# SEQUENCE STRATIGRAPHY AND DEPOSITIONAL HISTORY OF THE ARTINSKIAN TO KUNGURIAN SEQUENCE, OTTO FIORD AREA, NORTHWESTERN ELLESMERE ISLAND

by

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## ABSTRACT

The Artinskian to Kungurian Sequence of the Otto Fiord area is dominated by the Great Bear Cape, Raanes and Trappers Cove formations in addition to the upper portions of the Nansen and Hare Fiord formations. The Great Bear Cape Formation (10 - 300 m), in the Otto Fiord area, is a yellowish-weathering, cliff-forming, packstone to grainstone dominated by echinoderms, bryozoans, and brachiopods. The Raanes Formation (10 - 225 m) is greenish-weathering, recessive to resistant, shaly to silty, variably cherty wackestone to packstone dominated by bryozoans, brachiopods, crinoids, and sponge spicules in addition to resistant, massive, very fine-grained, bryozoan-lime mud wackestone forming bioherms. The Trappers Cove Formation (55 - 1000 m) is black to dark gray spiculitic chert that is interfingered with thinly-bedded, black, recessive shales and siltstones.

The Artinskian to Kungurian Sequence of the Otto Fiord area, best resembles a Transgressive-Regressive (T-R) Sequence consisting of a lower sequence boundary (LSB), transgressive systems tract (TST), maximum flooding surface (MFS), regressive systems tract (RST), and upper sequence boundary (USB). The LSB and USB are subaerial unconformities on the shelf that become correlative conformities basinward. The MFS is characterized by silty sediment in shelfal areas and by papery black shales in basinal regions in addition to concentrations of pyrite and phosphate. The TST is subdivided into an early transgressive systems tract (ETST) and a late transgressive systems tract (LTST). The ETST records the initial deepening phase and is represented by the uppermost Nansen Formation on the shelf and by the Hare Fiord Formation in the basin. The LTST records a phase of significant deepening that is represented by the entire Raanes Formation. In the basin the LTST is a condensed section merging with the MFS at the top of the Hare Fiord Formation. The RST is represented by: i) shallowing upward, progradational, cool-water shelf carbonates of the Great Bear Cape Formation, and ii) laterally equivalent slope and basinal cherts and shales of the Trappers Cove Formation.

The facies of the Artinskian to Kungurian Sequence in the Otto Fiord area represent four distinct facies associations, identified on the basis of their biotas as the Chloroforam Facies Association, Bryonoderm-Extended Facies Association, Bryonoderm Facies Association, and Hyalosponge Facies Association. Eleven facies within these associations were identified and distinguished on the basis of the dominant depositional texture:

Chloroforam Grainstone: Chloroforam Wackestone to Packstone: Bryonoderm-Extended Grainstone: Bryonoderm-Extended Packstone: Bryonoderm-Extended Reefal Limestone: Bryonoderm Grainstone: Bryonoderm Wackestone to Packstone: Bryonoderm Spiculite: Hyalosponge Mudrock: Siliceous/Spiculitic Shale: and Debrite/Turbidite. These facies represent inner to outer shelf. shelf margin. and slope-to-basin depositional settings of an open-marine. distally steepened shelf.

The distribution of facies across the shelf and slope was complex as. not only did the facies change spatially with water depth. but they also changed temporally. The spatial distribution of the facies was controlled by the location of the fair-weather wavebase. resulting in grainstones and packstones dominating shelf regions and wackestones and mudstones dominating the shelf margin. slope and basin regions. The spatial distribution of facies was also dictated by depth- or upwelling-related temperature changes. The Bryonoderm Association occupied deeper water environments or shelf environments exposed to upwelling currents while the more diverse and tropical Chloroforam Association was restricted to shallow. warm-water shelf environments.

The temporal distribution of facies through the Artinskian to Kungurian Sequence indicates that the facies association dominating the shelf was dependent on the existing climatic conditions. shelfal sedimentation rates. and shelfal accommodation space. Facies associations indicate that early in the sequence the shelf was exposed to tropical-like conditions while at the end of the sequence cool-water conditions prevailed. Shelfal sedimentation rates increased from the early portions of the sequence to the later portions as shelfal production and sedimentation rates during Great Bear Cape time exceeded sedimentation rates of the older Raanes Formation. Major changes in shelfal accommodation space occurred through the Artinskian to Kungurian Sequence. indicated by the changing depositional style of sediments on the shelf. During the TST. in the early portion of the sequence. an overall increase in shelfal accommodation space occurred while during the RST. in the latter portion of the sequence. shelfal accommodation space decreased. The long term fluctuation in relative sea-level and accommodation space was tectonically driven by intermittent rifting during the Artinskian.

## RÉSUMÉ

La Séquence d'âge Artinskien-Kungurien de la région d'Otto Fiord comprend les formations de Great Bear Cape, de Raanes et de Trappers Cove ainsi que le sommet des formations de Nansen et de Hare Fiord. La Formation de Great Bear Cape (10-300 m) dans la région d'étude forme des escarpements rocheux bien distincts de couleur jaunâtre en surface altérée. Cette formation est principalement composée par des packstones/ grainstones à crinoïde, bryozoaire et brachiopode. La Formation de Raanes (10-225 m) est verdâtre en surface altérée, récessive à résistante en affleurement, et composée de wackestones/packstones argileux à silteux, parfois cherteux, à bryozoaire, brachiopode, crinoïde, et spicules d'éponge. On y retrouve aussi plusieurs biohermes à boue calcaire riches en bryozoaire. La Formation de Trappers Cove (55-1000 m) est composée de chert à spicule de couleur noir à gris foncé en surface altérée et interlité avec des shales et siltstones de couleur foncée.

La Séquence d'âge Artinskien - Kungurien de la région d'Otto Fiord forme une succession transgressive-regressive (T-R). Cette séquence, délimitée par des discordances majeures à la base (LSB) et au sommet (UBS), comprend un system tract transgressif (TST) et un system tract régressif (RST) séparés par une surface d'inondation maximale (MFS). Les discordances à la base et au sommet de la séquence ont une origine subaérienne à la marge du bassin mais passe graduellement à une surface concordante vers le centre du bassin. La surface d'inondation maximale est caractérisée par des sédiments silteux en milieu de plate-forme et par des shales noirs avec des concentrations de phosphate et de pyrite en milieu de bassin. Le system tract transgressif est subdivisé en un sous-système transgressif précoce (ETST) et un sous-système transgressif tardif (LTST). Le ETST représente le lent début de l'inondation de la plate-forme par une hausse relative du niveau marin. Le sommet de la Formation de Nansen a préservé cet évènement en milieu de plate-forme tandis qu'en milieu de bassin on le retrouve au sommet des strates de la Formation de Hare Fiord. Le LTST, associé aux strates de la Formation Raanes, représente l'inondation rapide de la plate-forme par une importante hausse relative du niveau marin. Dans le milieu de bassin, le LTST représente une période de sédimentation condensée

correspondant à la surface d'inondation maximale (MFS) au sommet de la Formation de Hare Fiord. Le system tract regressif (RST) comprend les calcaires de la Formation de Great Bear Cape déposés sur une plate-forme en milieu froid et les cherts et shales de la Formation de Trappers Cove déposés en milieu plus profond de pente et/ou de bassin.

Quatre grands assemblages de faciès sédimentaires ont été identifiés dans la Séquence d'âge Artinskien-Kungurien de la région d'Otto Fiord : i) assemblage de faciès à Chloroforam; ii) assemblage de faciès à Bryonoderme-Étendu; iii) assemblage de faciès à Bryonoderme; et iv) assemblage de faciès à Hyalosponge. Ces assemblages sont constitués de 11 faciès distincts comprenant: grainstone à Chloroforam; wackestone/wackstone à Chloroforam; grainstone à Bryonoderme-Étendu; packstone à Bryonoderme-Étendu; bioherme à Bryonoderme-Étendu; grainstone à Bryonoderme; wackestone/packstone à Bryonoderme; chert spiculitique à Bryonoderme; mudrock à Hyalosponge; Shale spiculitique; et Debrite-Turbidite. Ces faciès représentent des milieux sédimentaires formant un continum de la plate-forme ouverte au bassin délimité par un bris de pente en milieu relativement profond (distally steepened, open-marine shelf).

