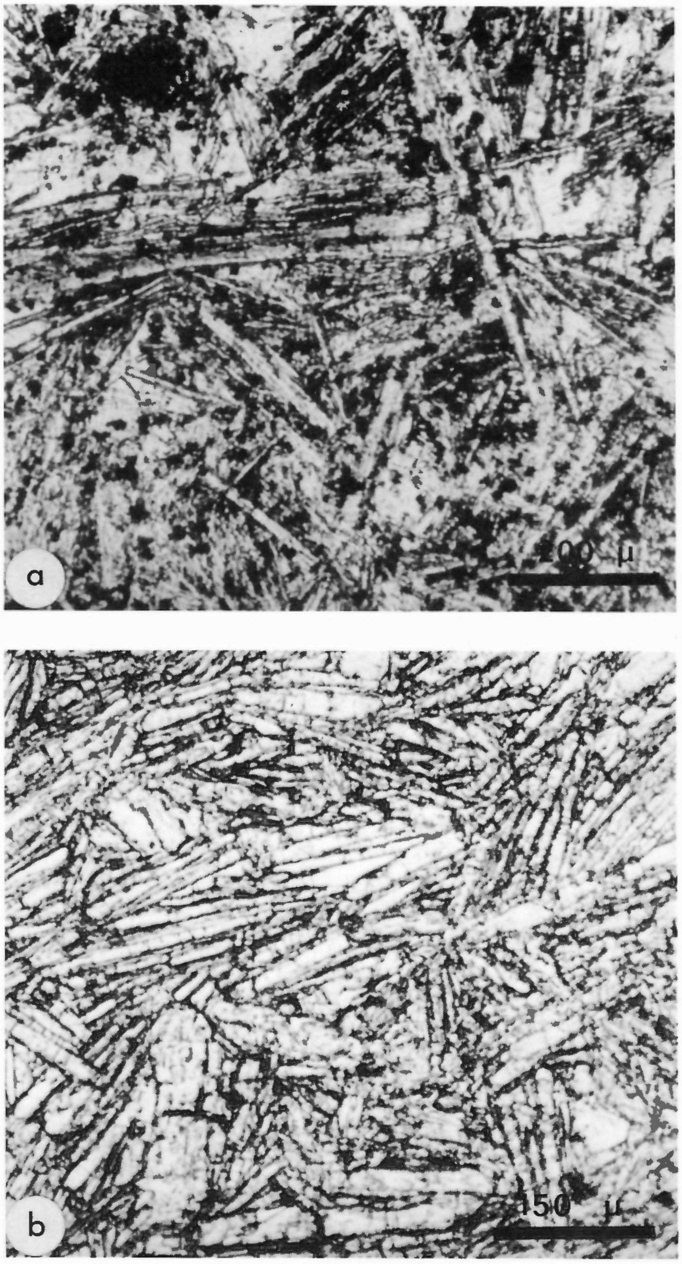


FIGURE 18.

a. Photomicrograph of nodular anhydrite from the Recent sabkha, Trucial Coast, ordinary light. Note decussate arrangement of the anhydrite cleavage flakes. Photograph courtesy of D.J. Shearman. (GSC 203463-Q)

b. Photomicrograph of nodular anhydrite from the Baumann Fiord Formation, ordinary light. Note the textural similarity to that in the Recent anhydrite. (GSC 203463-R)

A second mechanism assumes relatively constant subsidence rates and calls upon sedimentary factors to control the observed periodicity. Consider a single point in a sabkha complex and assume that subsidence at that point proceeds at a constant rate. At the beginning of a given cycle, that point will be in the shallow lagoon. As the progradational front passes, shoreline accumulation of detrital carbonate will be very rapid at the point and it will go from below mean sea level to a metre or so above in a relatively short period of time. During the passing of the front, then, accumulation rate greatly exceeds subsidence rate. Subsequently, vertical accretion will diminish, for as the shoreline progrades farther and farther away, so the mechansims of sediment supply become less and less efficient. Washover mud will be less likely to reach the point and vertical jacking by displacive anhydrite growth will diminish because brine supply mechansims will become less efficient. As the vertical accumulation rate wanes, subsidence will begin to dominate and the point will start to sink relative to mean sea level.

Figure 19 schematically depicts how the above corollary may be expanded to encompass the whole of a sabkha complex. Assumptions inherent in the depicted scheme are as follows: at any given point in the complex, subsidence proceeds at a constant rate; seaward parts of the complex are subject to slightly higher subsidence rates than are landward portions, and there is complete gradation in subsidence rate between the two end members; carbonate sedimentation is concentrated in the shoreline zone, lagoonal areas away from the shoreline receiving very little detritus, and supratidal areas well back from the shoreline receiving very little washover sediment; displacive anhydrite growth, which effects a measure of vertical jacking of the sabkha surface, is concentrated in the near-shore supratidal area and diminishes inland; anhydrite forms only in the capillary zone, but subsequently may subside below the sea level datum without being destroyed (Bush, 1973a, b; *see* below). The seaward extremity of the sabkha system may be marked by a barrier complex analogous to the Trucial Coast islands and shoals. Alternately, the seaward extent of progradation may be limited by the capacity of shoreline sedimentation processes to build into ever deeper water - that is, essentially a self-limiting mechanism (Fig. 19).

It should be emphasized that this 'constant-subsidence' model is strictly conceptual. It involves a theoretical balance between sedimentary accretion and subsidence, a balance that is extremely delicate and thus subject to considerable disruption by minor spatial or temporal changes in either subsidence rates or sedimentation patterns (*see* below for discussion). Nevertheless, the model accords with both the observed nature of ancient sabkha cycle successions and the stable tectonic setting normally inferred therein.

A third mechanism involves periodic eustatic fluctuation in conjunction with constant subsidence. Sabkha progradation could take place during high stands of sea level within a framework of constant subsidence, as outlined above. A drop in sea level would terminate accretionary processes within the sabkha and progradation would cease. However, during the low stand of sea level, subsidence would be expected to continue and when sea level again rose to its equilibrium datum, the whole of the sabkha plain would be immediately transgressed, thereby initiating a new cycle.

One obvious cause of sea level lowering relates to the onset of continental glaciation in the polar regions followed by world-wide eustatic rise with the onset of interglacial periods. Rhythmic periodicity in glacial-interglacial cycles is well known in the Pleistocene and may have been an important phenomenon throughout much of geological history. Steiner and Grillmair (1973) reviewed Ordovician glacial deposits from Russia, Europe, Africa and South America. However, of the many examples they cite, none can be dated precisely as a definite time-stratigraphic equivalent of the Baumann Fiord Formation.

It is not yet possible to assess completely the applicability of the models discussed above. All are theoretical. The constant-subsidence model appears viable in itself. Constant subsidence with an overprinting of periodic eustatic change broadens the scope of the model and insures that transgression is relatively rapid.

VERTICAL FACIES VARIATIONS - COMPOSITE CYCLES

According to the theoretical model outlined above, steady and uninterrupted subsidence should provide for the generation of repeated cycles with little or no variation in their character or lateral extent. For the Baumann Fiord Formation, the model would seem to apply in a number of cases, as exemplified in the near-perfect rhythmic cyclicity of the sequence in Section 1a, levels 100-225 (Fig. 4), where there are 32 complete cycles in 120 m of section. At least certain parts of the other sections also appear to accord with the model. According to the model, there must have been long periods during the buildup of the Baumann Fiord Formation when subsidence was constant and rhythmic compounding of cycles was possible.

Accepting the dictum that constant subsidence rate over a very broad area is a requisite for the development of rhythmic sabkha cycles, it seems logical to postulate that slight local or temporal changes in subsidence rate could promote considerable diversification in the way cycles are compounded. Indeed, it is argued below that fluctuation in subsidence rate is the key factor in the generation of 'non-rhythmic' or 'composite' cycles.

In order to explain what is meant by composite cycles, it is best perhaps to consider specific instances in which the Baumann Fiord sequence departs from conventional rhythmic compounding of cycles. One of the most obvious departures from rhythmic cyclicity is the case where anomalously thick limestone units are developed (Figs. 4, 5). In the field, it is immediately plain that these are comprised of the same type of lime mudstone that normally makes up the carbonate component of a typical cycle. However, close examination of the sedimentary structures in a thick carbonate unit reveals that it is not made up of a single shallowing-upward sequence but rather of a number of incomplete lagoonal sequences. In cases such as these, it is clear that cyclical development was operative still within the system as a whole but that the progradational sabkha shoreline repeatedly failed to reach that specific locality before it was swamped by the next transgression. Thus, that particular carbonate unit, even though it was built up through continuous deposition, is in fact representative of a number of cycles, each of which was terminated prematurely in that particular area. One explanation of

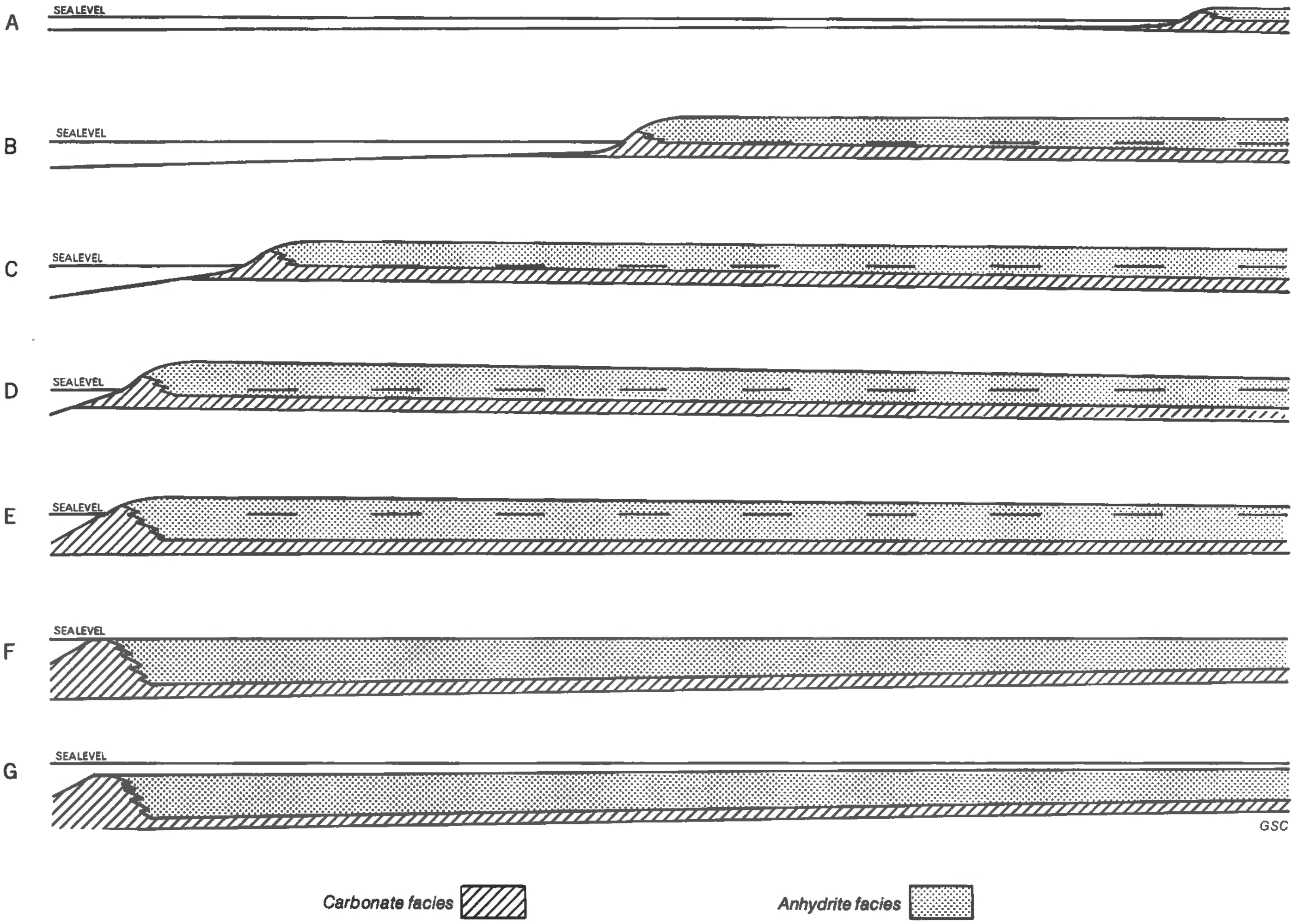


FIGURE 19. Conceptual model for repetitious superimposition of sabkha cycles. The seaward part of the system lies to the left of the illustrated sections, the landward part to the right. Mean sea level is considered to remain fixed and is used as a level reference datum through the entire time-sequence A to G. Subsidence at any given point is constant and unvarying, although the rate of subsidence in the seaward portion of the system slightly exceeds that in the landward portion, and there is complete gradation between the two. Accumulation of lagoonal carbonate is considered to be confined to the immediate shoreline zone. Build-up of the sabkha surface takes place in part by washover sedimentation of carbonate and, in part, by vertical jacking through displacive anhydrite growth within previously deposited shoreline and supratidal carbonate sediments. Both washover and jacking processes are considered to be most pronounced in the region immediately behind the advancing shoreline, decreasing in importance landward.

A. Progradation begins. The shoreline advances over the shallow but continually deepening lagoon.

B. Progradation continues. The seaward parts of the lagoon continue to deepen. The supratidal anhydrite facies thickens in the zone immediately behind the shoreline, but at the landward extremity of the system stabilizes in thickness (now well removed from the locus of washover and brine supply) and begins to subside below the groundwater reference datum.

C. Progradation continues, somewhat slowed by the necessity of building into ever deeper water. Earliest formed parts of the anhydrite facies, now having reached thickness equilibrium, continue to subside below the sea level datum.

D. Progradation essentially ceases, further significant advance precluded by deep water and continuing difficulty in keeping pace with the constant subsidence (here somewhat more pronounced). Stabilized landward portions of the anhydrite facies continue to subside.

E. Stagnation. Anhydrite growth continues in the near-shore supratidal zone but, because of anhydrite occlusion of porosity (restricting brine access), vertical jacking by displacive anhydrite growth is lessened and subsidence dominates.

F. Land level subsides to sea level, with transgression imminent.

G. Transgression, establishing a shallow lagoon over the whole of the pre-existing sabkha flat, preluding a re-initiation of progradational advance.

this is that subsidence rate increased for a time, throwing the system out of equilibrium and bringing about premature transgression.

Most of the thick carbonate developments are of this composite type, meaning that they are made up of two or more 'semi-cycles', each semi-cycle consisting of part or all of the carbonate component of the full cycle. The tops of these thick carbonate units characteristically exhibit normal transition into the overlying anhydrite: lime mudstone grading up into a stromatolite zone, immediately overlain by anhydrite. Subsidence ultimately slowed to the extent that the progradational front was able to reach and pass beyond that particular locality.

Locally, however, thick carbonate developments are not the composite type. In certain places, for instance, the carbonate component of a cycle may be enhanced by inordinate stromatolite development. The cycle is perfectly normal save that the stromatolite zone, instead of being about 30 cm in thickness, is 2.5 or 3 m thick (Fig. 20a). Accretion of such a thickness suggests temporary halting of the progradational front, the intertidal zone having remained in one place for an inordinate period of time. This could result from an increase in subsidence rate, not so pronounced as to induce a transgression, but sufficient to balance the accretion rate of the intertidal algal stromatolites. With the front of progradation stalled, the stromatolites in that particular locality would be free to build up apparently anomalous thicknesses. Only when the subsidence rate decreased could progradational advance of the intertidal zone once again proceed. Examples of thick stromatolite development of this type are relatively rare, however, and are of restricted areal extent.