La distribution des faciès de cette ancienne plate-forme est complexe parce que leur distribution a changé dans l'espace ainsi qu'avec le temps. La distribution spatiale montre des packstones/grainstones sur la plate forme interne/médiane au-dessus du niveau d'action des vagues mais des wackestones/mudstones sous ce niveau sur la plate-forme externe. La distribution spatiale de faciès est aussi liée à d'autres facteurs de contrôle comme les changements de température avec la profondeur et les phénomènes locaux d'upwelling. L'assemblage à Bryonoderme a occupé les milieux de plate-forme plus profonde et froide ou encore les régions de la plate-forme soumises aux effets d'upwelling tandis que l'assemblage à Chloroforam était limité aux milieux de plate-forme interne/médiane, peu profonde et à eau chaude.

La distribution temporelle des faciès de la Séquence d'âge Artinskien à Kungurien indique que les assemblages des faciès de la plate-forme ont été controlés par les chagements climatiques, les taux d'accumulation sédimentaire, et l'espace d'accommodation. La distribution temporelle des faciès de plate forme indique qu'elle était sous une influence climatique relativement chaude au début mais qu'on a assisté à une détérioration climatique qui a permis la déposition de calcaires de milieu froid sur la plate-forme à la fin de la séquence. Le taux d'accumulation sédimentaire sur la plate-forme a augmenté avec la déposition des calcaires de la Formation de Great Bear Cape qui a suivi celle des shales et cherts de la Formation de Raanes. L'espace disponible pour accommoder la sédimentation s'est grandement modifié au cours de la déposition de la séquence d'âge Artinskien-Kungurien dans la région d'étude. Au début de la déposition (TST), l'espace d'accommodation sur la plate-forme s'est accru puis a diminué lors de la déposition du system tract régressif (RST). Ce changement à long terme de l'espace d'accomodation a été probablement controllé par la fluctuation du niveau marin et par la subsidence tectonique périodiquement active dans le bassin à cette époque.

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# CHAPTER 1: INTRODUCTION

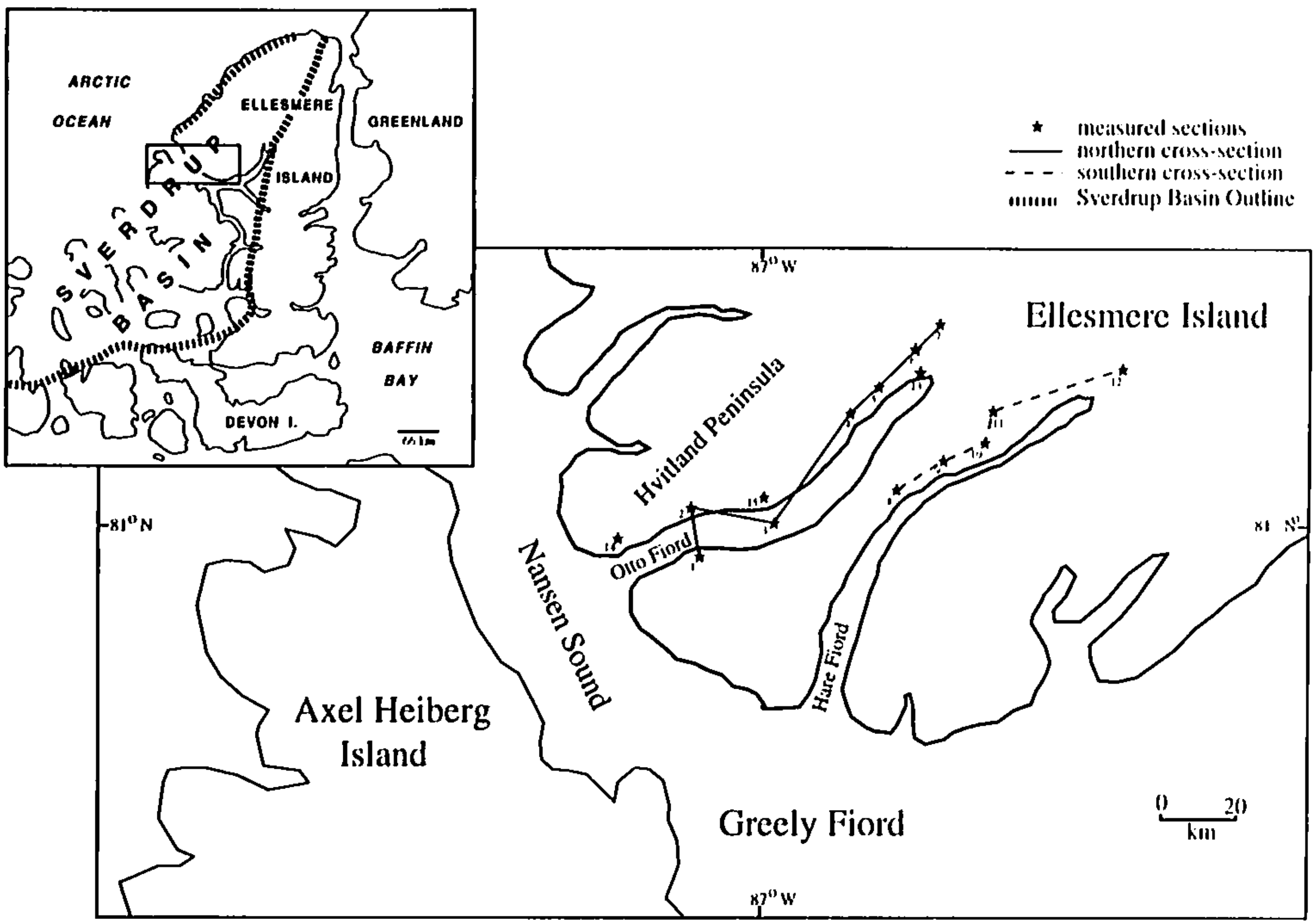
## 1.1 Study objectives

The Artinskian to Kungurian (Early Permian) Sequence of the Otto Fiord area, northwestern Ellesmere Island, is part of the upper Paleozoic strata that were deposited in the Sverdrup Basin (Figures 1 and 2). This particular sequence is of great interest and was chosen as the focus of this study for two main reasons: 1) The Artinskian to Kungurian Sequence has been studied, in terms of stratigraphy and depositional environments, along the southern and eastern margins (Beauchamp and Henderson, 1994; Scott et al., 1991) of the Sverdrup Basin but relatively little is known about its northwestern margin, and 2) the Artinskian to Kungurian Sequence recorded part of a dramatic climatic cooling event that occurred over the circum-Arctic region during Permian time (Beauchamp, 1994).

The study by Scott et al., (1991) focused on Artinskian to Kungurian strata that were deposited in the Fosheim-Hamilton subbasin of west-central Ellesmere Island. Shallow-water carbonate sedimentation in this subbasin was stressed because of extensive terrigenous clastic input and episodes of restricted circulation and elevated salinities. In addition, Beauchamp and Henderson (1994) indicated that there was a significant siliciclastic influx at the time of carbonate deposition along the southern margin. Therefore, the present study of Artinskian to Kungurian strata from the northwestern margin of the Sverdrup Basin is important as it will provide: 1) information about a carbonate platform, that was unstressed in terms of siliciclastic influx, and 2) tectonic and depositional information about the northwestern margin of the Sverdrup Basin exposures showing facies transition from platform to basin.