Enhancement of the carbonate component of a cycle may come about also by means that are seemingly not controlled by susidence variation. One example of this is the local occurrence of thick flat-pebble conglomerate units (Fig. 20b). Where such conglomerates were observed, they usually exhibited an imbricate configuration suggesting that they mark a former strand line. Another example of thick carbonate development is the local occurrence of 'algal mat breccia', consisting of disordered arrays of cryptalgalaminated clasts, some of which appear to have been contorted while still in a very 'rubbery' state (Fig. 20c). These accumulations of algal mat debris resulted from local rip-up of mat by severe storm action or by high-energy reworking during transgression. Occurrences of both beach-pebble conglomerate and algal mat breccia are relatively rare and they do not account for any areally extensive enhancement of carbonate thickness.

In any one section of the Baumann Fiord Formation, there are numerous examples of departure from rhythmic cyclicity. Thick carbonate development, usually taking the form of composite carbonate cycles, is one such departure. The other important variation on the cyclical theme is the development of anomalously thick anhydrite units. Like the composite carbonates, the thick anhydrites may originate in response to fluctuation in the subsidence rate.

The first question that must be answered is: what maximum thickness of supratidal nodular anhydrite can arise in the course of a single sabkha cycle? Recent nodular anhydrite has been shown to grow displacively within the capillary zone above the groundwater table (Shearman, 1966; Kinsman, 1966, 1969). But whereas evaporative concentration above the groundwater table may be a requisite of nodule growth, there is abundant evidence that, once formed, anhydrite can persist in the zone below the groundwater table (Bush, 1973a, b). Thus, it is apparent that the potential thickness of the nodular anhydrite facies is not restricted to the 1 m zone above the stable groundwater level. Given a background of steady subsidence, anhydrite may continue to grow within the capillary zone while previously formed nodules subside below the groundwater reference datum. As long as displacive nodule growth produces enough vertical jacking of the sabkha surface to keep pace with subsidence, marine transgression will not occur and the anhydrite facies may continue to thicken.

In summary, it is clear that although there may be no theoretical restrictions on the accumulation of sabkha facies anhydrite, there are practical restrictions. For the Baumann Fiord system, it would appear that these restrictions normally made their influence felt when the anhydrite facies reached 2.5 to 3 m. By the time the anhydrite facies had reached this thickness, brine supply mechanisms and washover sediment supply had decreased to the point where vertical accretion was no longer sufficient to offset continuing subsidence, and marine transgression terminated the cycle.

Extending the subsidence-accretion argument to the problem of anomalously thick anhydrite units, the following corollary seems applicable. If local or temporal increase in subsidence rate facilitates the compounding of thick composite carbonate units, then local or temporal decrease in subsidence rate may explain thick anhydrite units. Consider an area that for a time was subject to subsidence at a rate somewhat less than that of the remainder of the sabkha plain. That area would remain positive when the next transgression took place. More importantly, accretion of anhydrite within the positive area would be regenerated in direct response to its new found proximity to the shoreline and the enhancement of brine supply efficiency thereby afforded. In other words, conditions favourable to sabkha facies accretion would be restored despite the fact that transgression did not establish a new discrete cycle in that area. If subsidence were to lag behind that of the remainder of the system for a significant period of time and accretion of anhydrite was repeatedly regenerated, then there is no reason to believe that very thick anhydrite development could not take place.

The sabkha regeneration argument is theoretical but it may have considerable applicability in the Baumann Fiord sequence. Its validity can be evaluated only in conjunction with a knowledge of how the Baumann Fiord cycles vary laterally, how they intertongue and how they pinch out. These relationships are considered in detail below.

LATERAL FACIES VARIATIONS - INTERTONGUING

The cross-section shown in Figure 21 schematically depicts regional lithostratigraphic variation in the Baumann Fiord Formation. The left extremity of the section is representative of the sequence in the Franklinian Miogeosyncline - that part of the depositional belt farthest removed from the craton. The right extremity is representative of the sequence in the Arctic Platform region, immediately adjacent to the

FIGURE 20. Examples of thick carbonate development in the Baumann Fiord Formation apart from the standard 'composite' cycles.

a. Thick stromatolitic development(s) with laminar anhydrite (a) above. (GSC 203463-S)

b. Thick accumulation of limestone flat-pebble conglomerate. Note the tendency toward pebble imbrication, sloping downward to the left. (GSC 203463-T)

c. Algal mat breccia, here accumulated as a thick pile of ripped-up mat, contorted in an apparently rubbery fashion. (GSC 203463-U)

onlap edge of the formation. The cross-section thus transects the formation along a line normal to the depositional strike.

A number of fundamental relationships are illustrated in the section. First, it is clear that limestone comprises a greater proportion of the formation in the west than it does in the east. In the Franklinian Miogeosyncline (Fig. 4), the A member is made up of 34 per cent limestone, 66 per cent anhydrite on average (Table 2). These figures closely resemble the proportions in which the two components are represented in each of the cycles that make up the section: 1 to 1.3 m limestone (29-37%) and 2.2 to 2.5 m anhydrite (63-71%). But the proportion of carbonate in the sequence diminishes progressively in the direction of the craton. In the Arctic Platform sections (Fig. 5), the amount of carbonate in the A member averages 15 per cent (Table 2). There is a similar trend in the C member, carbonate being considerably more abundant in the west than in the east (Table 2). Clearly, the development of the lagoonal component of the cycle was more prevalent and more regular in the distal part of the depositional belt than it was in the part near to the craton.

The second fundamental relationship shown in Figure 21 is that the limestone stringers in the Baumann Fiord sequence tend to die out from west to east, toward the craton. This relationship is evident in the field. In places it is possible to follow individual beds for distances of up to 15 km. Where this was done along exposures that parallel the regional trend, the limestone stringers were observed to have remarkable continuity and uniformity. But where individual sets of strata were traced laterally from west to east along exposures that transect the regional trend, it was observed that, while the sequence still shows a considerable degree of continuity, some of the limestone stringers pinch out. In one such transverse section in the region of Section 1, two limestone beds were observed to terminate within 2 km whereas a further seven persisted virtually unchanged over the same distances, west to east. Attempts to correlate lithologic logs of the measured sections are facilitated greatly by the remarkable lateral continuity that is exhibited by most beds. Indeed, it is commonly possible to make reasonable correlations between sections that are some 20 or 30 km apart, so extensive are many individual beds. Figure 22 illustrates some correlations between Sections 1a, 2 and 3. Acknowledging that there is some risk in correlating over such extensive distances, the correlations shown in Figure 22 are probably justified and, as a rule, the Baumann Fiord sequence may be continuous over broad areas. Of course, it is the exceptions to the rule that are of immediate concern here. In this regard, the sections in Figure 22 appear to bear out the relationship that was observable locally in the field - that where carbonate units do pinch out, they do so in an easterly direction, toward the craton.

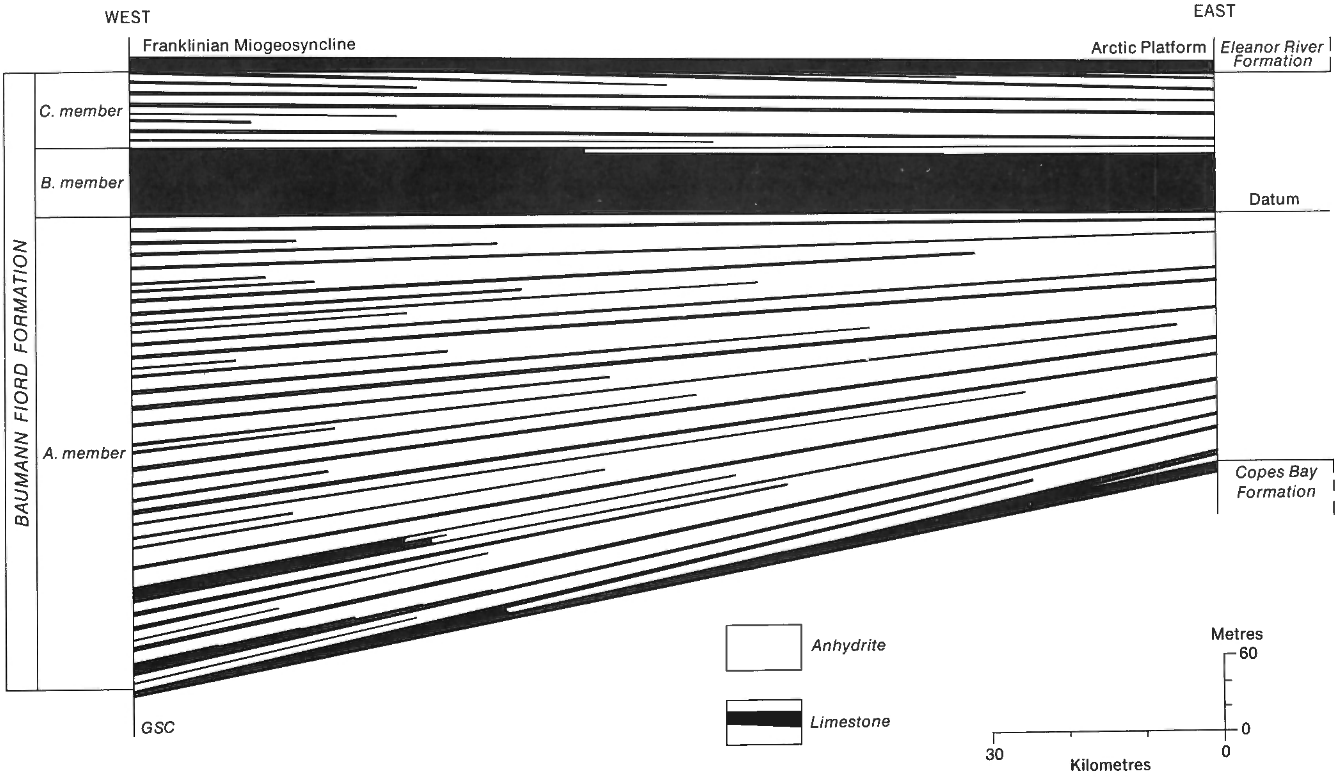


FIGURE 21. Schematic representation of the facies pattern within the Baumann Fiord Formation, Ellesmere Island. Note that carbonate units tend to die out toward the craton in the east. Time lines are parallel to the base of each limestone unit.

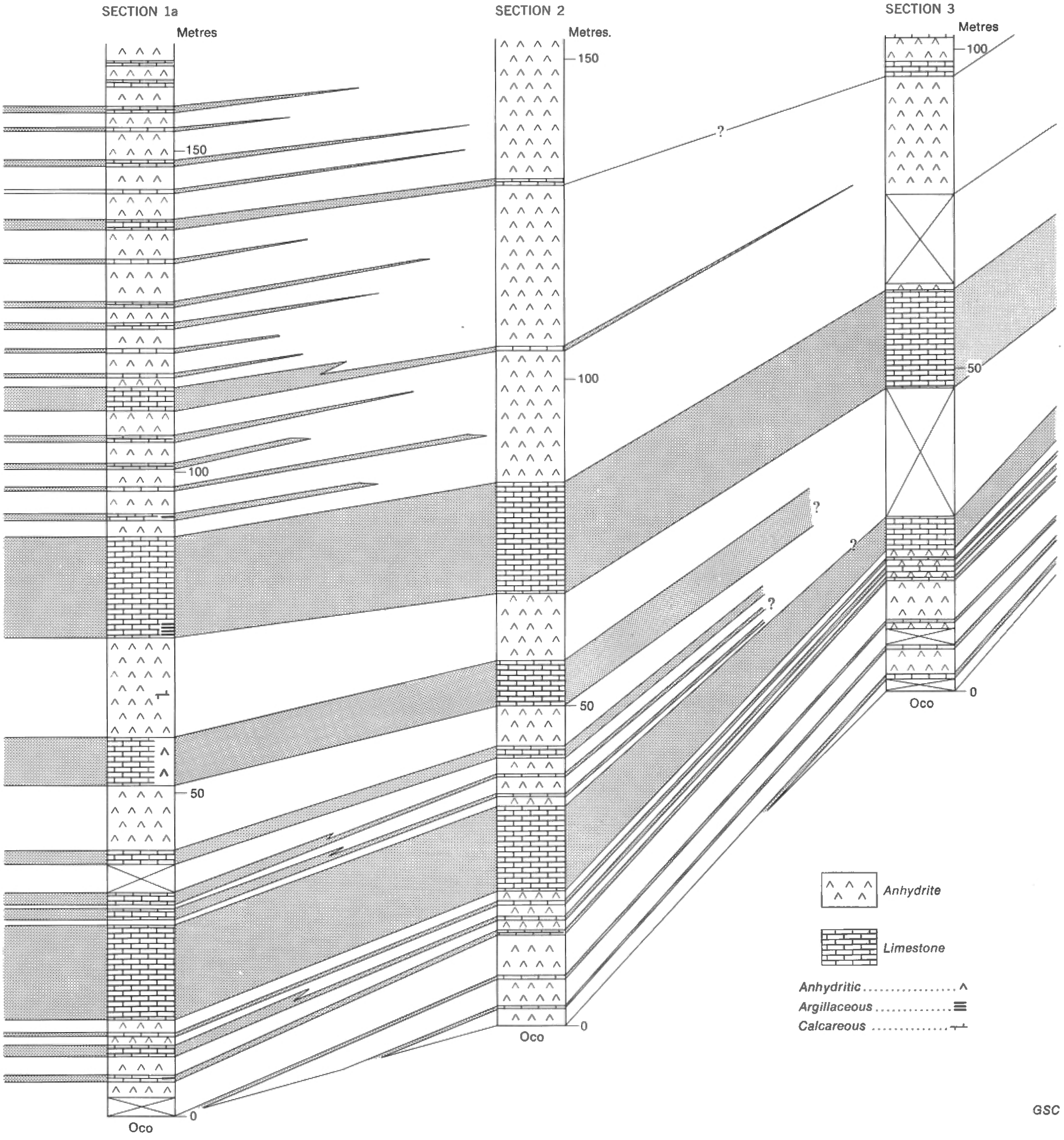


FIGURE 22. Correlations within the basal Baumann Fiord Formation, Trold Fiord region. Line of section is west to east toward the craton (*see* insert map, Fig. 4).

Figure 21 provides conceptual reconstruction of how the Baumann Fiord Formation was built up. The base of each limestone bed marks a marine transgression. Many of the transgressions penetrated right to the back of the sabkha system. Others only partly inundated the previous sabkha surface. The explanation for this probably lies in the application of arguments developed earlier based on subsidence versus accretion. If subsidence in the distal parts of the depositional belt exceeded that in the proximal parts to an extent that more than compensated for any accretionary advantage that the distal region may have had, then transgression could proceed only as far as that subsidence contrast allowed. As suggested earlier, a new and distinct cycle could be initiated in the miogeosynclinal region with commensurate regeneration of sabkha facies accretion in the Arctic Platform, proximal to the Shield. Numerous transgressions, each contingent upon subsidence balance and each followed by progradational advance of the sabkha, could produce the variability in sequence illustrated in Figure 21. It is thought that this reconstruction is both compatible with the observed character of the formation as a whole and intrinsically consistent with the sabkha model.

Application of the differential subsidence model is thought also to explain lateral variations along strike. In Section 2, for example, there is a preponderance of carbonate between levels 200 and 350 (Fig. 4), much of which is clearly equivalent to anhydrite in the sections to the north. This relationship can be explained by postulating that, for the time interval in question, subsidence in the vicinity of Section 2 tended to exceed that in the area to the north. That being the case, sabkha development would tend to be favoured in the north while lagoonal conditions would persist in the south. In other words, it appears that there was a semi-permanent embayment in the Section 2 region for that time interval.

Another example of 'along-strike' pinch out of sabkha facies anhydrite is the loss of the C member in the Trold Fiord area (Fig. 4). It is present in the north (Secs. 1, 1a) but it is not developed in the south (Secs. 2, 3). Fortunately, there are some exposures in the intervening area. Trending north from Section 3, for instance, there is a linear ridge that affords continuous exposure of the Baumann Fiord Formation (Fig. 23). At the northern end of the ridge, all three members of the formation are distinctly evident. Toward the south, the recessive C member becomes more and more ill-defined, anhydrite becomes less and less prevalent until, at the southern extremity of the ridge (Sec. 3 itself), there virtually is no evaporite development at the C member horizon, all the anhydrite having graded into limestone. During C member time there was a permanent lagoon in the southern region, induced and propagated as such by advanced subsidence in that area. Noteworthy in this regard is that the Trold Fiord region may mark the ultimate southern terminus of evaporite development in the C member for, in the area farther south, the C member is absent, both in the Ellesmere Island extension of the belt and on Devon and Cornwallis Islands to the south and west (Kerr *et al.*, 1973; Kerr, pers. com., 1974).