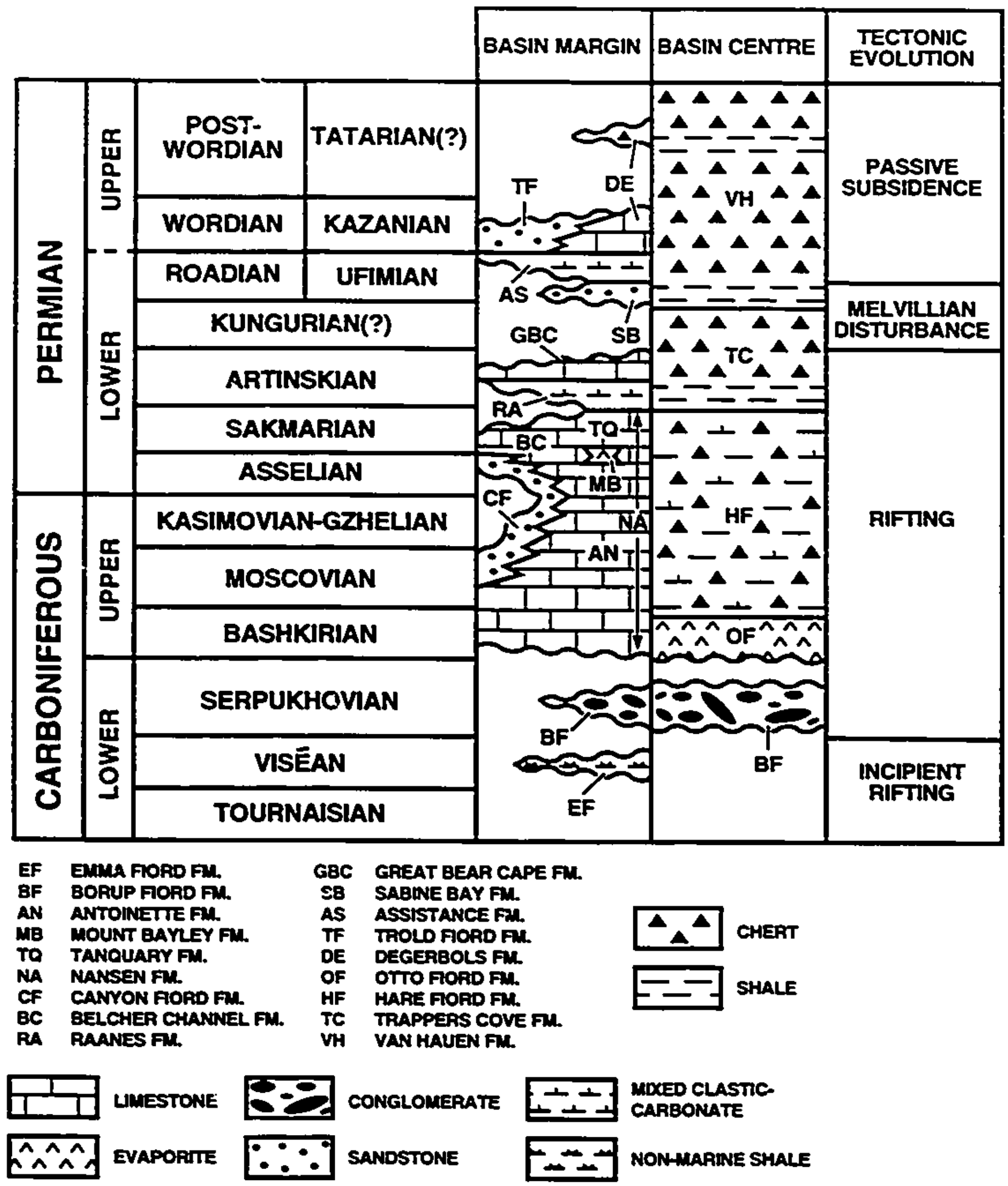
The dramatic climatic cooling trend recorded in Artinskian to Kungurian strata in the study area has also been documented in other circum-Arctic regions including Northern Alaska, North Greenland, Svalbard, Bjornoya, Barents Sea and Siberia (Beauchamp, 1994; Stemmerik and Worsley, 1989; Ustritsky, 1973). In the Sverdrup Basin, this event is evident from the skeletal and non-skeletal associations, and mineralogy in the strata from Serpukhovian (late Early Carboniferous) to Kazanian (Late Permian) time (Figure 2). The highly diverse, disparate fauna of the late Early Carboniferous became a low diversity, cool-water biotic association in Late Permian time (Bryonoderm-Extended Association of Beauchamp, 1994).

Figure 1 Map of study area showing the location of measured sections outlining the north and south cross-sections. Inset map illustrating the general outline of the Sverdrup Basin with shaded box showing the study area on Ellesmere Island.



ARCTIC
OCEAN
ELLESMERE
ISLAND
GREENLAND
SVERDRUP
BASIN
BAFFIN
BAY
DEVON I.
measured sections
northern cross-section
southern cross-section
Sverdrup Basin Outline
87° W
81° N
Ellesmere Island
Hvitland Peninsula
Otto Fiord
Nansen Sound
Hare Fiord
Axel Heiberg
Island
Greely Fiord
0
20
km

Figure 2 Upper Paleozoic stratigraphic chart of the Sverdrup Basin (from Beauchamp, 1994). The present study focuses on the Artinskian to Kungurian Sequence.


BASIN MARGIN
BASIN CENTRE
TECTONIC EVOLUTION
PERMIAN
CARBONIFEROUS
UPPER
LOWER
UPPER
LOWER
POST-WORDIAN
TATARIAN(?)
WORDIAN
KAZANIAN
ROADIAN
UFIMIAN
KUNGURIAN(?)
ARTINSKIAN
SAKMARIAN
ASSELIAN
KASIMOVIAN-GZHELIAN
MOSCOVIAN
BASHKIRIAN
SERPUKHOVIAN
VISÉAN
TOURNAISIAN
TF
DE
VH
AS
GBC
SB
TC
RA
TQ
BC
MB
CF
NA
HF
AN
OF
BF
BF
EF
PASSIVE SUBSIDENCE
MELVILLIAN DISTURBANCE
RIFTING
INCIPIENT RIFTING
EF EMMA FIORD FM.
BF BORUP FIORD FM.
AN ANTOINETTE FM.
MB MOUNT BAYLEY FM.
TQ TANQUARY FM.
NA NANSEN FM.
CF CANYON FIORD FM.
BC BELCHER CHANNEL FM.
RA RAANES FM.
GBC GREAT BEAR CAPE FM.
SB SABINE BAY FM.
AS ASSISTANCE FM.
TF TROLD FIORD FM.
DE DEGERBOLS FM.
OF OTTO FIORD FM.
HF HARE FIORD FM.
TC TRAPPERS COVE FM.
VH VAN HAUEN FM.
CHERT
SHALE
LIMESTONE
CONGLOMERATE
MIXED CLASTIC-CARBONATE
EVAPORITE
SANDSTONE
NON-MARINE SHALE

Warm-water biotic associations existed in the Sverdrup Basin throughout Serpukhovian to Sakmarian time. Evidence for such a climate is the biota of the Chloroforam Facies Association (Beauchamp, 1994) which includes various green algae, foraminifera (including fusulinids, and encrusting and small benthic foraminifera), bryozoans, echinoderms, brachiopods, pelecypods, gastropods, solitary and colonial rugose corals, red algae and incertae sedis (*Tubiphytes* and *Palaeoaplysina*). In addition to skeletal grains, various non-skeletal grains such as ooids, peloids and oncoids, and the presence of algal reefs, mixed reefs and bryozoan reefs are also indicative of a warm climate. Mineralogy within this stratigraphic interval is dominantly aragonite and high-Mg Calcite which are also commonly found in warm-water settings (Lees, 1975; Beauchamp, 1994).

The Artinskian is characterized by the Bryonoderm-Extended Facies Association (Beauchamp, 1994). This association typically includes bryozoans, echinoderms, brachiopods, minor amounts of solitary and colonial rugose corals, fusulinacean and a limited range of small benthic foraminifera. Red algae, *Tubiphytes*, pelecypods, and gastropods are also present. The Artinskian is characterized by low Mg calcite with various proportions of high Mg calcite and very rare occurrences of aragonite. Ooid or botryoidal cements are not present. According to Lees (1975) and Beauchamp (1994) this type of assemblage is transitional between warm- and cool-water carbonates.

Further information provided from this study on this cooling trend is expected to add to the data from previous studies to help broaden our understanding of such large scale occurrences.