In summary, the Baumann Fiord cycles tend to be very widespread and persistent. If the carbonate components do pinch out laterally, they do so either in an easterly direction, toward the craton, or in a north-south direction, roughly parallel to the depositional strike. These relationships may be explicable in terms of differential subsidence and it is concluded that the sabkha model is viable for the origin of the formation as a whole.

PALEOENVIRONMENTAL RECONSTRUCTION OF THE BAUMANN FIORD FORMATION

The Copes Bay Formation and equivalent rocks, which underlie the Baumann Fiord Formation, were described by Kerr (1968) and interpreted as being of very shallow marine origin. The upper part of the Copes Bay Formation contains abundant limestone flat-pebble conglomerate and, locally, anhydrite beds (Kerr, *ibid.*). Clearly, near the end of Copes Bay time, depositional conditions in the study-area were very similar to those which later developed in the Baumann Fiord complex.

The contact between the Copes Bay Formation and the Baumann Fiord Formation is diachronous in the study-area. Some of the lowermost Baumann Fiord anhydrite units in the region proximal to the craton are demonstrably equivalent to the uppermost limestone beds of the Copes Bay Formation in the distal region. This relationship, schematically depicted in Figure 21, is evident in the correlation section shown in Figure 22. Thus, the transition from Copes Bay to Baumann Fiord development apparently proceeded as a series of regressive cycles which prograded successively farther and farther westward in the depositional belt. The transition was completed when progradational advance of the sabkha system penetrated to the most distal parts of the region.

Accumulation of the A member of the Baumann Fiord Formation took place by compounding of successive sabkha cycles, each marine transgression marking the initiation of a new regressive cycle. Many of the transgressions penetrated to the eastern extremity of the sabkha system. Others inundated only the western regions. Throughout the time interval involved, subsidence in the Franklinian Miogeosyncline clearly exceeded that in the Arctic Platform region, since the

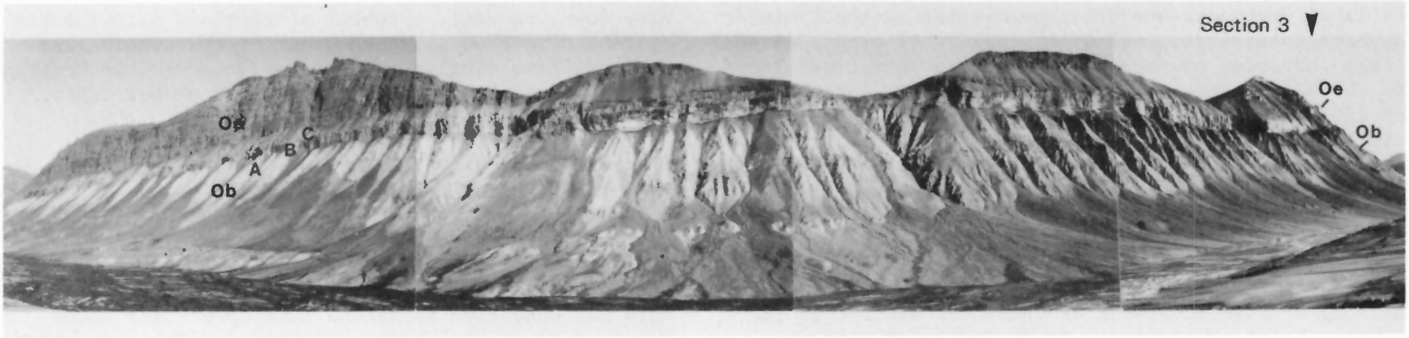


FIGURE 23. Panoramic view of a linear ridge trending north from Section 3, encompassing a 180 degree arc. (The ridge, which is 18 km long, here appears distorted due to the effect of parallactic imbalance). The Baumann Fiord C member, clearly evident in the north (left), dies out toward the south by gradual facies transition from anhydrite to carbonate. (GSC 203463-V)

A member thins significantly from west to east (Fig. 23). Subsidence differentials were probably the principal control on the extent of successive transgressions.

In Section 7, a red sandstone unit occurs at the top of the A member (Fig. 5). The sandstone consists of medium-grained quartz sand, which is moderately well sorted and well-rounded, cemented with calcite spar. The unit is cross-stratified with cut-and-fill structures, and small channel scours. Because the sandstone unit is confined laterally and is close to the stable Precambrian paleo-landmass, it is probably representative of foreland detrital fan deposition. The well-rounded and well-sorted nature of the sands suggest, however, that they may be of a secondary nature, and perhaps originated by fluvial reworking of former dune sands. Nonmarine clastics also were noted in the vicinity of Section 4 (levels 60 to 75).

The onset of B member deposition could have resulted as a function of increased subsidence over the whole of the study-area. Although the B member is widespread and relatively thick, it clearly was not deposited under open-marine conditions. B member strata are, in most cases, virtually identical with the carbonate units of the A and C members: laminated lime mudstone, massive lime mudstone, some flat-pebble conglomerates and, in the upper reaches, cryptalgalaminated lime mudstone and stromatolites. It is concluded, therefore, that the B member is representative of long-standing lagoonal deposition, perpetuated as such by subsidence rates that were sufficient to prevent sabkha development, even in the Arctic Platform region. The fact that the B member is characteristically devoid of fossils supports this 'shallow-lagoonal' interpretation, elevated salinites induced by rapid evaporation under arid zone climatic conditions having had an inhibitory effect on faunal development. Noteworthy in connection with the question of the influence of salinity on restricting faunas is the occurrence in Section 7 of numerous fossil-rich horizons in the B member (brachiopods, gastropods and arthropods; *see* Appendix B). At these horizons the limestones consist dominantly of biopelmicrite with intraclasts, pellets and skeletal grains (Fig. 14). Invariably associated with the fossiliferous horizons are intercalations of red marl of probable fresh-water origin. The conclusion drawn from this association is that during B member time there was a fresh-water influence in the Section 7 region, periodically diluting the concentrated lagoonal waters and thereby permitting development of a faunal community.

Transition from B member limestone deposition to cyclical carbonate-anhydrite deposition in the C member appears to have resulted when a series of progradational sabkha advances eventually brought the supratidal front to the most westerly regions. Many of the sabkha cycles in the basal C member in the east apparently are time-equivalent to uppermost B member limestones in the west (Fig. 21). The C member apparently was deposited in a manner similar to that which characterized the A member, by successive compounding of sabkha cycles.

The basal part of the Eleanor River Formation is made up of lime mudstones of character similar to the Baumann Fiord carbonates. It is concluded that the transition to Eleanor River deposition marks the widespread restoration of lagoonal conditions in the study-area. The return to lagoonal conditions over the whole of the depositional belt may have been somewhat diachronous, however. Eleanor River strata in the west apparently are equivalent to upper C member sabkha cycles in the eastern part of the depositional belt (Fig. 21).

In summary, it is evident that, from Copes Bay to Eleanor River time, paleoenvironmental conditions were such that deposition was temporally and spatially partitioned into two major categories: lime mud facies development and anhydrite facies development. This duality is reconcilable if the system is viewed in terms of the sabkha model, taking into account all the variability that the model allows and at the same time adhering to its prescribed restrictions.

PALEOGEOGRAPHY

The paleogeography of the study-area is synthesized in a series of paleogeographic maps (Figs. 24-26), using all available stratigraphic control and utilizing all the paleoenvironmental interpretations deduced above.

During A member time, sabkhas were prevalent over the whole of the study-area on Ellesmere Island. Figure 24 depicts a point in time in which the sabkha front has prograded to the distal reaches of the belt. Periods of maximum sabkha development such as this were interspersed with periods in which, depending upon the stage of marine transgression, lagoonal conditions prevailed over part or all of the area between the landmass and the open-marine front. Some embayments along the front of the sabkha are shown in an attempt to depict how some of the 'along-strike' facies variation may have arisen. At Section 2, for example, there were long periods in which lagoonal conditions prevailed despite the existence of major sabkha facies anhydrite development in more distal areas farther north. The open-marine front marked on the map delineates the inferred limit of the sabkha system. The exact location of this front is not known but it is probably parallel to the regional depositional trend, as shown. The open-marine front may have been marked by a barrier complex similar to that developed in the Trucial Coast (Evans *et al.*, 1973), however, this remains a matter of conjecture because the relevant rocks are not exposed on Ellesmere Island.

During B member time (Fig. 25), the essentials of the physiography remained similar to those developed previously save for the fact that lagoonal conditions prevailed over the whole of the platform. There may have been, as well, a number of foreland alluvial fan systems developed along the edge of the stable landmass, systems similar to that delimited in the Section 7 region during latest A member and B member times.

C member time saw the return of major sabkha development (Fig. 26). In many regards, the paleogeography during this period was similar to that of A member time. The sabkhas were of a more patchy nature, however, as evidenced by the fact that the C member is not developed in certain areas. Clearly, after B member time, conditions in some parts of the depositional belt were not conducive to sabkha development and these remained as shallow lagoonal regions. The area south of Sections 1 and 1a appears to be in this category (Fig. 26).

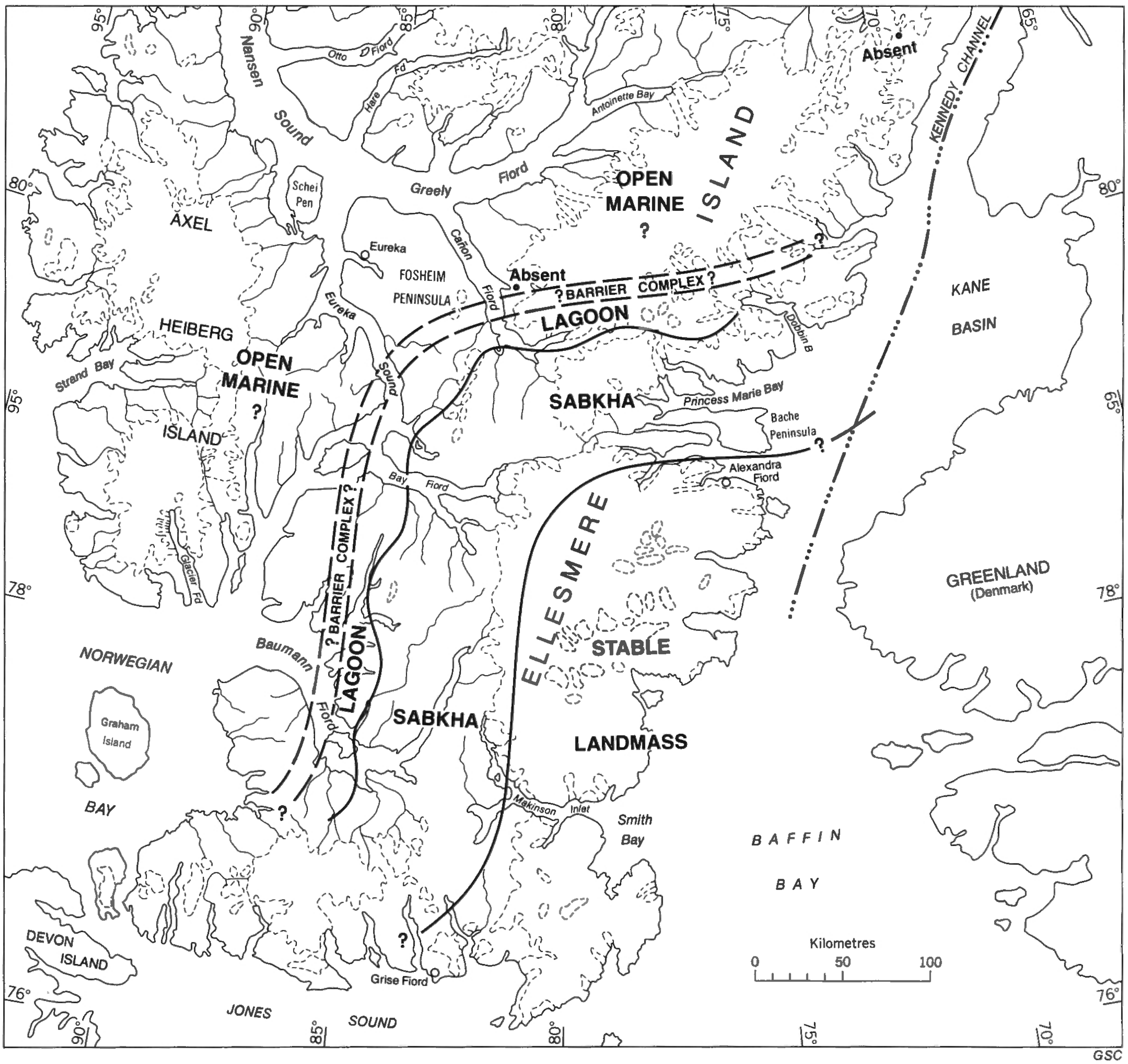


FIGURE 24. Paleogeography during Baumann Fiord A member time. The sabkha plain is shown here in a position of near-maximum progradational advance.

On central Ellesmere Island, the sabkha system was possibly some 110 km wide and it can be traced for well over 300 km along strike. The reported occurrences of Baumann Fiord evaporite development extend well beyond the confines of the present study-area, however. Kerr *et al.* (1973) and Kerr (pers. com., 1974) report Baumann Fiord anhydrite with associated limestone flat-pebble conglomerates and stromatolites in parts of the Grinnell Peninsula, Devon Island (Fig. 27). Thorsteinsson and Kerr (1968) documented thick Baumann Fiord anhydrites with associated limestones in the central dome of Cornwallis Island (Fig. 27). If these occurrences in fact, are, parts of one continuous belt, then the Baumann Fiord sabkha system extended for at least 1100 km along the edge of the Franklinian Geosyncline (Fig. 27).

A very extensive sabkha evaporite complex along the southeastern margin of the Franklinian sea thus is indicated for Baumann Fiord time. The region to the south and east of the sabkha complex probably was one of cratonic exposure, characterized by nondeposition and/or erosion (Trettin, 1975). The whole of the marine-margin belt must have been characterized by stable tectonic conditions, allowing, with only very minor fluctuation, the steady and gradual subsidence that sabkha development requires. Climatically, the region must have lain within an arid torrid zone and in this regard it is interesting to note that paleomagnetic reconstruction of the relative positions of the continents during the Ordovician places the Arctic Islands region well within the equatorial zone (Smith, *et al.*, 1973).