The specific purposes of this study are to:

1) document lithostratigraphic boundaries, sequence stratigraphic boundaries and systems tracts of the Artinskian to Kungurian Sequence in the Otto Fiord area of northwestern Ellesmere Island.

2) describe and interpret the depositional facies assemblages and devise a depositional model showing facies location on the shelf during Artinskian to Kungurian time.

3) compare these observations with those of the previous study of Beauchamp and Henderson (1994) of the Artinskian to Kungurian Sequence on southwestern Ellesmere Island.

4) compare and contrast results of the study to other recently published studies of cool-water carbonate shelves in the Ordovician, mid-Tertiary and Holocene.

**1.2 Geologic Setting**

The Sverdrup Basin, a northeasterly trending rift basin approximately 1000 km long by 400 km wide and containing more than 12 km of sediments and minor volcanics, represents a major depocenter that was active during Carboniferous through to Tertiary times (Thorsteinsson, 1974; Balkwill, 1978; Beauchamp et al., 1989a). The basin formed in the Early Carboniferous during 80 Ma of intermittent rifting of underlying Precambrian to Devonian rocks, following the Late Devonian to Early Carboniferous Ellesmerian Orogeny (Thorsteinsson, 1974; Beauchamp et al., 1989a; Thériault, 1991). The Sverdrup Basin was created as part of an extensive rift system that extended from northern Alaska to northern Greenland, Svalbard and the Barents Sea (Beauchamp, 1994). The basin itself was a largely landlocked narrow seaway that bordered land masses to the northeast and southwest (Figure 3). Due to rifting, the paleolandscape of the Sverdrup Basin was tectonically controlled by extensional half grabens, forming a series of parallel subbasins separated by linear highs (Thériault and Beauchamp, 1991; Thériault et al., 1995). The half grabens, such as those occurring along the basin margin, were infrequently active during the deposition of the upper Paleozoic sediments, affecting sedimentation and rates of accumulation (Morin, 1992; Thériault and Beauchamp, 1991; Scott, 1992; Reidiger and Harrison, 1993).

Rifting ended with a short but dramatic tectonic event called, the Melvillian Disturbance, in early Permian time (Figure 2). The Melvillian Disturbance was a period of folding and faulting that affected Upper Carboniferous to Lower Permian and older strata (Beauchamp, 1994). In general the disturbance created structural inversions, local uplifts, transtensional growth faulting and net subsidence throughout the basin. It was followed by a period of passive thermal subsidence in mid-Permian time (i.e. post-Kungurian).

Sedimentation style of the Sverdrup Basin changed from carbonate-dominated to clastic-dominated during late Paleozoic time. In the Carboniferous and Early Permian carbonate sedimentation predominated in shallow platformal areas but changed in Late Permian and Mesozoic time with major influx of siliciclastic sediments from continental landmasses to the south and east and from Crockerland to the north (Figure 3; Beauchamp et al., 1989b; Embry, 1992; Beauchamp, 1994).

The present day exposures of the upper Paleozoic succession on Ellesmere Island and across the High Arctic are the result of uplift, deformation and subsequent erosion associated with the Tertiary Eurekan Orogeny (Thorsteinsson, 1974; Trettin, 1989), that created superb exposures along mountain ranges and coastal fiords.

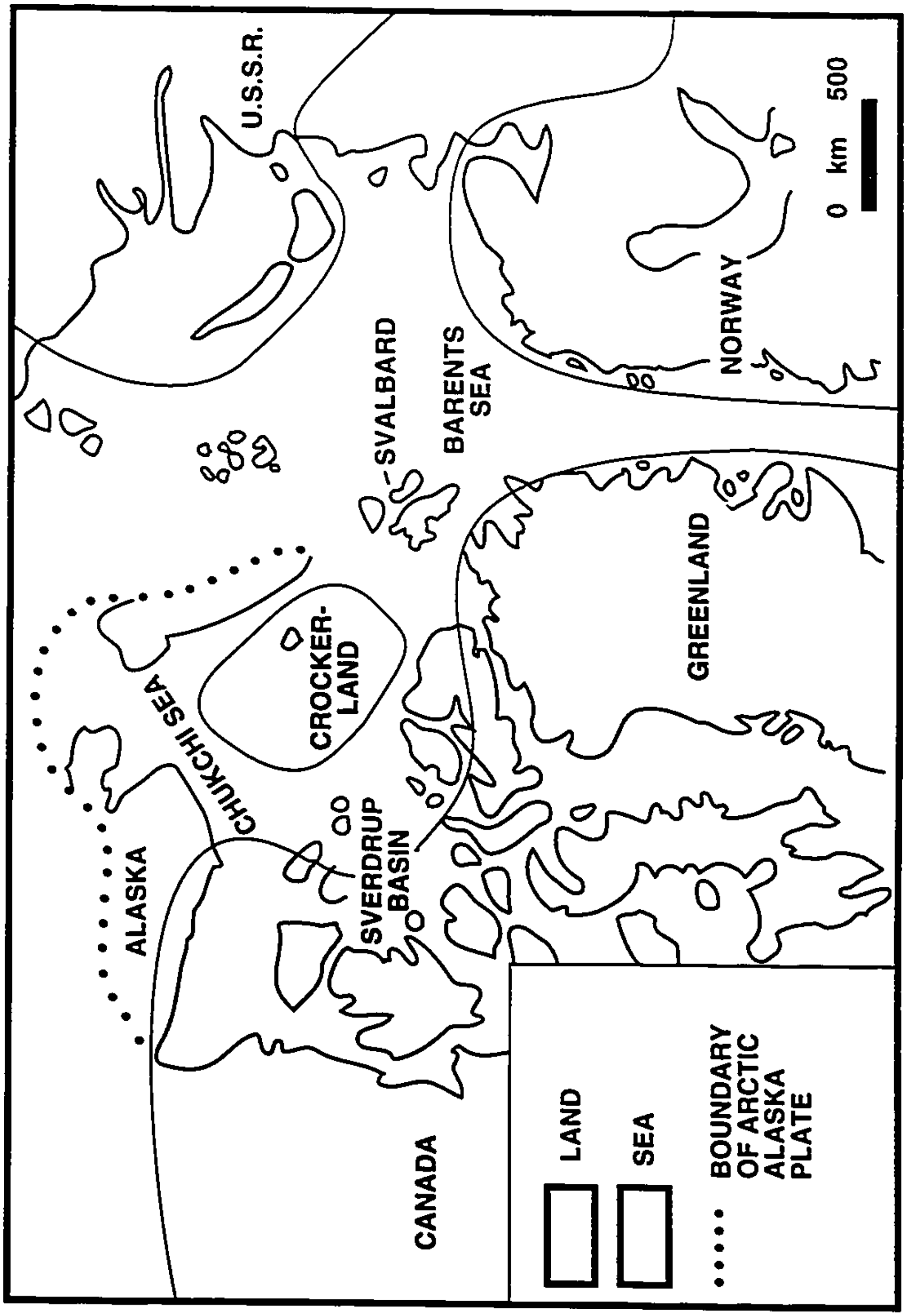
The paleoclimatic indicators (e.g. Chloroforam Association of Serpukhovian-Sakmarian time and Bryonoderm Association of Artinskian-Kungurian time) indicate that the late Paleozoic climate of the Sverdrup Basin evolved from a tropical sub-humid climate in the Early Carboniferous to a tropical semi-arid to arid climate in the Late Carboniferous-Early Permian, followed by a temperate sub-humid climate in the middle Permian, and finally to a sub-polar to polar climate in the latest Permian (Beauchamp et al., 1989a; Beauchamp, 1994). These climatic changes paralleled the northward drift of the landmass from approximately $10^{\circ}$N in the Early Carboniferous to 40 to $50^{\circ}$N in the Late Permian (Zeigler, 1988). Evidence of this cooling trend is not restricted to the Sverdrup Basin but is also present in Northern Alaska, North Greenland, Svalbard, Bjornoya, Barents Sea and Siberia (Beauchamp, 1994; Stemmerik and Worsley, 1989; Ustritsky, 1973).

The upper Paleozoic succession of the Sverdrup Basin has been divided into eight, low-order, transgressive-regressive, unconformity-bounded sequences (Beauchamp and Henderson, 1994). These unconformity-bounded sequences pass basinward into correlative conformities. The sequences represent 5 to 50 million year time intervals (Beauchamp et al., 1989b). Of these low-order sequences the Artinskian to Kungurian Sequence, representing 5 -10 million years, was the last succession to occur during the rifting phase before the onset of the Melvillian Disturbance. This sequence is represented in the uppermost Nansen and Hare Fiord formations, by the entire Raanes Formation and most of the Great Bear Cape and Trappers Cove formations in the study area (Figure 2; Beauchamp and Henderson, 1994).

### 1.3 Previous work

Samples of the Artinskian strata, although their age was unknown at that time, were first collected in 1901 by a Norwegian geologist, Per Schei, from Great Bear Cape in the southwestern corner of Bjorne Peninsula. These samples were later examined by a number

Figure 3 Late Paleozoic circum-Arctic paleogeography map (from Embry, 1992) showing the location of the Sverdrup Basin in relation to Crockerland. Note the position of Alaska, Svalbard and the Barents Sea during this time.


U.S.S.R.
0 km 500
NORWAY
SVALBARD
BARENTS SEA
GREENLAND
CROCKER-LAND
CHUKCHI SEA
ALASKA
SVERDRUP BASIN
CANADA
LAND
SEA
BOUNDARY OF ARCTIC ALASKA PLATE

of paleontologists who established that they were of Permian age (Tschernyshew and Stepanov, 1916; Troelson, 1950; Dunbar, 1955; Minato, 1960; Gobbet, 1963; Nassichuk and Wilde, 1977).

McLaren (1963) described about 90m of yellowish weathering, medium-bedded, bioclastic rock belonging to the Great Bear Cape Limestone on the Bjorne Peninsula and collected two suites of brachiopods. On the west side of Blind Fiord on the Raanes Peninsula, Tozer (1963) also described Permian rocks as the Grey Beds and the Dark Beds.

Thorsteinsson (1974) examined the Bjorne and Raanes peninsulas and assigned formation names to the upper Paleozoic succession at these locations. The Grey Beds and Dark Beds of Tozer (1963) were assigned to the Nansen and Van Hauen formations, respectively, and the Great Bear Cape Limestone was assigned to the Degerbols Formation.

Beauchamp and Henderson (1994) revisited the Raanes and Bjorne peninsulas and measured more than 30 stratigraphic sections and collected 400 conodont samples from this area. Other areas of the Sverdrup Basin were also visited, including northern Axel Heiberg Island, northwestern Devon Island and west-central and northwestern Ellesmere Island. Based on this extensive field work, the previous nomenclature of Schei (1901) and Thorsteinsson (1974) was altered considerably. Beauchamp and Henderson (1994) formally defined, dated, and put into a sequence stratigraphic context three new mappable formations; Great Bear Cape, Raanes and Trappers Cove formations, comprising the majority of the Artinskian to Kungurian Sequence.

## 1.4 Methodology

Extensive field work was completed by the author in the Otto Fiord area of northwestern Ellesmere Island in the summer of 1994, and included the measuring and describing of 15 sections composed mainly of Artinskian strata. These sections in total represent 5100 m of measured strata and are grouped into northern (sections 1 to 7) and southern (sections 8 to 12) shelf-to-basin cross-sections (figure 1). These cross-sections include the upper and lower boundaries of the Artinskian to Kungurian Sequence of Beauchamp and Henderson (1994), and display the shelf-to-basin facies transition within the Artinskian to Kungurian Sequence. From these sections over 700 lithologic hand samples were collected and of these, approximately 400 small thin sections were made and stained with alizarin red and potassium ferricyanide according to Dickson (1966). These thin sections were examined under the petrographic microscope for facies analysis. Thirty-seven conodont samples from key horizons in the Artinskian to Kungurian Sequence were collected from the region for examination and age dating by Dr. Charles Henderson at the University of Calgary.

# CHAPTER 2: STRATIGRAPHY

This chapter is divided into three parts addressing the lithostratigraphy, biostratigraphy and sequence stratigraphy of the Artinskian to Kungurian Sequence exposed in the Otto Fiord area and adjacent areas. In each part, results are compared with other recent studies from the Blind Fiord area (Beauchamp and Henderson, 1994) where type sections for these stratigraphic units are well exposed.

## 2.1 Lithostratigraphy

### *2.1.1 Raanes Formation*

***Blind Fiord Area***

The type section of the Raanes Formation is located on the Raanes Peninsula and the formation is well developed along the southern and eastern margins of the Sverdrup Basin (Beauchamp and Henderson, 1994).

The Raanes Formation in the Blind Fiord area has been divided by Beauchamp and Henderson (1994) into two units having distinct lithotypes. The first of the units is a medium-bedded, recessive, greenish-weathering, shale to siltstone and argillaceous limestone that passes upward into a thickly-bedded, packstone to grainstone containing fossils including dasycladaceans, phylloid and red algae, *Palaeoaplysina*, encrusting foraminifers and fusulinaceans. In some areas this unit is capped by an echinoderm-, bryozoan-, brachiopod-rich wackestone to packstone with argillaceous and silty components (Beauchamp and Henderson, 1994). This unit locally shoals upsection, however, the overall trend is one of deepening. The second unit is similar to the first, but does not contain the varied fossil assemblage that is present in the first unit. Bryozoans, echinoderms and brachiopods are the main biotic components characterizing the second unit. Differences between these units are interpreted to be the result of a growth fault that was active only during the deposition of the second unit, resulting in a thicker succession with deeper- and cooler-water facies (Beauchamp and Henderson, 1994).

In the Blind Fiord area, the Raanes Formation conformably overlies the Nansen Formation. This contact is easily mapped, as resistant thickly-bedded Nansen Formation gives way to recessive, shaly and argillaceous limestone of the Raanes Formation, creating a prominent break in slope. Closer to the basin margin, this contact is a minor unconformity as indicated by evidence of karstification, calichification and erosion in the Belcher Channel Formation, where the Raanes Formation overlies the Nansen-correlative Belcher Channel Formation (Figure 2). Overlying the Raanes Formation are the Trappers Cove or the Great Bear Cape formations. In distal areas, dark, spiculitic chert of the Trappers Cove Formation conformably overlies the shaly carbonate of the Raanes Formation. In proximal sections, the contact between the Raanes and the Great Bear Cape formations is generally conformable and places spiculitic and silica-rich carbonates of the Great Bear Cape Formation over shale-rich, spicule-poor carbonates of the Raanes Formation (Beauchamp and Henderson, 1994).

The Raanes Formation is interpreted to be of Artinskian age based on the presence of the following species of conodonts: *Adetognathus paralautus, Sweetognathus inornatus* and *Neogondolella bisselli* (Beauchamp and Henderson, 1994).