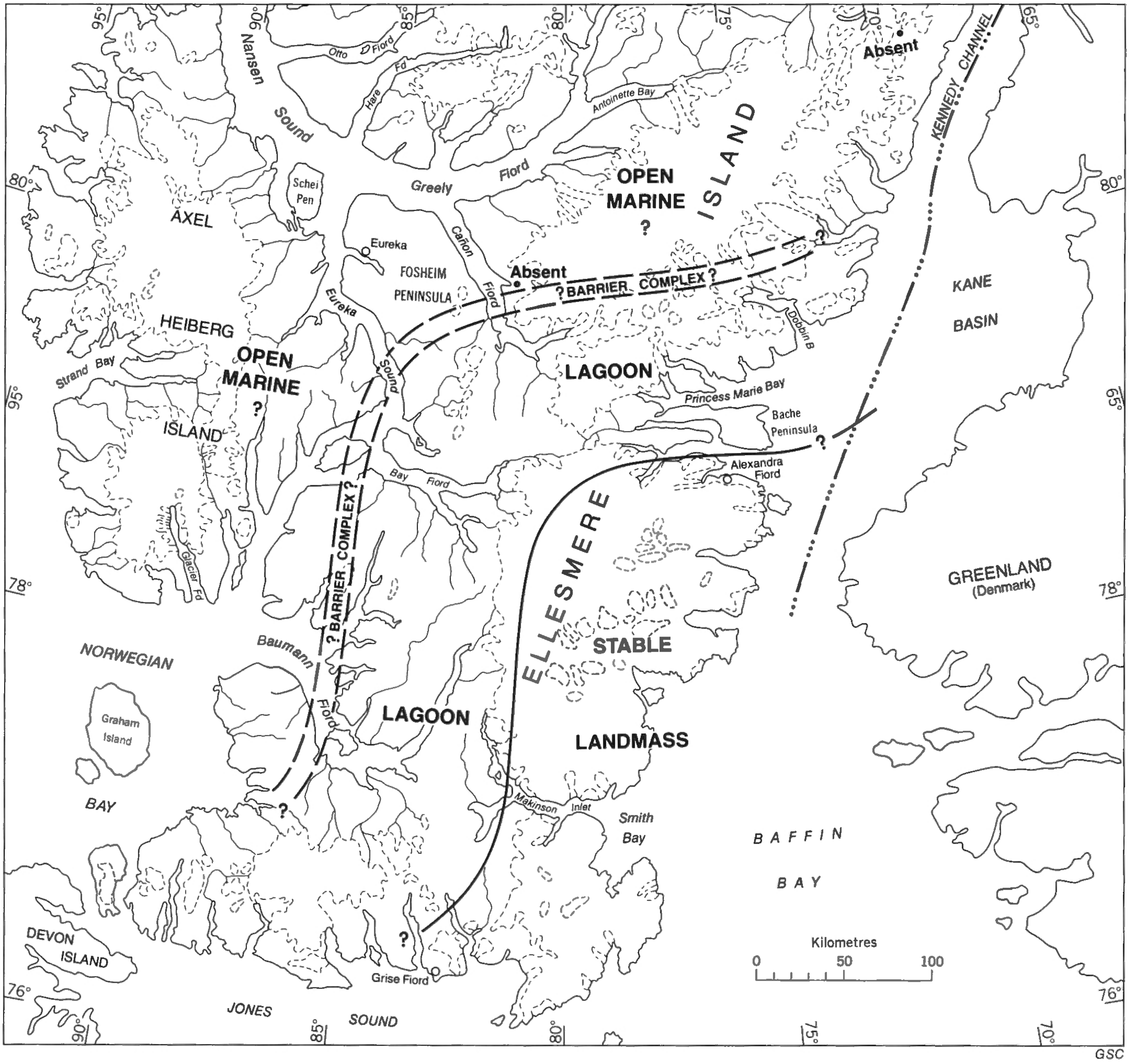


FIGURE 25. Paleogeography during Baumann Fiord B member time. Lagoonal conditions prevailed over the whole of the depositional belt.

DISCUSSION

Possible alternatives to the foregoing supratidal interpretation for the origin of Baumann Fiord Formation are confined to those involving very shallow water deposition for the anhydrites. A deep-water origin must be rejected on the grounds that the associated carbonates and stromatolites are almost certainly of shallow-marine (if not intertidal) origin. Because at present it is not possible to prove conclusively that the carbonates and stromatolites are intertidal in origin (they could be shallow subtidal), it is not possible to assert firmly that the overlying anhydrites must be of supratidal origin. A very shallow lagoonal origin for the anhydrites thus is conceivable, perhaps with carbonate deposition taking place during periodic influxes of marine water, and anhydrite being precipitated when open access to the sea was periodically cut off (perhaps by a seaward barrier complex). The main difficulty with this type of approach is that everything is based on theoretical arguments about facies distributions and environmental conditions - for there is no convincing Recent analogue for shallow sub-aqueous anhydrite deposition. The sabkha model, on the other

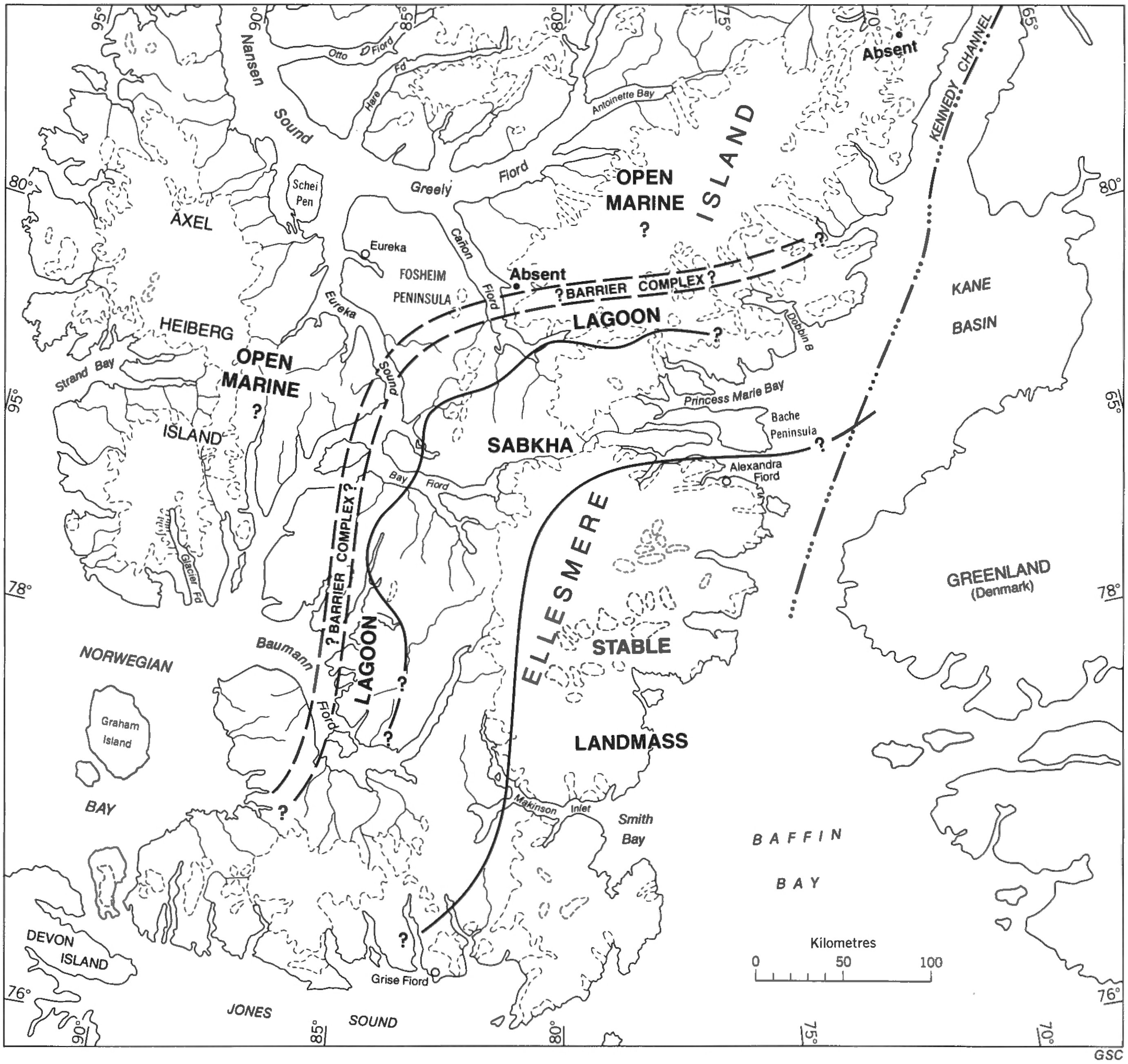


FIGURE 26. Paleogeography during Baumann Fiord C member time. Sabkha development less prevalent than during A member time.

hand, is based on a demonstrably viable Recent analogue (the Trucial Coast). There is nothing in the Baumann Fiord Formation that cannot be explained in terms of the sabkha model and, given the basis of a Recent analogue, a supratidal origin for the Baumann Fiord anhydrites is favoured over the conceivable alternatives.

ANHYDRITE DIAGENESIS AND METAMORPHISM

The anhydrite rocks of the Baumann Fiord Formation are of three distinct types. First are those that exhibit nodular mosaic structure. These are preserved only in a few places. Second are those that are of bedded or laminar appearance. Anhydrite rocks of this type are peculiar to the Arctic Platform region proximal to the Precambrian Shield (Fig. 1). Finally, there are those that exhibit massive structure. These are confined to the Franklinian parts of the outcrop belt - Localities 1, 1a, 2 and 3 (Fig. 1). Of the three, the nodular mosaic form most likely represents the original aspect of the anhydrite, the other two being secondary derivatives thereof.

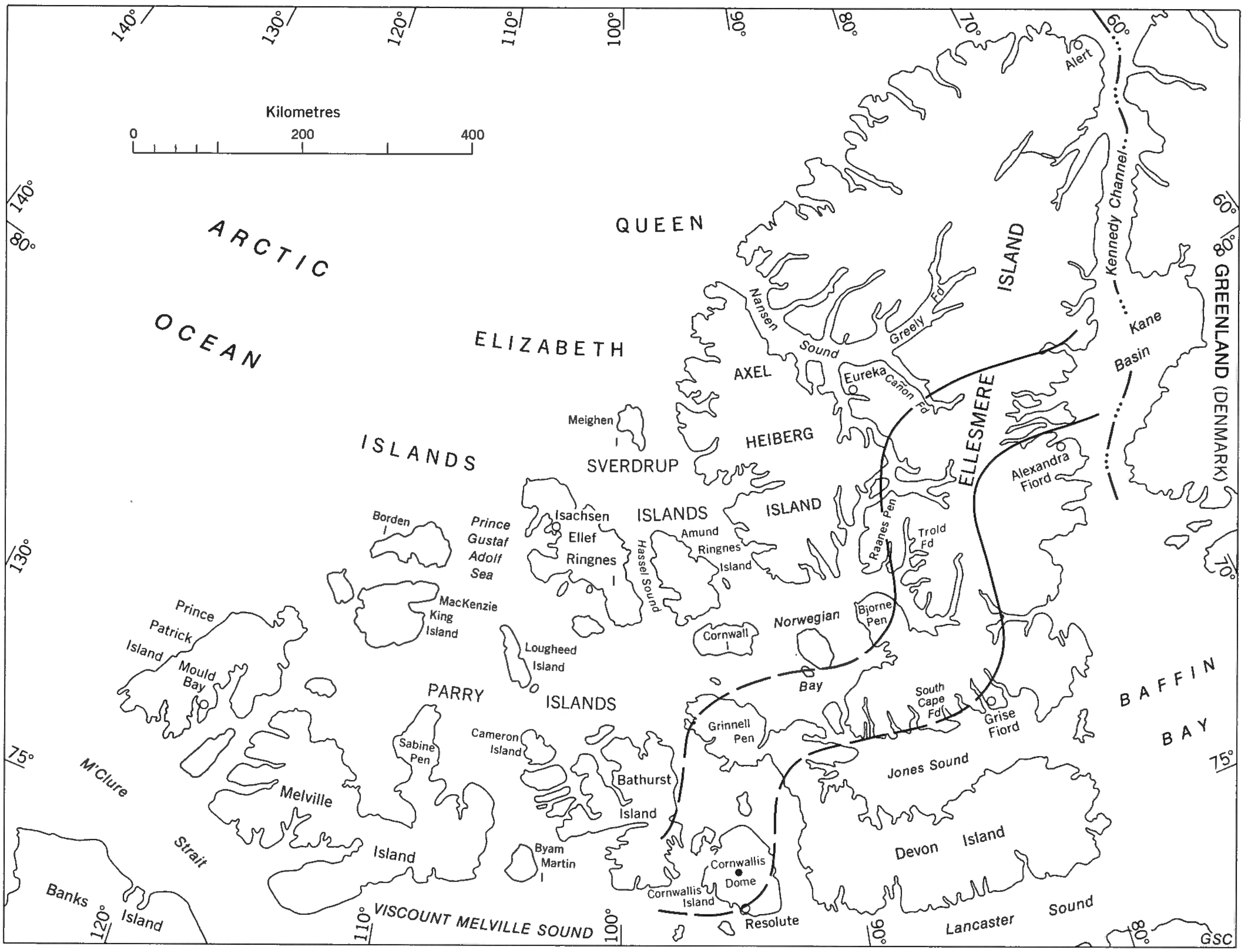


FIGURE 27. Map of the projected regional extent of the Baumann Fiord sabkha complex. Apart from the study-area in central Ellesmere Island, evaporites and associated facies are known at: South Cape Fiord, southern Ellesmere Island; Grinnell Peninsula, Devon Island; and Cornwallis Dome, Cornwallis Island.

Genetic affinities among the three basic types are postulated below and a model is formulated accounting for the progressive secondary modification of the anhydrite. In its essentials, the model comprises the following elements: early diagenetic displacive growth of nodular anhydrite; compactional flow of anhydrite during early burial stages, yielding laminar anhydrite; and dynamic burial metamorphism of the anhydrite inducing pervasive recrystallization with consequent transformation to massive anhydrite.

LAMINAR ANHYDRITE

Compaction of nodular anhydrite

Anhydrite nodules in the Recent Trucial Coast sabkha grow by displacement of host carbonate sediment. The fabric resultant upon displacive growth is normally that of decussate aggregates of platy anhydrite cleavage flakes (Shearman, 1966; Shearman and Fuller, 1969). Fibroradiating fabrics and 'wheatsheaf' fabrics are known also but are less common (Shearman, 1966; Holliday, 1973). Where original nodular form has been preserved in the Baumann Fiord anhydrites, it is the open 'felted' texture that is in evidence (Fig. 18b).

Compaction of decussate textured anhydrites can proceed in several ways (Shearman and Fuller, 1969). If the host is free-draining and there is nothing to support the delicate lath framework during loading, the constituent laths fracture one another along cleavage planes and 'pile-of-bricks' fabric is generated (Fig. 28a). If, on the other hand, drainage in the host is impeded during loading, pore-water pressure builds up within the lath framework, thereby easing the frictional contact between laths. Slippage at the contact points induces temporary quickening of the system and, by virtue of their platy habit, the laths flow easily past one another to assume an aligned fabric [termed 'felted-aligned' texture (Maiklem *et al.*, 1969)] (Fig. 28b). Shearman and Fuller (1969) compare the process to the collapse of a house of cards.

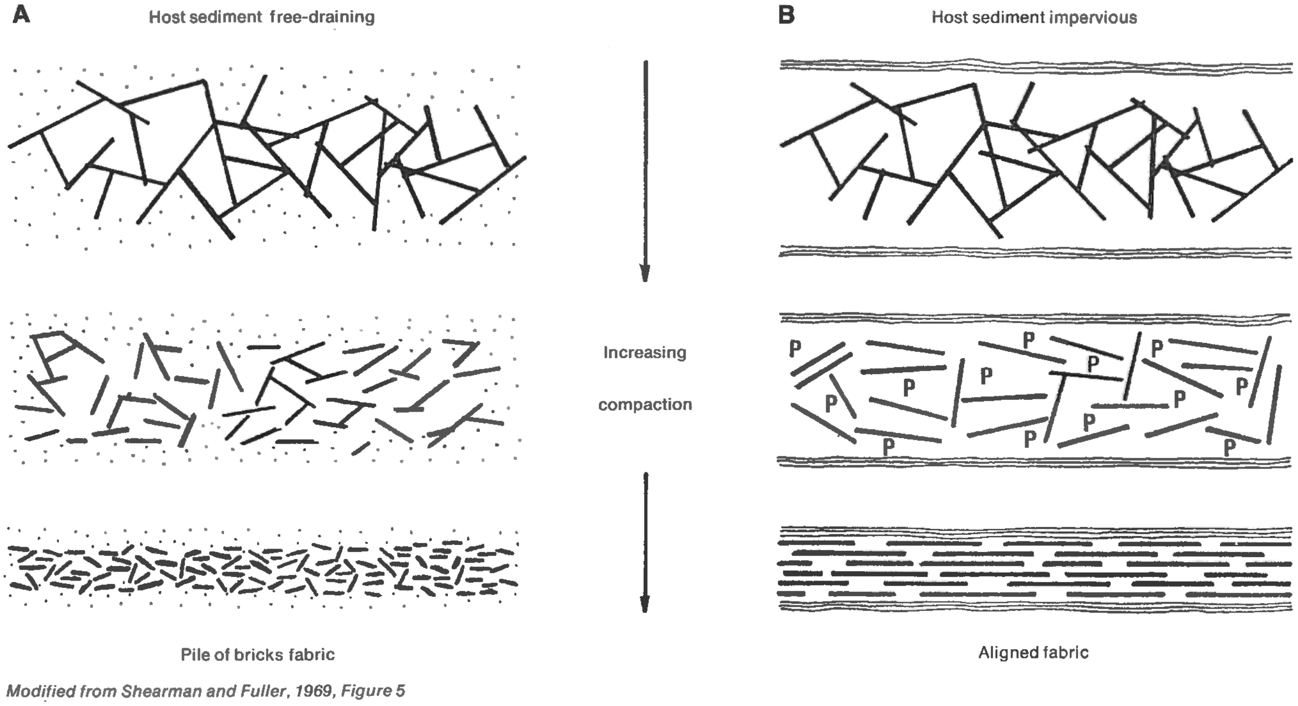


FIGURE 28. Schematic representation of the effect of drainage parameters on compactional modification of anhydrite fabrics. With the host sediment free-draining, laths are unsupported and the original fabric breaks down into 'pile-of-bricks' (A). With the host sediment impervious, pore-water pressure builds up in the interstices between laths, inducing temporary quickening and flow (B). Diagram after Shearman and Fuller (1969, p. 506).