***Otto Fiord Area***

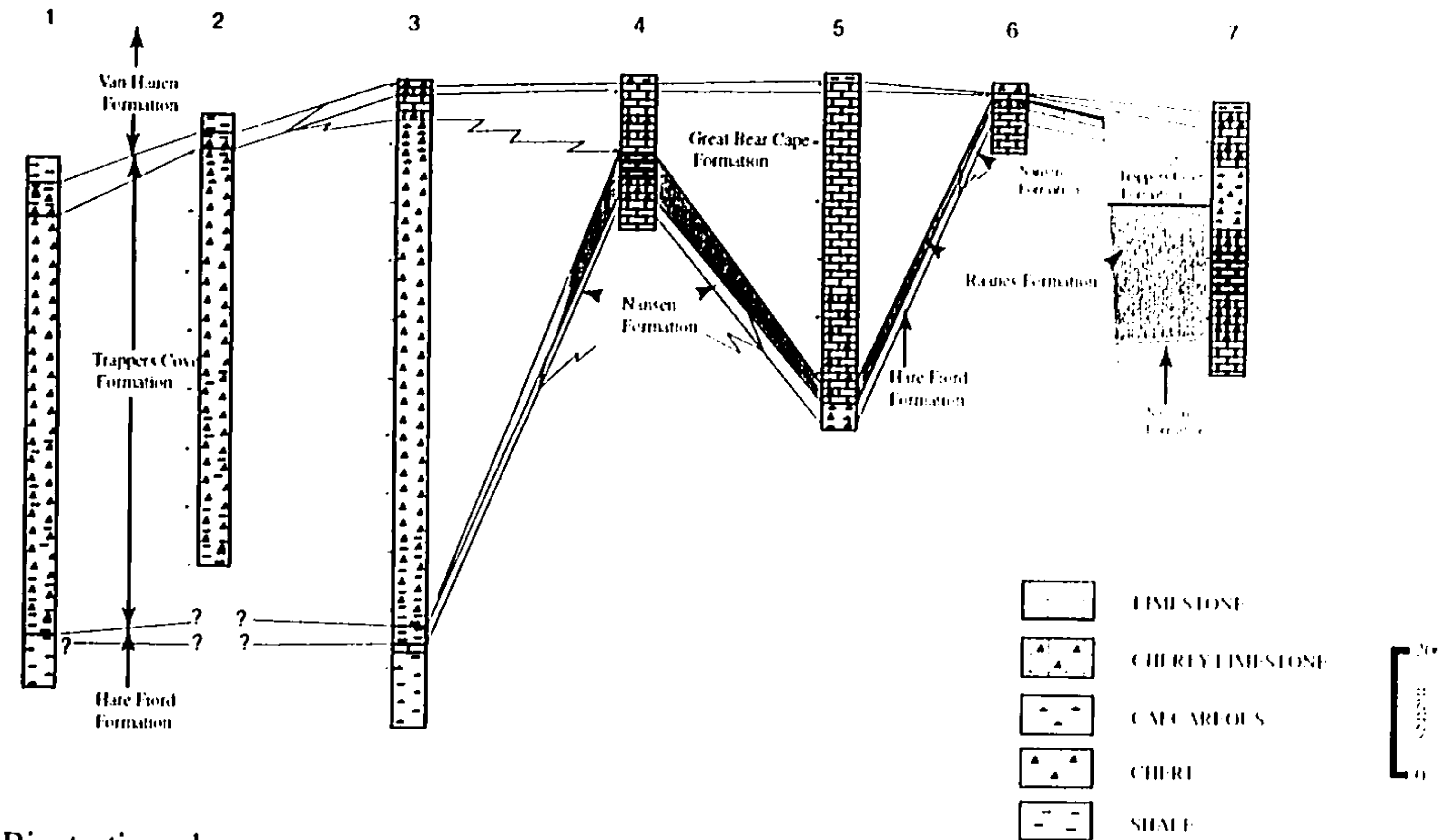
The Raanes Formation is well exposed in the Otto Fiord area of northwestern Ellesmere Island where the formation ranges from 10 m to 225 m thick, suggesting faulting during deposition (Figures 4A and 5A; Appendix 2).

The Raanes Formation of the Otto Fiord area consists of three distinct lithotypes, two of which are similar to the two units described from the Blind Fiord area by Beauchamp and Henderson (1994). The first and most geographically abundant lithotype of the Raanes Formation is a greenish-weathering, dominantly recessive, locally resistant, thinly- to medium-bedded, shaly to silty and variably cherty wackestone to packstone (Plate 1), containing bryozoans, brachiopods, crinoids, and sponge spicules (small and large). This unit is similar to the second unit of Beauchamp and Henderson (1994) and is located in sections 4, 5, 6 and 11 (Figures 4A and 5A; Appendix 2). The second lithotype of the Raanes Formation is very similar to the first with the addition of less abundant, resistant, light-grey weathering, thickly- to very-thickly bedded, very fine grained unit. These units are similar to the first unit described by Beauchamp and Henderson (1994)

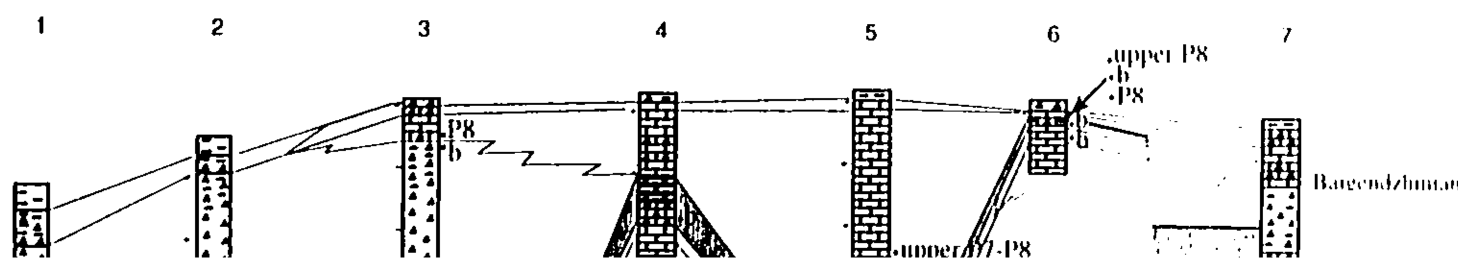
Figure 4 Northern shelf-to-basin cross section: A) relative lithostratigraphic positions of the Great Bear Cape, Raanes, Nansen, Trappers Cove and Hare Fiord formations; B) locations of conodont assemblages (see Tables 2 and 3 for details); C) sequence stratigraphic surfaces and systems tracts (see p. 33-38 for abbreviations). LTST in basin sections (sections 1, 2, 3) is represented by a condensed zone existing just below the MFS. This zone is not indicated on the cross-section. Numbers 1 - 7 on the cross-section represent measured sections across the shelf and basin through the Artinskian to Kungurian Sequence.

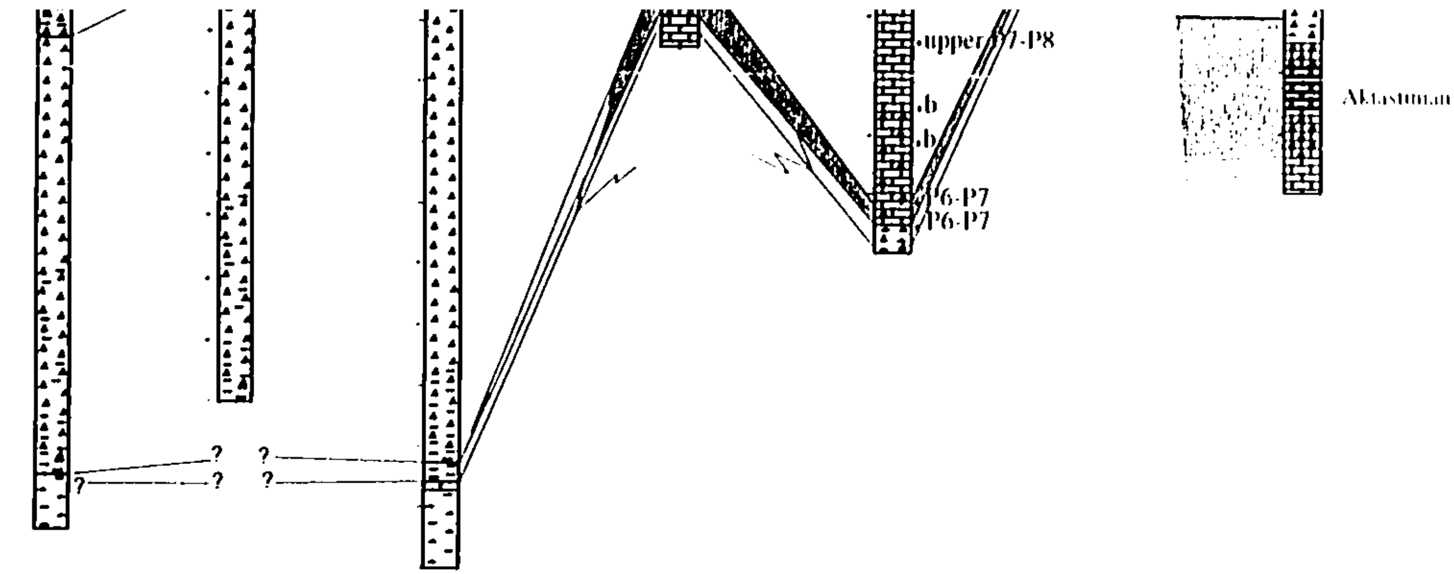
# Northern Cross - Section

## A. Lithostratigraphy




## B. Biostratigraphy






## C. Sequence Stratigraphy

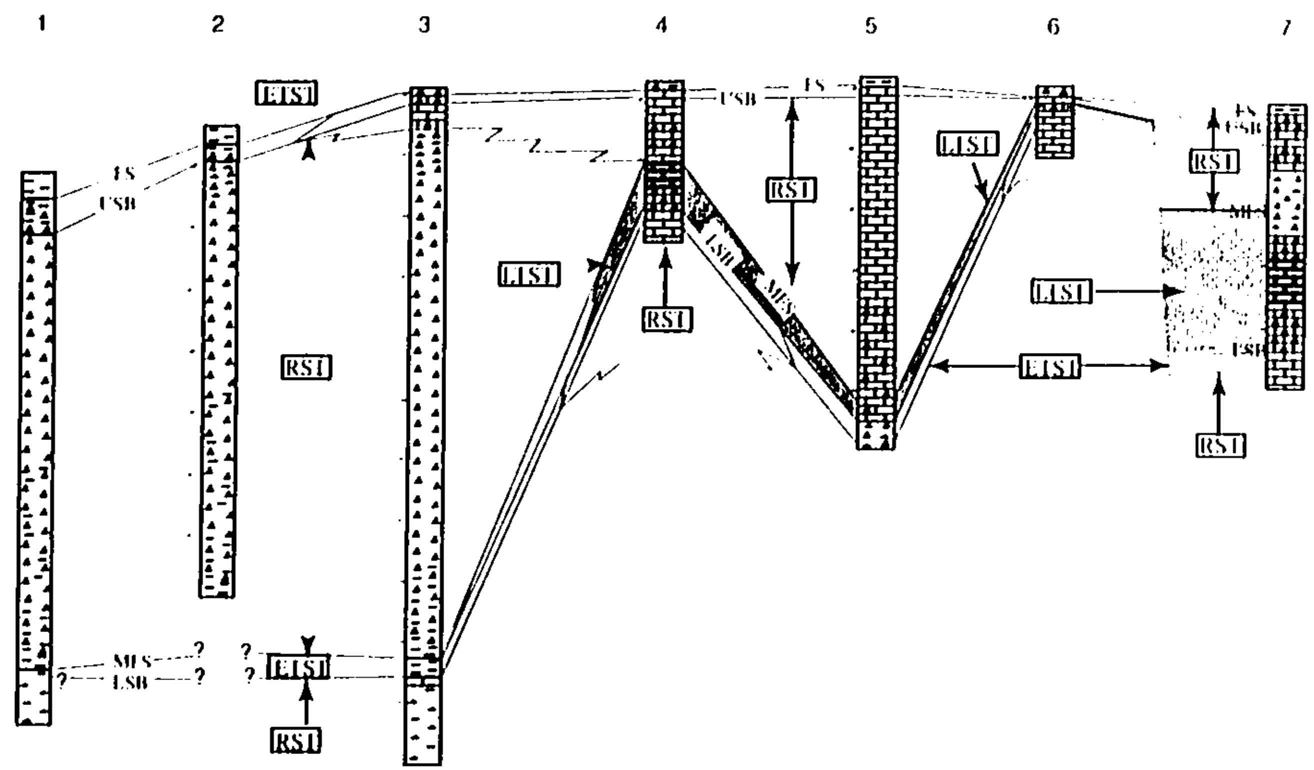
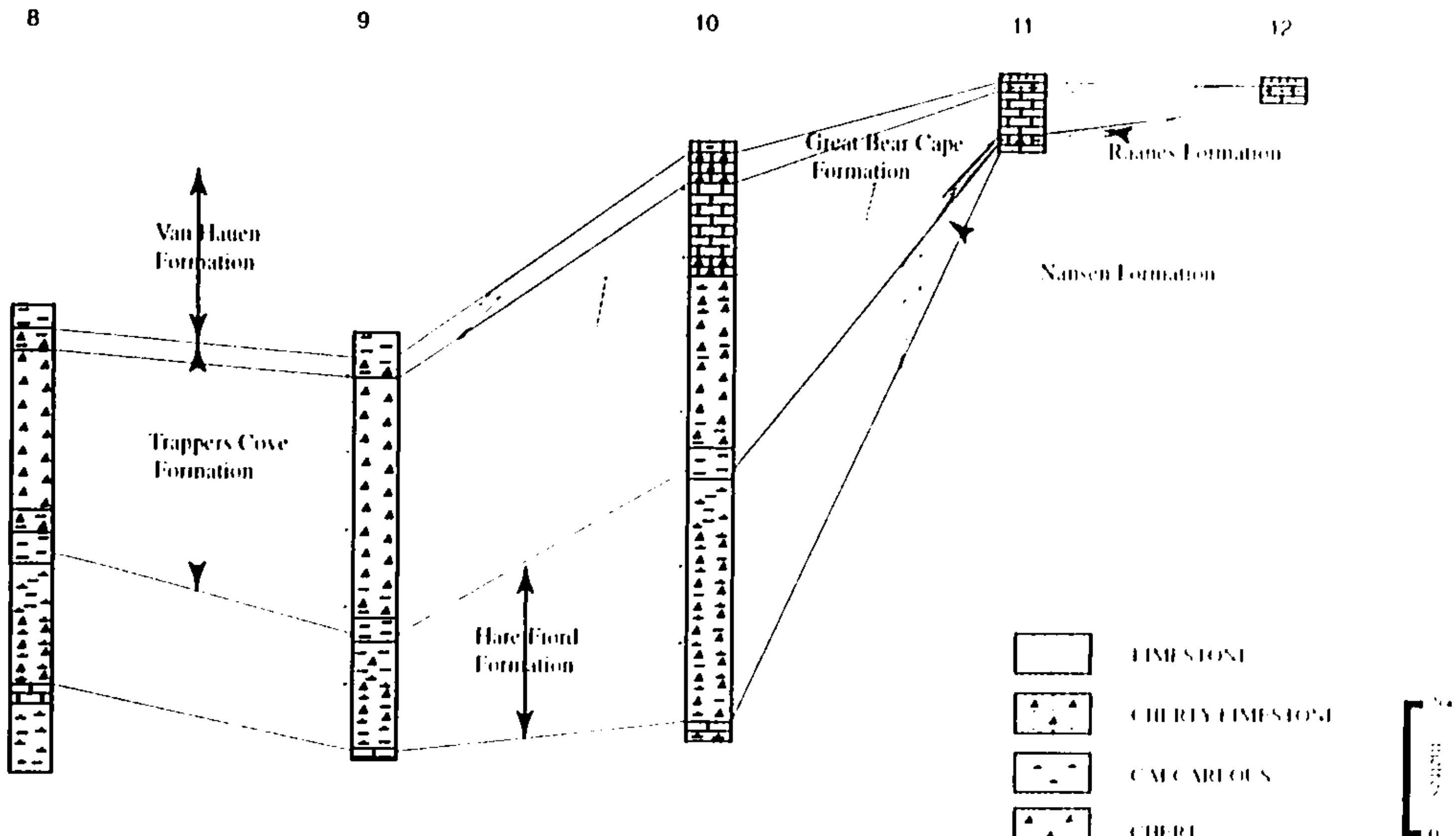