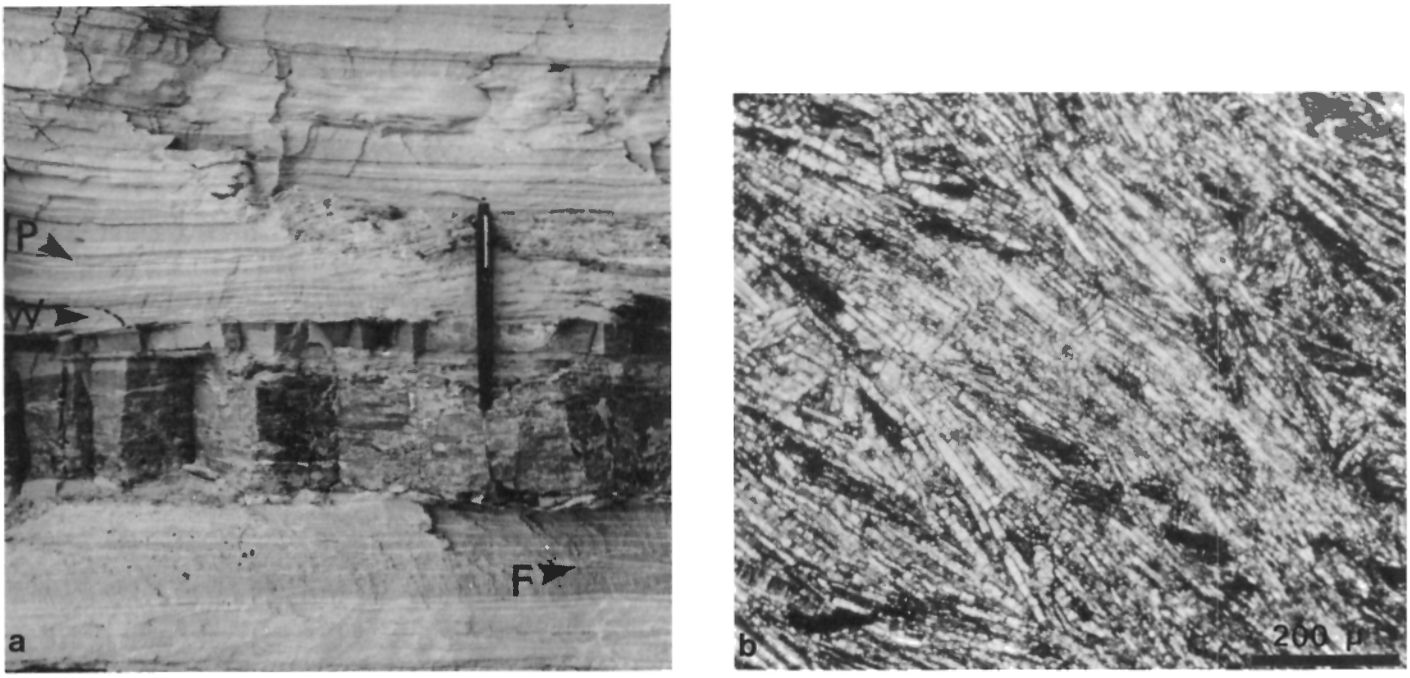


FIGURE 29.

a. Baumann Fiord laminar anhydrite (light tones) with intervening bed of limestone flat-pebble conglomerate (dark tones). Note pinch-and-swell structures (P), wavy lamination (W), and small-scale overfolds and flame structures (F). (GSC 203463-W)

b. Photomicrograph of aligned fabric in flowed anhydrite, shown in 45 degree position of maximum illumination, crossed nicols. The fabric is defined by anhydrite cleavage flakes. (GSC 203463-X)

It has been suggested that compactional flow of nodular anhydrite by degrees can result in flattened or discoidal nodules depending on the proportional abundance and compactibility of the host material (Shearman and Fuller, 1969). That extreme compactional flow yields delicately laminar anhydrite may be considered a theoretical possibility, a natural end-member to the compaction spectrum. But this contingency has not been fully documented by examples from the rock record. The laminar anhydrites of the Baumann Fiord Formation afford an opportunity to test the extreme compactional flow theory.

Baumann Fiord laminar anhydrites

In the field, the laminar Baumann Fiord anhydrites consist of delicate and persistent layers. The layering is defined by minor differences in the proportion of accessory carbonate or organic matter in individual laminae. Some layers are as much as 6 or 8 cm thick, but most laminae are on the order of 0.2 to 1 cm. Superficially, the appearance is one of a sedimented deposit, perhaps originating as a direct precipitate from a standing body of water. However, small pinch-and-swell structures can be distinguished (Fig. 29a); some laminae are wavy or show irregular undulations (Fig. 29a); some laminae are extremely contorted, with small-scale recumbent folds and flame structures (Fig. 29a) - all features that are suggestive of flow. Cognizance of these flow structures indicate that the present configuration of the laminae is not primary.

Petrographic examination of the laminar material shows that the fabric is defined by aligned cleavage flakes of anhydrite, not discrete anhydrite crystals (Fig. 29b). Such cleavage flakes are known to be generated as a natural function of nodule growth, the force of crystallization producing breakage along the pinacoidal cleavages of anhydrite, yielding cleavage flakes. From a fabric constituent point of view, then, a nodular precursor for the laminated anhydrite is a distinct possibility.

On the other hand, one would expect anhydrite precipitate to crystallize as discrete crystals, probably in the lanceolate habit, elongate in the c-crystal direction and flat parallel to 010 (Cuff, 1969). No crystals of this type have been found in any of the Baumann Fiord anhydrite rocks. This strongly suggests that the material did not originate as a primary precipitate of anhydrite. There remains the possibility, however, that the material originated as a primary precipitate of gypsum, subsequently altered to anhydrite. The difficulty with this postulate is that anhydrite after gypsum tends to be very finely crystalline (Bush, 1973b). Only with growth beyond the original confines of the pseudomorphs do cleavage flakes appear, at which time the anhydrite assumes a nodular aspect with decussate internal fabrics (Bush, 1973b). Thus, for the Baumann Fiord laminar anhydrites to have originated from a laminar gypsum precursor involves a nodular intermediary between the primary laminated gypsum and the laminated anhydrite. It still involves secondary flow alignment of the cleavage flakes.

Examination of the laminar material itself does not provide conclusive evidence of any direct genetic link between the laminar anhydrite and any presumed nodular precursor. It is only in the few localities where some nodular anhydrite has been preserved that it becomes possible to document a textural continuum between nodular and laminar anhydrite. A 2 m anhydrite interval at Locality 5 (Fig. 1) is one such instance. This exposure (Figs. 7e, 8) lies well within the Arctic Platform. The beds are flat-lying and there appears to be virtually no possibility that the anhydrites have been texturally altered by tectonic movements. One end of the relevant exposure is comprised of mosaic anhydrite, preserved in an almost completely undistorted state (Fig. 30a). Tracing the horizon laterally, one finds that the nodules become elongated, flattened and otherwise distorted (Fig. 30b). Farther on the nodules become so distorted that they lose their individual outline and, at the far end of the exposure, the anhydrite is of a bedded or laminar character (Fig. 30c). In the space of about 10 m, the anhydrite grades laterally from distinctly nodular to distinctly laminar structure (mosaic → distorted mosaic → bedded massive in the classification scheme of Maiklem *et al.*, 1969). This is viewed as supportive of the premise that the laminar Baumann Fiord anhydrites originated through flow of pre-existing nodular anhydrite.

Compactional flow of anhydrite theoretically requires fulfillment of two essential requisites: (a) the host must be itself susceptible to extreme compaction; and (b) the enclosing host sediments must be relatively impervious (Shearman and Fuller, 1969). With regard to the former, the matrix in which the Baumann Fiord anhydrites grew, in that it consisted dominantly of mud-size carbonate and organic matter, would appear to be highly compactible in its own right. Furthermore, because matrix material usually constituted less than 10 per cent of the bulk volume of the sediment, it is expected that the matrix would be carried along easily with the anhydrite during flow. Regarding the permeability of the enclosing host sediments, the Baumann Fiord system appears to offer satisfactory 'self-sealing' properties. Both mud-size carbonate sediments and organic matter have high entry-pressure characteristics, especially after having undergone initial compaction. For the small pore-water pressure enhancement required, they would seem to be capable of providing a suitable seal.

FIGURE 30. Transition continuum between nodular anhydrite and laminar anhydrite, as manifest by lateral change within a single stratigraphic level (Fig. 1, Sec. 5). Mosaic anhydrite→distorted mosaic anhydrite→laminar anhydrite.

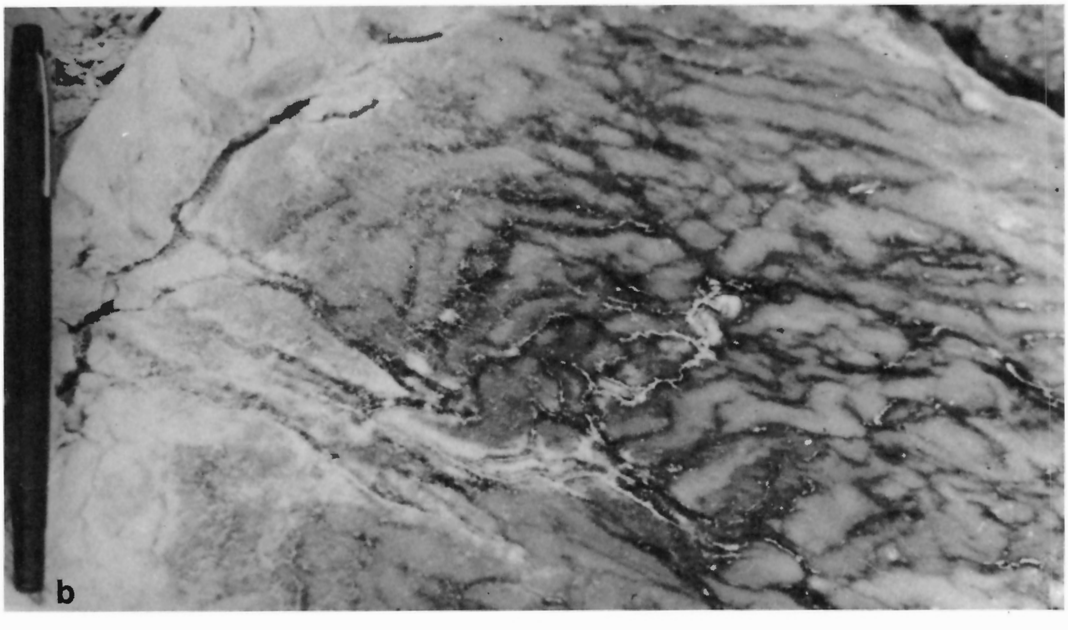
a. Mosaic anhydrite (with slight distortion). (GSC 203463-Y)

b. Distorted mosaic anhydrite. White material is surficial secondary gypsum. (GSC 203463-Z)

c. Laminar anhydrite. Some surficial gypsum is present but the dark band at the base of the hammer is anhydrite. (GSC 203464)


a


c


b

The Trucial Coast anhydrites provide evidence that flow is viable, even at a very early stage. Numerous workers have reported the occurrence of soft and pliable anhydrite layers within the supratidal facies (e.g., Shearman, 1966; Kinsman, 1966, 1969), the so-called 'cream-cheese' anhydrite (Park, 1969). Although it has not proved possible to sample this anhydrite without disturbing the fabrics, it is possible locally to discern flowlines within the anhydrite mass and, in places, small diapirs are developed (Shearman, 1966; and pers. com., 1973). If flow can take place only 50 or 60 cm below the surface of the Trucial Coast sabkha, with its relatively high proportion of permeable calcarenite host, then flow under a few metres of overburden in the Baumann Fiord setting would appear to be possible as well, considering the relatively impermeable nature of its host materials.

Compactional flow of pre-existing nodular anhydrite may have affected all of the Baumann Fiord sabkha-facies deposits. Preservation of nodular anhydrite was certainly the exception rather than the rule. Drainage conditions in this ancient sabkha system must have been inherently conducive to early-stage flow. Of course, the drainage characteristics of the Baumann Fiord sediments were themselves a function of the rather specialized high-mud, high-organic nature of the depositional environment. Thus there is a direct causal relationship between genesis and early stage flow diagenesis.

Aspects of petrography

During the compactional flow process, there is a short period of time when the overburden is supported by the water only, the framework of laths having given way. This condition persists only until the water finds its way out, at which time it moves in the escape direction. Expectedly, laths caught up in this flow will align themselves according to the hydrodynamic dictates of the system. In the field, it is difficult in many places to assess the direction of escape flow, especially as the laminar rocks rarely exhibit reliable vector structures. But where nodules have been distorted, by flattening and extension, as in Figure 30b, it is clear that escape flow was parallel to the axis of nodule elongation. Thin sections cut at various attitudes relative to this elongation help show how felted-aligned texture is generated and how compactional flow operates.

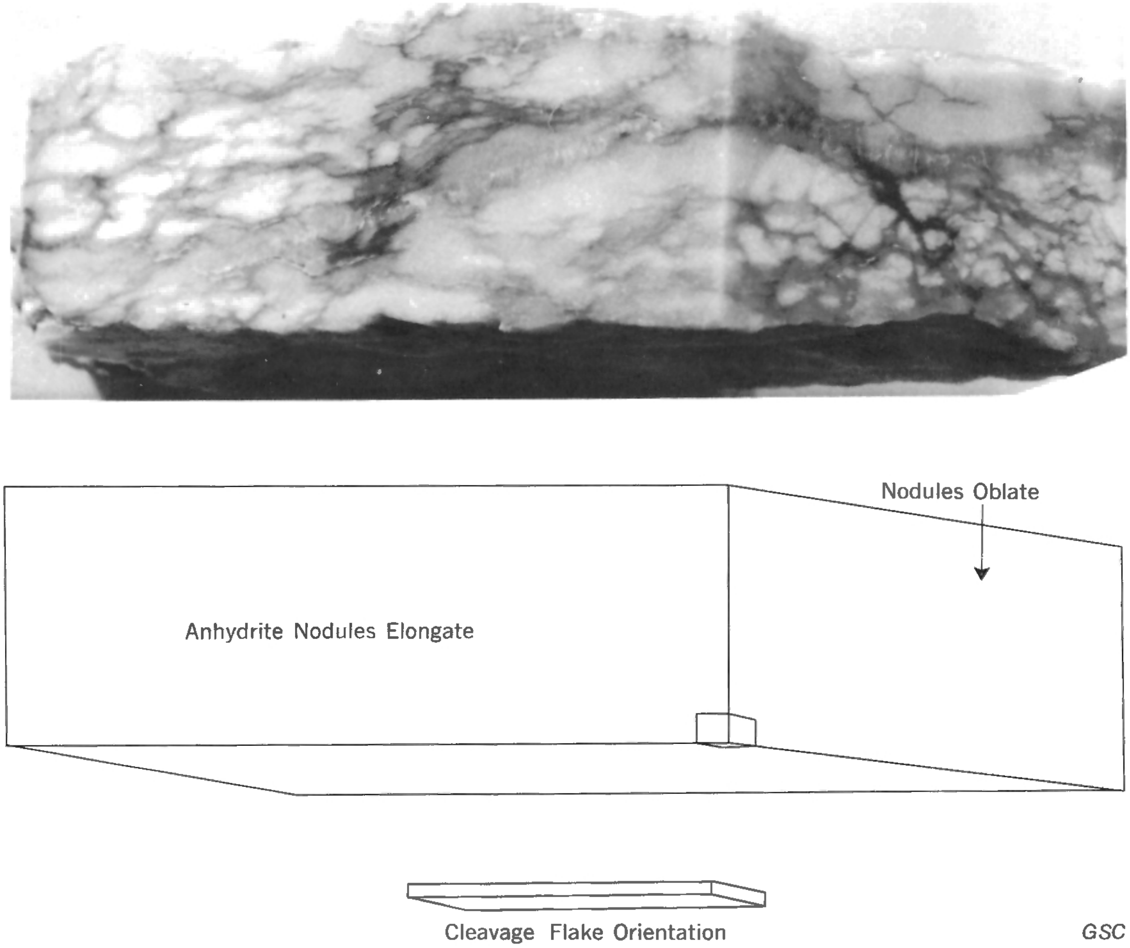


FIGURE 31. Anhydrite nodule elongation, as shown in a block of flattened and elongated Baumann Fiord anhydrite nodules. The slabbed surface on the left parallels the nodule elongation axis and is perpendicular to the plane of flattening of the nodules. The surface on the right is normal to the axis of nodule elongation. Block is 4 cm thick. (GSC 203264-A)

Figure 31 illustrates a hand sample of 'pulled-out' anhydrite nodules from the Baumann Fiord Formation. Besides being elongated, the nodules are, of course, somewhat flattened in the plane of the sample. The sample has been slabbed such that one face lies perpendicular to the axis of nodule elongation, the other face parallel to it. Thin sections cut from this sample reveal that the nodules were deformed by flow within certain wispy sub-parallel zone (1-2 mm spacing), the laths in the other parts of the rock having been spared from flow and having thereby retained their felted fabric. That flow was localized, not all-pervading, indicates that the paleodrainage in this particular rock may have been relatively free, small pore-pressure anomalies giving rise to lath-slippage only along segregated planes (Fig. 32).

The zones that have undergone flow (i.e., those with felted-aligned texture) exhibit a number of striking optical features when viewed in thin section under crossed nicols. In order to understand the significance of these features it is necessary to first review the crystallographic and optical properties of anhydrite.

For an orthorhombic mineral such as anhydrite, there are six possible ways of assigning the crystal axes, three of which have been widely employed in the literature on anhydrite*. That of Deer *et al.* (1962, p. 219-225) is employed here (Fig. 33). In dealing with anhydrite of nodular origin, it is the cleavage characteristics of the mineral that are of critical importance. According to the determined cleavage fissility ratings of anhydrite in its three pinacoidal planes, cleavage flakes of the mineral should tend to assume the habit illustrated in Figure 33: platy in the plane of the best cleavage (010), and elongate in the direction of intersection of the best cleavage (010) and the next best cleavage (100), that is, elongate in the c-crystal direction. Many of the optical peculiarities of anhydrite rocks which have flowed can be explained in terms of the shape and orientation of the constituent cleavage flakes, as outlined below.

- Aligned anhydrite cleavage flakes, such as those pictured in Figure 32, exhibit an obvious optical fabric when viewed under crossed nicols. Rotating the stage, one finds that all the cleavage flakes show extinction simultaneously. This is simply a function of the fact that anhydrite, being orthorhombic and having pinacoidal cleavages, characteristically exhibits straight extinction. If the cleavage of all the flakes are parallel, they will all extinguish together.

- Use of a quartz wedge reveals that the cleavage flakes within the aligned zones all show positive elongation (length slow). This observation simply confirms that the flakes are platy in the (010) plane, normal to the X vibration axis (assuming, of course, that the thin section is cut normal to the plane of alignment, as are those in Fig. 32). No matter how such a plate is cut, the X direction will be normal to the elongation of the flake.

The ultimate key to the orientation of the cleavage flakes in the aligned zones stems from the following observations. In sections cut parallel to the nodule elongation axis (but still normal to the alignment plane), the flakes characteristically show near-normal birefringence (0.030-0.045). But in sections cut perpendicular to the nodule elongation axis, there is a high proportion of flakes that show anomalously low birefringence (0.005-0.014). Point counts on the flowed zones in elongation-normal sections in fact reveal that 71 per cent of the flakes exhibit birefringence of less than 0.014 (first-order yellow). Clearly, these flakes are oriented preferentially such that the Z vibration axis lies normal to the plane of the thin section, parallel to the axis of nodule elongation.

This unique solution to the optical orientation of the cleavage flakes allows two important conclusions to be drawn. First, it appears that cleavage flakes generated during growth of nodular anhydrite do in fact tend to be platy in the (010) plane and elongate in the c-crystal direction, as one would expect from the cleavage ratings (Fig. 33). Second, it is apparent that, during flow, anhydrite cleavage flakes tend to align themselves such that the long axes of the plates (c-crystal direction) parallel the escape-flow vector, as depicted in Figure 31.

Discussion

The Baumann Fiord rocks illustrate that early-stage compactional flow is capable of transforming nodular anhydrite into delicately laminar anhydrite. This does not imply, however, that laminar anhydrite cannot form by other means. For instance, the anhydrite-calcite 'varves' of the Permian Castile Formation of Texas and New Mexico are widely considered by many to have originated by precipitation from a standing body of brine (Anderson and Kirkland, 1966; Davis and Kirkland, 1970; Anderson *et al.*, 1972). Intensely sheared anhydrite also may assume a layered or laminar appearance (e.g., Windsorian anhydrites of Nova Scotia - Schenk, 1969; Evans, 1967). Of course, one would not expect the anhydrite in these cases to consist of cleavage flakes or to exhibit 'felted-aligned' texture. It is only in cases where laminar anhydrite consists of felted-aligned cleavage flakes that flow of pre-existing nodular anhydrite should be considered as a possible mechanism of formation.

MASSIVE ANHYDRITE

In the Baumann Fiord outcrop belt adjacent to the Shield (Fig. 1, Secs. 4-7), laminar anhydrites with felted-aligned texture are preserved because they were spared from any form of major post-compactional textural transformation. However, in the Franklinian Miogeosyncline (Fig. 1, Secs. 1-3), there is abundant evidence that the anhydrites did undergo further textural modification, over and above that dependent upon early compactional flow. This is immediately evident in the field, for the Franklinian anhydrites are of massive aspect (Fig. 34a) - medium to finely crystalline, light to dark bluish grey in hand specimen. Close inspection reveals, however, that the anhydrite is not entirely homogeneous but is thinly banded, the layering being defined by subtle colour differences between adjacent bands.

---

*eg. a = Y b = X c = Z (Deer *et al.*, 1962)
a = X b = Y c = Z (Shearman and Fuller, 1969; Cuff, 1969)
a = Z b = Y c = X (the morphological designation - Dana, 1932)

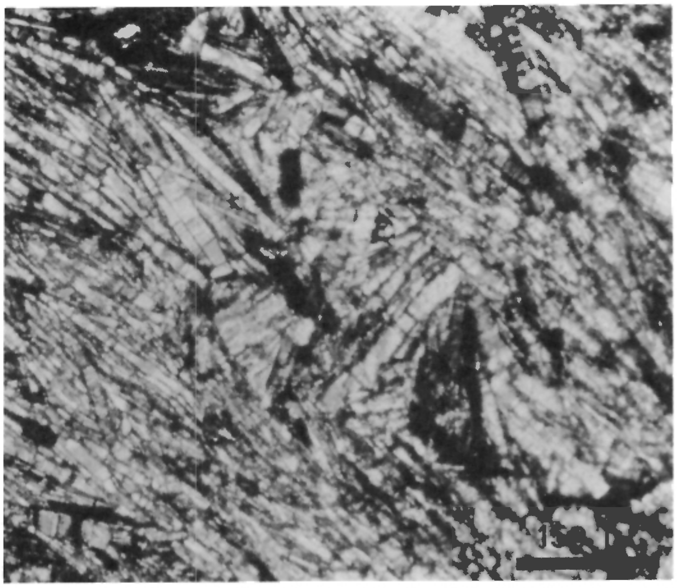


FIGURE 32. Anhydrite fabric in a thin section cut perpendicular to the plane of nodule flattening, crossed nicols, 45 degree position. Aligned anhydrite cleavage flakes occur in wispy, co-parallel zones, the intervening anhydrite retaining its felted texture. In this thin section, the anhydrite in the aligned zones exhibits near-normal birefringence (0.030-0.045); i.e., it is an elongation parallel section. In elongation normal sections, birefringence in the aligned zones is anomalously low (0.005-0.014). (GSC 203264-B)

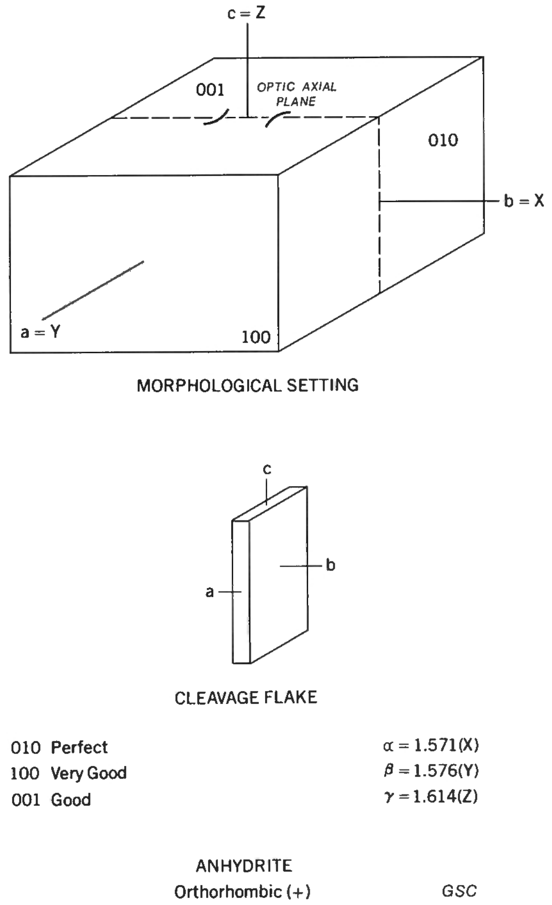


FIGURE 33. Crystallographic and optical orientation of anhydrite. Given the illustrated cleavage fissility ratings, cleavage flakes of the mineral tend to be platy in the a-c plane and elongate in the c-crystal direction.

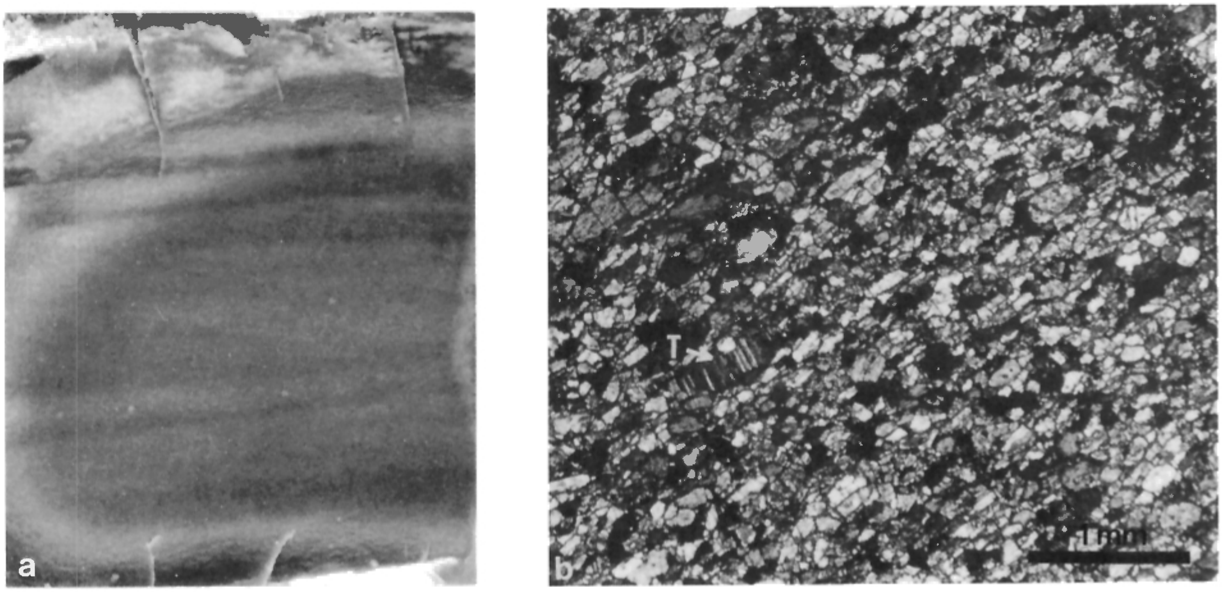


FIGURE 34.

a. Slabbed surface of massive Baumann Fiord anhydrite showing relict internal proto-lamination. Light-coloured halo around the periphery of the sample is due to partial gypsification at outcrop. The sample is 10 cm high. (GSC 203264-C)

b. Photomicrograph of massive anhydrite, showing blocky crystal habit and moderate foliation, crossed nicols, 45 degree position. Note twinning in some of the crystals (T). (GSC 203264-D)

In thin section (Fig. 34b), the anhydrite consists of blocky subhedral crystals, characteristically elongate in outline with diameter/thickness ratios of about 2.5/1. The size of individual crystals generally ranges between 50 and 200 μm but some crystals are as large as 800 μm. Twinning (sometimes repeated) can be seen in certain crystals (twinned on 011). The crystals are aligned parallel to bedding and, on the whole, these anhydrites have a weak to moderate dimensional foliation.

The layering in these massive anhydrites is due to differences in the accessory compositions of individual bands. For instance, some laminae are rich in calcite or dolomite (to 30%), others contain little calcite or dolomite. This compositional differentiation is petrographically reinforced by distinct textural differentials among the laminae (Fig. 35). In bands that are relatively rich in accessory carbonate, the anhydrite is finely crystalline; bands with lesser amounts of matrix material are more coarsely crystalline in their anhydrite component; pure anhydrite, such as that shown in Figure 34b, is the most coarsely crystalline end-member. The banding in these massive anhydrites is usually co-planar and the preferred orientation of the component crystals is parallel to bedding. In a number of places, however, the laminae are contorted, with small-scale overfolds and flame structures. Pinch-and-swell structures also are evident locally. In fact, the proto-lamination of the massive anhydrites is comparable in every essential regard to the 'compactional-flow' structures described earlier. In places where the proto-lamination is contorted, as in the rock pictured in Figure 35, the plane of flattening of the blocky anhydrite is oblique to the disturbed laminae, parallel to the bedding of the unit as a whole. In other words, the foliation is pervasive and through-going, always parallel to overall bedding, nothwithstanding small-scale contortions.

These observations allow some conclusions to be drawn regarding the origin of the massive Baumann Fiord anhydrites. First, there can be little doubt that the massive anhydrites stem from a laminar precursor since the pre-existing laminae are preserved in relict form. The only major difference between the laminar 'flow' anhydrites of the Arctic Platform and the massive anhydrites of the Franklinian Miogeosyncline is that the textural character of the latter has been transformed to the extent that the previous cleavage flake 'platy' habit of the constituent anhydrite has been converted totally to a blocky habit. Second, it is clear that the foliation in the massive anhydrites was not inherited directly from the pre-existing laminar anhydrites, for in the cases where the proto-laminae are contorted the present foliation cuts the inferred direction of 'flow' preference.

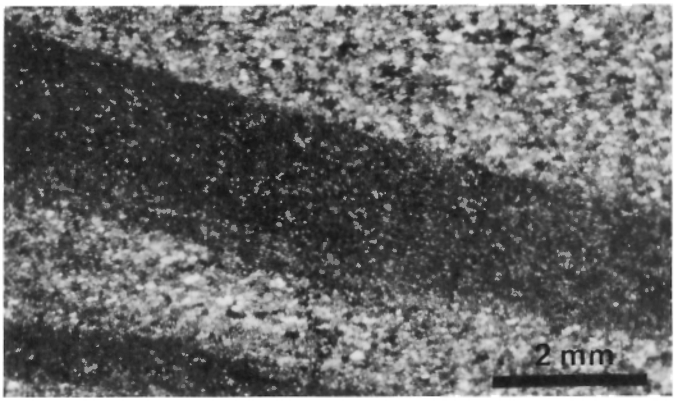


FIGURE 35. Photomicrograph of massive anhydrite with preferred dimensional fabric (horizontal), crossed nicols. The proto-lamination, here defined by sloping bands of carbonate-rich anhydrite, lies oblique to the gravity-normal foliation. (GSC 203264-E)

What was the nature of the textural transformation from platy to blocky anhydrite; what was the physico-chemical environment in which the transformation occurred; and when did the transformation take place? Precedents are lacking. Of the metamorphic anhydrite textures described by Borchert and Muir (1964), none is comparable to that of the massive Baumann Fiord anhydrite. Hoen (1964) and Schwerdtner and Clark (1967) described textural changes in anhydrites involved in major diapiric activity but none of the resultant fabrics resembles that under consideration here. Goldman (1952) set forth a great deal of textural detail relating to the anhydrites of salt dome cap rock. He showed how pervasive recrystallization can bring about dramatic textural changes in sedimentary anhydrites. The recrystallization processes he outlined were shear-induced and the fabrics thereby generated revealed a history of granulation, crushing and mylonitization. Evidence of shearing is lacking in the majority of massive Baumann Fiord anhydrites.

Some insight into the textural modification of the Baumann Fiord anhydrites may be gleaned through the application of some basic principles of metamorphic transformation. In monominerallic aggregates, thermally activated changes in atomic arrangement are well known. These give rise to what is normally referred to in metamorphic petrology as simply 'recrystallization' or "the reconstitution of an existing mineral phase" (Spry, 1966). Recrystallization during the early (pre-tectonic) stages of metamorphism often produces preferred orientation in monomineralic rocks because the stress field is uniaxial (σ_1 vertical $\equiv$ gravity) and the rate of grain growth in the plane normal to σ_1 exceeds the rate in the σ_1 direction (Spry, 1969). It is this type of thermally activated recrystallization that is envisaged for the Baumann Fiord anhydrites. The rationale behind such a mechanism is as follows. The foliation invariably is parallel to bedding, suggesting (a) that the stress indicatrix during recrystallization was uniaxial, with $\sigma_1 \equiv$ gravity, and (b) that the recrystallization was pre-tectonic, induced before the beds were tilted relative to the gravity-induced principal stress. The fact that the mean crystal size of the blocky anhydrites is significantly larger than that of its laminar precursor and that substructure in the anhydrite crystals is lacking suggest that grain growth, as opposed to coalescence, was the dominant recrystallization agent. Development of primary twins commonly accompanies recrystallization (Spry, 1969), thus the twinned anhydrite crystals of the Baumann Fiord rocks are to be expected.

The massive Baumann Fiord anhydrites are restricted to the most distal reaches of the outcrop belt (Trold Fiord region; Fig. 1). Conservative estimates of the thickness of Franklinian overburden in the area run to 6000 m or more (Thorsteinsson and Tozer, 1970; Mossop, 1973a). Assuming average geothermal gradients of 34°C/1000 m, the temperature at 6000 m should be on the order of 220°C. That thermally activated recrystallization can take place in evaporites at such comparatively low temperatures has been established (Borchert and Muir, 1964). Thus, it is likely that recrystallization to produce massive anhydrite was a result of pre-Ellesmerian burial metamorphism. Anhydrites in the Arctic Platform region were not recrystallized because they were never buried to a sufficient depth.

TECTONIC INFLUENCE ON ANHYDRITE TEXTURES

Folded anhydrite

In parts of the deformed belt close to the Arctic Platform, where burial was not sufficient to promote metamorphism, the anhydrite is not recrystallized to any significant degree, despite being deformed under what, at certain localities, must have been very great tectonic stress. At Locality 8 (Fig. 1), for example, tight chevron folds are exposed (Fig. 36a). These structures die out laterally and it is clear that the extreme deformation in this zone is strictly localized, for the deformation in the region as a whole is more subdued.

In the field, it is evident immediately that the contrast in competence between the anhydrites and the interbedded limestones was very marked. The anhydrites show every sign of having behaved in an extremely ductile manner during folding. Minor s-folds and z-folds are very common in the limbs of the structures. In one place, a syncline hinge has been breached and anhydrite injected into the core, forming a small-scale fan fold with minor m-folds (Fig. 36b), an indication of the extreme plasticity of the anhydrite. The limestones, on the other hand, behaved in a much more competent manner, deforming principally by brittle failure rather than by plastic flow. Radial tension fractures are common in limestones of the hinge zones. In the limbs of the folds, boudinage structure commonly is developed, with anhydrite bridging the necks between the limestone boudins (Fig. 36c).

That the anhydrites deformed by plastic flow is shown further by their petrographic character (Fig. 36d). The anhydrites are made up almost entirely of platy cleavage flakes, aligned parallel to the external lamination. Where the laminae are contorted in small-scale overfolds or flexures, the cleavage flakes are tangentially aligned along the contours of the structures, giving sweeping extinction under crossed nicols. There is no evidence of recrystallization in any of the material examined.

In many regards, these deformed anhydrite rocks closely resemble the laminar anhydrites, in their megascopic as well as their microscopic characteristics. Individual laminae are defined according to their accessory composition just as is the case in the undeformed 'flow' anhydrites. The cleavage flakes are identical in size and habit to those of the laminar 'flow' anhydrites. The lack of granulation and/or recrystallization indicates that deformation took place neither by intra-crystalline distortion nor by cataclasis. It is possible that the Locality 8 anhydrites, already of laminar aspect due to compactional flow, underwent renewed flow under conditions of enhanced pore-water pressure, triggered in response to the deformation. The form and configuration of the flow laminae would have been controlled by lateral compressional forces rather than by gravitational stresses. Except for this, the physical conditions under which the flow took place would have been similar to those that operated in the compactional flow regime. If compactional flow is viable mechanically, then the evidence at Locality 8 indicates that remobilization of the same rocks by deformation-induced pore-pressure buildup may be possible as well.

Sheared anhydrite

The Ellesmerian Orogeny that ended the life of the Franklinian Geosyncline (Trettin *et al.*, 1972) passed without leaving any regionally significant textural imprint on the Baumann Fiord anhydrites. The order of folding (600-1000 m amplitudes, 3-5 km wavelengths) is not consistent with development of any form of stress-related foliation, even in anhydrite rocks (N.J. Price, pers. com., 1972).

Subsequent tectonic overprinting on the Franklinian rocks by the Tertiary Eurekan Orogeny was limited to low-angle thrust faulting (Thorsteinsson and Tozer, 1970; Trettin *et al.*, 1972). These faults, which normally strike parallel to the Ellesmerian structures, preferentially follow the Ordovician evaporites. The thrust zones tend to be strictly confined. Rarely does the affected level exceed 3 m in thickness and the vertically adjacent anhydrite strata invariably appear unaffected by the shearing. The influence of thrusting on anhydrite textures proved very difficult to assess, however. Apparently, under Arctic weathering conditions, intensely sheared anhydrite alters to gypsum much more readily than does undeformed anhydrite. Near the edge of some shear zones it is possible to find extremely contorted material (Fig. 37), not itself sheared in the strict sense but obviously affected by the associated shear translation. Such contorted strata were altered completely to gypsum. Clearly, the assessment of anhydrite textural changes related to shearing must await the time when borehole cores of the relevant material are made available. It is apparent, nevertheless, that the Baumann Fiord anhydrites have a very low shear yield threshold and it is for this reason that the formation served as a major décollement during deformation.

SECONDARY GYPSUM IN THE BAUMANN FIORD FORMATION

As anhydrite rocks approach the surface in the course of normal uplift and erosion, steadily decreasing temperature eventually renders anhydrite ($CaSO_4$) unstable as a mineral phase and gypsum ($CaSO_4 \cdot 2H_2O$) assumes thermodynamic preference. Once calcium sulphate rocks are raised to levels above the anhydrite-gypsum transition depth, which commonly lies between 1000 and 1200 m, hydration of anhydrite to secondary gypsum is dependent solely on the availability of water. In most parts of the world, hydrologic conditions are such that water is made available at some time during the final stages of exhumation and anhydrite is rarely preserved at outcrop. In the permafrost zone of the Arctic region, however, all the water that normally would be available for the hydration of the near-surface anhydrite is perennially locked up as ice. In consequence, much of the Baumann Fiord anhydrite has escaped pervasive alteration to gypsum and is preserved at outcrop in a largely unaltered state (Mossop and Shearman, 1973).

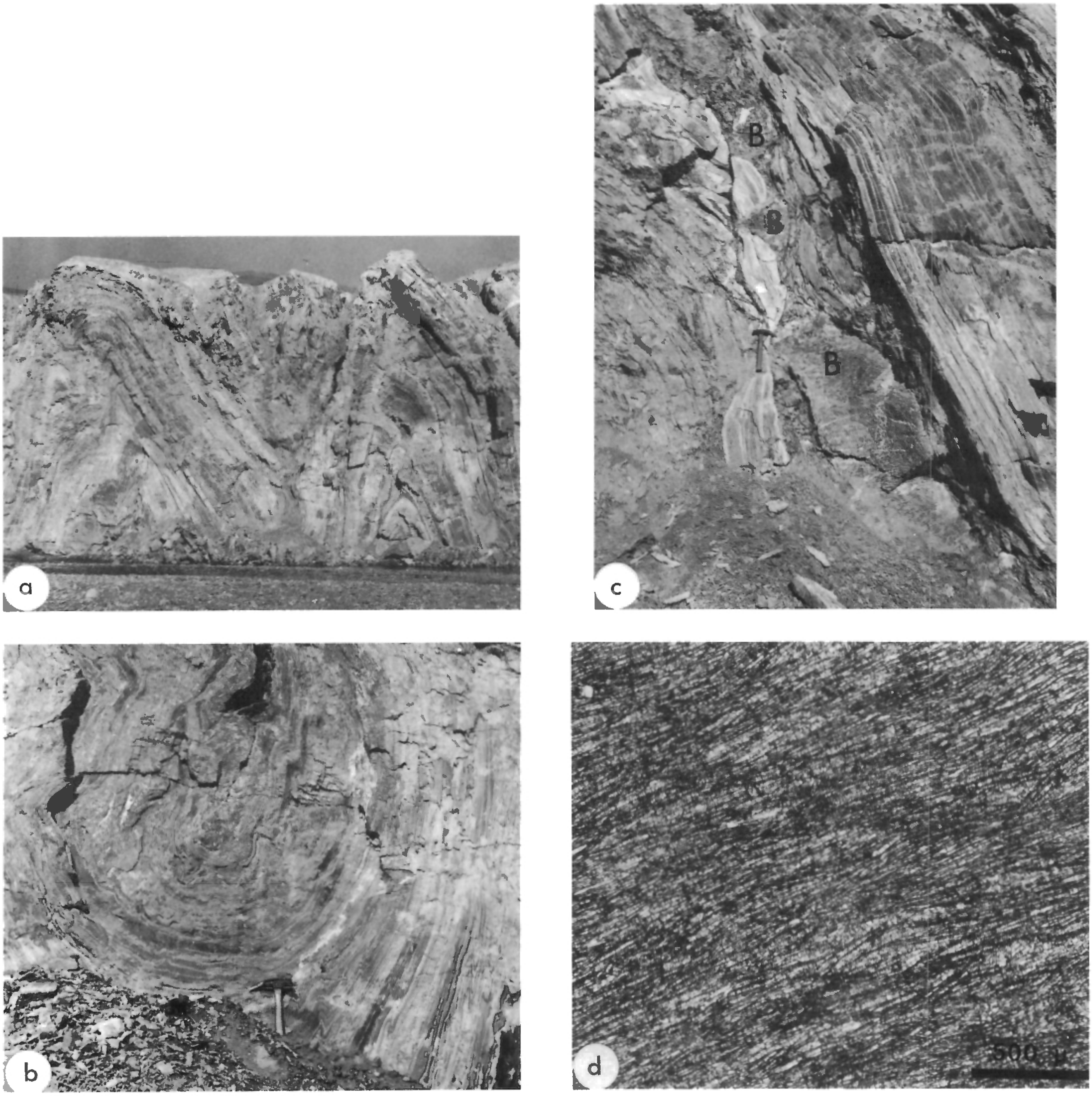


FIGURE 36.

a. Chevron folds in Baumann Fiord anhydrite and carbonate rocks, Locality 8 (Fig. 1). Note the small fan fold in the hinge of the central syncline. Cliff exposure is 24 m high. (GSC 203264-F)

b. Detail of minor folds in Locality 8 chevron fold. The left half of the photograph constitutes the fan fold injection structure in the hinge of the central syncline, Figure 36a. (GSC 203264-G)

c. Limb of chevron fold, Locality 8. Boudinage limestone in centre (B) with laminar anhydrite either side and necking the boudins. (GSC 203264-H)

d. Photomicrograph of aligned fabric in the anhydrite from Locality 8 chevron folds, ordinary light. The fabric is defined by anhydrite cleavage flakes. Scattered dolomite rhombs were apparently carried along with the anhydrite during flow. (GSC 203264-I)

There is, however, a significant amount of secondary gypsum present in the Baumann Fiord Formation and it occurs in two distinct forms. One type consists principally of replacive porphyroblastic gypsum and is found in association with satin-spar veins (Fig. 38a). This type of secondary gypsum is developed only in certain parts of the Baumann Fiord outcrop and, where it is in evidence, invariably is confined to the basal parts of the formation (Fig. 5). The second type is that which consists largely of replacive alabastrine gypsum (Fig. 38b, c). Its development is confined to the outermost surfaces of the present-day outcrops and is present at nearly every level in all of the sections examined. The porphyroblastic gypsum is thought to have formed when water moved up into the basal parts of the Baumann Fiord Formation evaporites from the underlying aquifer during pre-Pleistocene hydraulic fracturing. This promoted *in situ* gypsification of the anhydrite with concomitant precipitation of gypsum in the fractures, forming satin-spar veins (Shearman *et al.*, 1972; Mossop and Shearman, 1973). The alabastrine type gypsum appears to result from present-day weathering, when meteoric waters enter the summer thaw zone and promote a measure of surficial hydration.

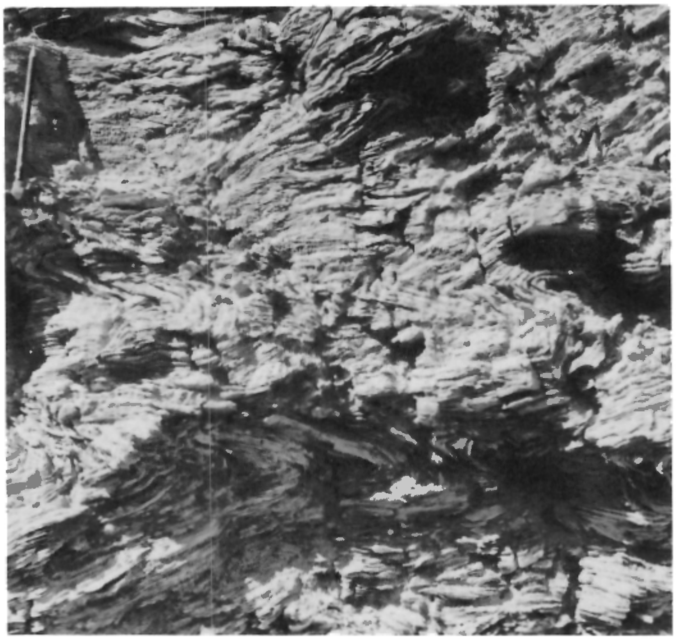


FIGURE 37. Tectonized Baumann Fiord anhydrite rock at the edge of a major shear zone. The anhydrite is in fact invariably altered to secondary gypsum in such instances, meteoric water having brought about hydration of at least the outermost 40 to 60 cm of the exposures. (GSC 161520)

Gypsification of anhydrite involves a 63 per cent increase in bulk volume and it is possible locally to document a measure of *in situ* expansion of the hydrated surficial material. However, the extent of disturbance usually is much less than that which would be expected to be produced by *in situ* emplacement of the full 63 per cent additional volume of gypsum. Thus, commonly a small amount of gypsum is present in the cracks between adjacent weathered blocks (Fig. 38d), calcium sulphate that clearly has been leached out of the parent rock and precipitated as an efflorescence on the outer surface. In some instances the efflorescent gypsum has been redistributed over an outcrop surface by the action of trickling rainwater (Fig. 38c) and, of course, in many cases the excess gypsum has been dissolved and washed away.

The powdery efflorescent gypsum has a trace strontium content that always is higher than that of the anhydrite rock from which it is derived (Appendix C). Furthermore, the alabastrine replacement gypsum in these cases always carries less strontium than does the parent anhydrite. From these relationships it is concluded that, during surficial alabastrine gypsification, strontium is leached preferentially from the anhydrite, a disproportionate amount of strontium diffusing out to the rock surface and being incorporated in the efflorescent gypsum. Preferential leaching of strontium during hydration (sometimes with consequent crystallization of celestite) has been noted in a number of secondary gypsum rocks from diverse settings (Goodman, 1952; Ham, 1962; Stewart, 1963; Holliday, 1967, 1970).

ECONOMIC CONSIDERATIONS

Anhydrite is a source mineral for the chemical industry and is of particular importance in the manufacture of sulphuric acid. The principle uses of gypsum are in the construction industry, for plaster of paris and plasterboard, and as a retarder in cement.

FIGURE 38. Gypsum in the Baumann Fiord Formation: Anhydrite - a; Gypsum (*in situ* alabastrine type) - g; Efflorescent gypsum - e; Chert - c.

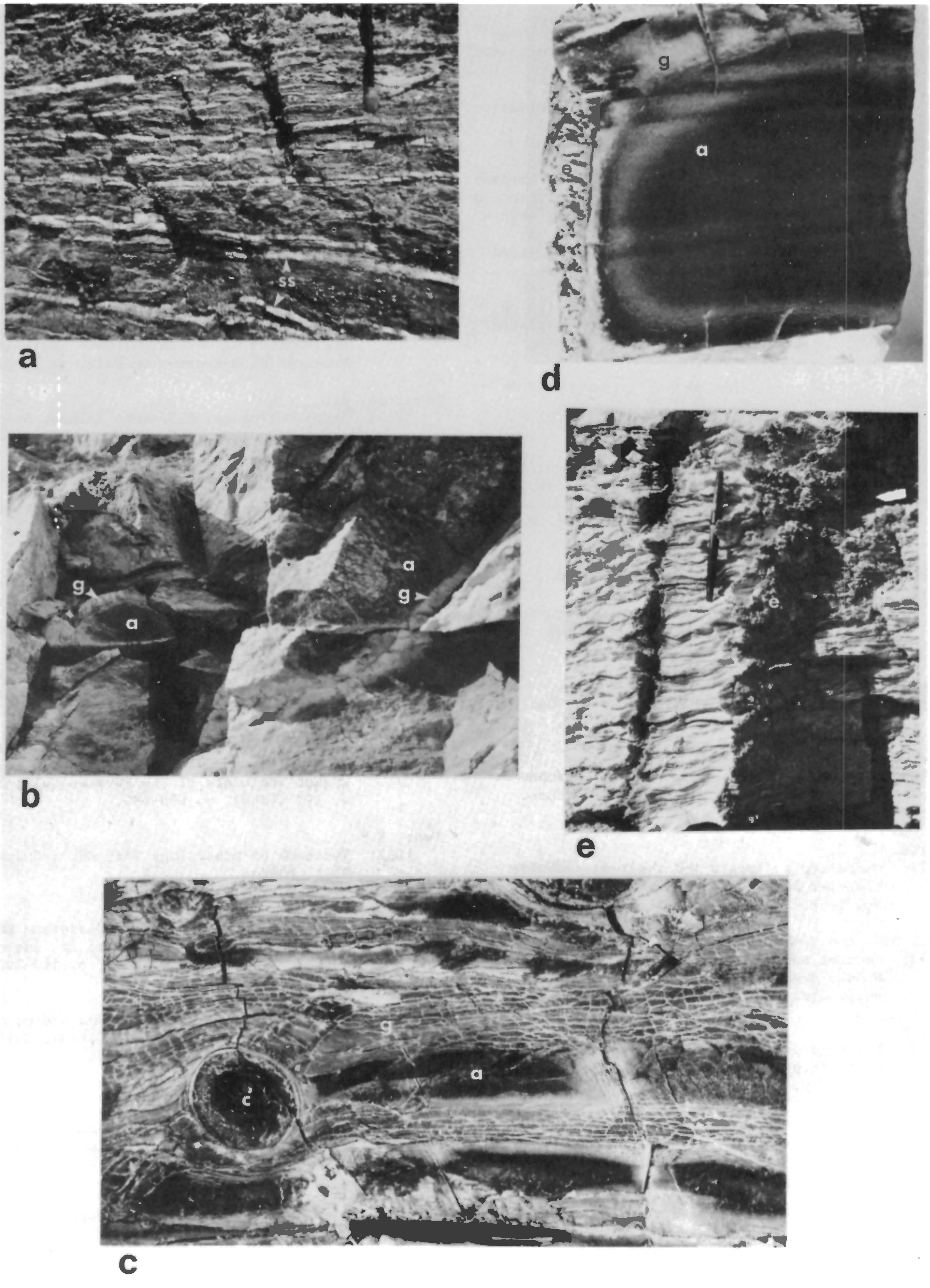
a. Satin-spar veins (ss) in secondary gypsum rock in the basal part of Section 4. (GSC 161503)

b. Secondary gypsum developed on exposed surfaces and along joint planes in nodular anhydrite rock, Section 5. (GSC 203264-M)

c. Surficial veneer of alabastrine secondary gypsum (cracked) on exposed surface of massive anhydrite. (GSC 161550)

d. Gypsification halos in slabbed surface of Baumann Fiord sulphate rock showing gradation from unaltered massive anhydrite (a) in the core of the sample through a partially hydrated zone to *in situ* alabastrine secondary gypsum (g). Excess $CaSO_4$ generated as a by-product of volume-for-volume replacement is precipitated on the outer surface as an efflorescence (e). (GSC 203264-N)

e. Crust of white powdery gypsum on the surface of an exposed block. On the sunlit portion, the gypsum has been washed over the surface by trickling rainwater. Along the shaded surfaces, the efflorescent gypsum is present in its original form. (GSC 161518)


ss
a
g
a
e
d
g
a
a
g
b
e
e
g
a
c
c

Vast quantities of both minerals are present in the Baumann Fiord Formation, especially in the Bache Peninsula area (Fig. 1). The great distance of these deposits from a market means that they have no economic value at the present time.

The carbonate rocks of the Baumann Fiord Formation in the study-area have little, if any, potential as petroleum reservoirs. However, laterally equivalent rocks, in the region of the supposed barrier complex (Figs. 24-26) may be of reservoir quality. The barrier complex along the Trucial Coast consists of oolitic and skeletal calcarenites and coralline reef facies (Evans *et al.*, 1973), good potential reservoir rocks. By analogy, the seaward equivalents of the Baumann Fiord sabkha cycles may be hosts for petroleum accumulation. The relevant sabkha equivalents are not exposed on central Ellesmere Island and borehole information on their character and distribution is not yet available.

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APPENDIX A

PUBLISHED GEOLOGICAL MAPS OF THE STUDY-AREA

Listed below are the principal reference maps for the study-area on Ellesmere Island. Maps that do not encompass sections measured in this study are included in order to provide for a complete geological picture of the region. All such listed maps do encompass Baumann Fiord Formation outcrops.

NTS	Geological Map	Section Localities Encompassed
49C	Baumann Fiord. Geological Survey of Canada Map 1312A. Scale 1:250,000. Compiled by J.Wm. Kerr and R. Thorsteinsson, 1971.	
49F	Eureka Sound South. Geological Survey of Canada Map 1300A. Scale 1:250,000. Compiled by R. Thorsteinsson, 1971.	1, 1a, 2, 3
49E	Strathcona Fiord. Geological Survey of Canada Map 1307A. Scale 1:250,000. Compiled by R. Thorsteinsson, 1971.	
49G	Eureka Sound North. Geological Survey of Canada Map 1302A. Scale 1:250,000. Compiled by R. Thorsteinsson, 1971.	
49H	Cañon Fiord. Geological Survey of Canada Map 1308A. Scale 1:250,000. Compiled by R. Thorsteinsson, 1971.	4, 7, 8
39G	Sawyer Bay. Geological Survey of Canada Map 1357A. Scale 1:125,000. Compiled by J.Wm. Kerr, 1972.	5
39H	Dobbin Bay. Geological Survey of Canada Map 1358A. Scale 1:125,000. Compiled by J.Wm. Kerr, 1972.	6
120B	Kennedy Channel and Lady Franklin Bay. Geological Survey of Canada Map 1359A. Scale 1:250,000. Compiled by J.Wm. Kerr, 1972.	
340A	Greely Fiord East. Geological Survey of Canada Map 1348A. Scale 1:250,000. Compiled by R. Thorsteinsson and J.Wm. Kerr, 1972.	

APPENDIX B

NEW PALEONTOLGICAL INFORMATION ON THE BAUMANN FIORD FORMATION

Macrofauna

Field No. and Stratigraphy
Baumann Fiord Formation
38-44 m above base of
B member, Section 7;
GSC locality C-19559

Locality, Fauna and Age
Latitude 79°09'N, Longitude 80°16'W,
Witch Mountain, Sverdrup Pass

indeterminate gastropods
fragments of trilobites
conodonts
Polytoechia sp.

age: late Early Ordovician, late Canadian or early Middle Ordovician (Whiterock)

comments: The genus *Polytoechia* is not well known. Most of the described species are late Early Ordovician in age, but an undescribed species similar to the present material has been collected by Christie (C-3307) from rocks on Devon Island that probably are Whiterock in age.

Determinations and comments by B.S. Norford, Institute of Sedimentary and Petroleum Geology, Calgary.

Conodonts

Total number of specimens: 257
GSC locality C-19559 (as above)

Conodonts were sorted and identified as follows (the number of specimens noted in parentheses). All are form taxa.

Acodus oneotensis Furnish (9)
Acontiodus staufferi Furnish (2)
Drepanodus arcuatus Pander (25)
D. sp. cf. *D. homocurvatus* Lindstrom (16)
D. subarcuatus
D. sp. cf. *D. suberectus* Branson and Mehl (2)
D. n. sp. (4)
Oistodus sp. cf. *O. inclinatus* Branson and Mehl (4)
O. sp. aff. *O. lanceolatus* Lindstrom (22)
O. linguatus Lindstrom (4)
Scandoldus pipa Lindstrom (9)
S. n. sp. (2)
Scolopodus cornutiformis Branson and Mehl (56)
S. gracilis Ethington and Clark (48)
S. quadraplicatus Branson and Mehl (27)
Stolodus (=*Distacodus*) *stola* Lindstrom (5)
Ulrichodina sp. (1)

taxonomic note: *Acodus oneotensis*, *Oistodus* sp. aff. *O. lanceolatus*, *Scolopodus gracilis*, and *Stolodus stola* are interpreted widely for each represents a transition series for which additional form species have been applied in the past. In terms of multi-element species, *D.* sp. cf. *D. homocurvatus*, *D.* sp. cf. *D. suberectus*, and *O.* sp. cf. *O. inclinatus* belong within the single natural species of *D.* sp. cf. *D. homocurvatus*.

comments: The large conodont fauna is characterized by scolopodid and drepanodid elements characteristic of platform facies of the Lower Ordovician in North America. A few elements, notably *Oistodos linguatus* and *Stolodus stola*, are typical components of Early Ordovician faunas of the North Atlantic provinces.

Conodonts were picked and mounted by T.T. Uyeno, Institute of Sedimentary and Petroleum Geology, Calgary. Identifications and comments are by C.R. Barnes, University of Waterloo, Ontario.

APPENDIX C

STRONTIUM CONTENTS IN BAUMANN FIORD FORMATION ANHYDRITE AND GYPSUM ROCKS

Trace strontium analyses were carried out by atomic absorption methods. Material analyzed included anhydrite rock, alabastrine gypsum rock (late *in situ* hydration), surficial efflorescent gypsum, porphyroblastic secondary gypsum (early *in situ* hydration), and some satin-spar gypsum. All values are expressed in parts-per-million strontium:

Sample (Section No.)	Anhydrite	Weathering Product Alabastrine Gypsum	Surficial Efflorescent Gypsum
26b(1)	2752	2558	
29f(1a)		2262	2740
30a(1a)		2794	3000
33d(1)		1749	
*37b(1)	2687	2380	3091
39e(1a)	2721	2535	
*43c(1a)	2762	1965	2991
52a(2)	2741	2082	
*57a(2)	2209	1831	3265
*65a(3)	2650	2208	2941
72b(3)	2481		2887
79c(4)		2362	2793
*102a(5)	2644	1931	2986
105b(5)	2763		
105c(5)	2692	2226	
111a(6)		2408	2977
*115c(7)	2641	1994	2760
117d(7)	2740	2322	

Sample (Section No.)	Porphyroblastic Secondary Gypsum	Satin-Spar
76b(4)	2256	
76c(4)		3143
107b(5)	1994	
+118c(7)	2006	4016
+119a(7)	2331	2976

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*Denotes analyses that include original anhydrite, its alabastrine gypsum hydration product, and the surficial efflorescent gypsum.

+Denotes cases where porphyroblistic gypsum and satin-spar determinations were ibtainable from the same hand specimen.

APPENDIX D

SULPHUR ISOTOPE DATA FOR BAUMANN FIORD FORMATION SULPHATE ROCKS

The following sulphur isotope determinations were carried out by the United States Atomic Energy Commission (H.H. Adler, Washington, D.C.). Analyses were based on 20 g hand samples of Baumann Fiord Formation gypsum and anhydrite rocks.

Sample Number*	S^{34}°/oo
GM-7-2	+28.2
GM-7-4	+27.6
GM-7-6	+28.7
GM-7-8	+30.9
GM-7-10	+28.3
GM-7-12	+25.4
GM-7-14	+24.0
GM-8-1	+28.0
GM-8-3	+26.0
GM-8-12	+27.0
GM-8-13	+28.2
GM-8-14	+28.2
GM-8-15	+30.4
GM-8-16	+29.2
GM-8-17	+27.6

Within the S^{32}/S^{34} spectrum for marine sulphate deposits, the above determinations "agree very well with the published data on Ordovician sulphate, particularly with the data provided by Thode and Monster (1964) on the sulphate of the Red River Formation, Saskatchewan" (H. Adler, pers. com.).

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*Samples were derived from localities 7 and 8 (Fig. 1), as denoted in the middle digit of each sample number.