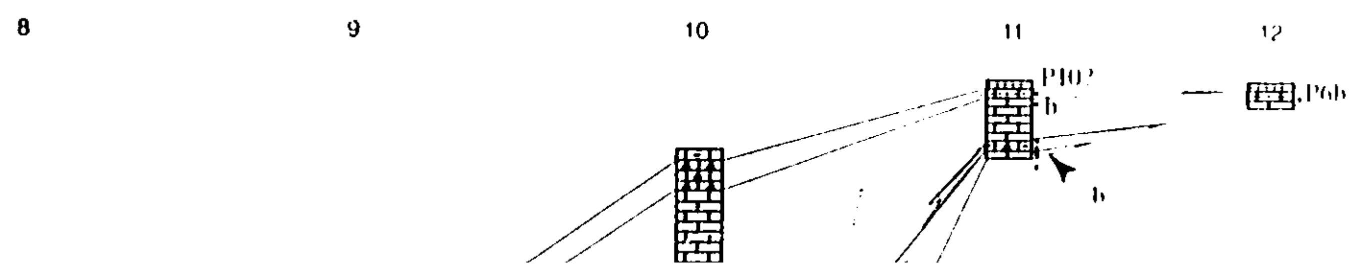
Figure 5 Southern shelf-to-basin cross section showing: A) relative lithostratigraphic positions of the Great Bear Cape, Raanes, Nansen, Trappers Cove and Hare Fiord formations; B) locations of conodont assemblages (see Tables 2 and 3 for details); C) sequence stratigraphic surfaces and systems tracts (see p. 33-38 for abbreviations). LTST in basin sections (sections 8, 9, 10) is represented by a condensed zone existing just below the MFS. This zone is not indicated on the cross-section. Numbers 8 - 12 on the cross-section represent measured sections across the shelf and basin through the Artinskian to Kungurian Sequence.

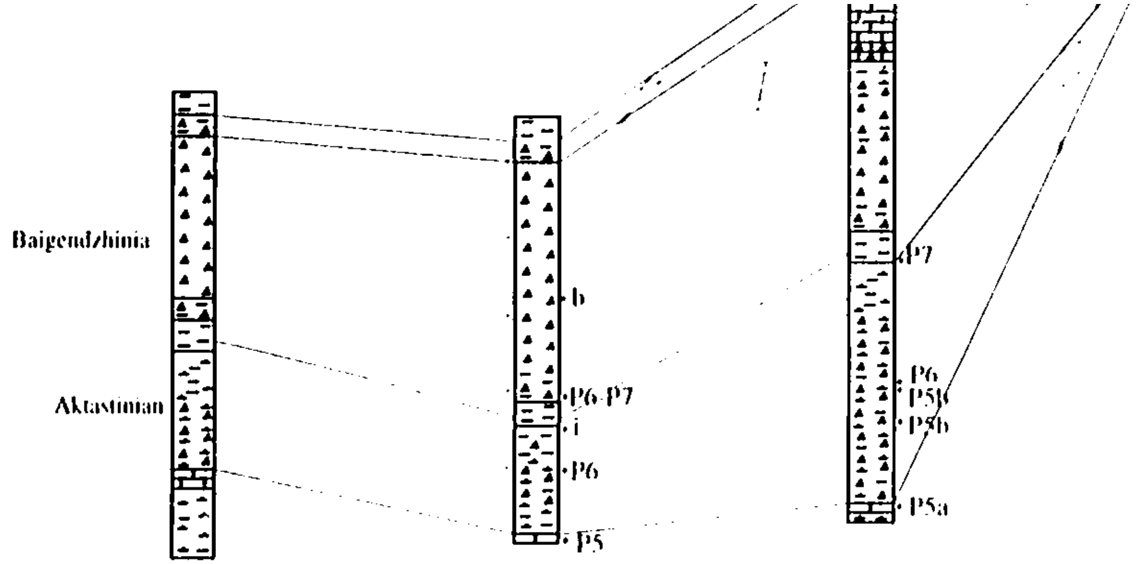
# Southern Cross-Section

## A. Lithostratigraphy

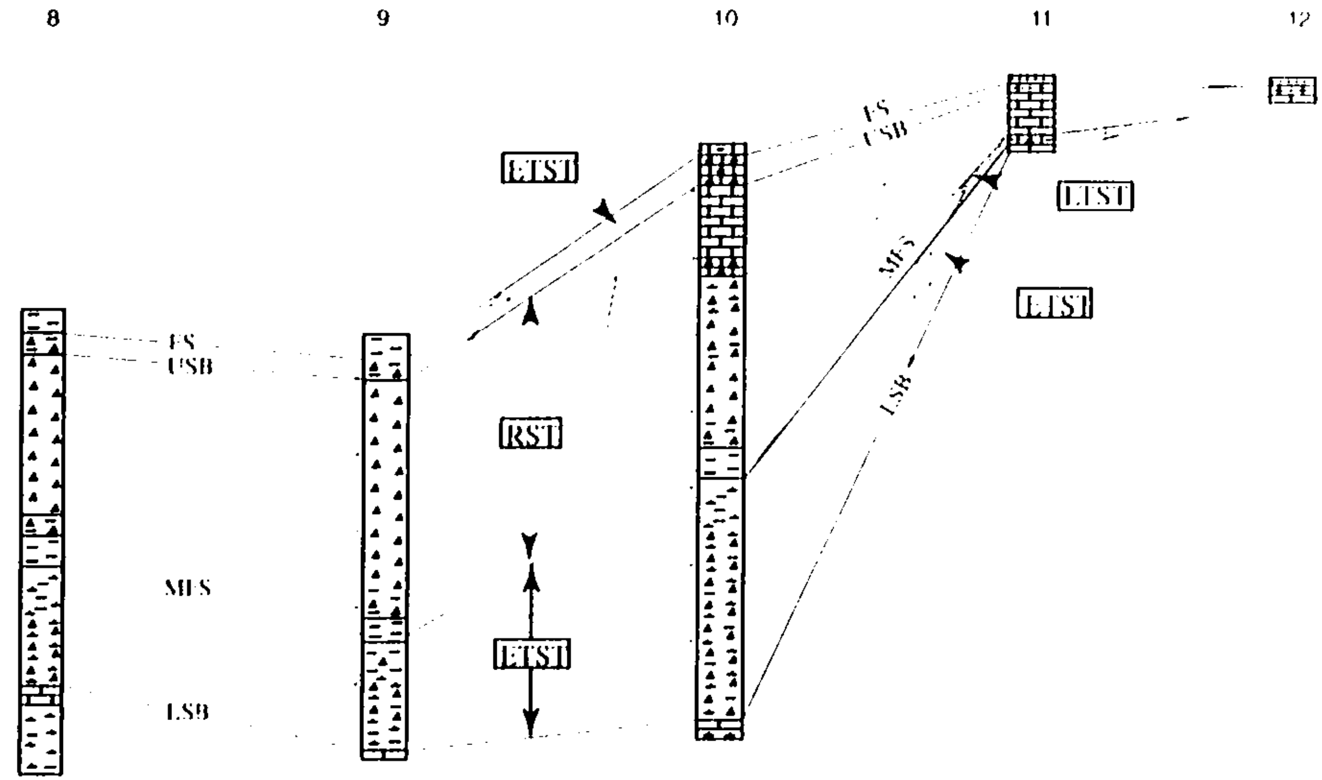



## B. Biostratigraphy






C. Sequence Stratigraphy



containing a diverse fossil assemblage (Section 7; Figures 4A and 5A; Appendix 2). The third unit is light-gray weathering, resistant, massive, very fine-grained bryozoan-lime mud wackestone forming bioherms that may also contain *Tubiphytes* (sections 4 and 7; Appendix 2). These mounds range in height from 10 m to 60 m at section 7. Red weathering colour is often associated with the base of these buildups: the origin of this weathering colour is unknown but the irregular distribution suggests a post-depositional origin.

The Raanes Formation of the Otto Fiord area is lithologically slightly different than the Raanes Formation in the type area. The formation in the study area contains a reduced siliciclastic component, being only slightly argillaceous to silty compared to the formation of southern Ellesmere Island. This difference reflects the close proximity of a siliciclastic source on southern Ellesmere Island whereas no proximal source was probable or close at the time of deposition of the Raanes Formation now outcropping on northwestern Ellesmere Island.

In the Otto Fiord area the Raanes Formation conformably overlies the light-grey, thickly bedded, resistant Nansen Formation. This lower contact is easily mapped as it is similar in character to that in the type area, and is marked by an abrupt change in lithologic character. Light-grey, thickly-bedded, resistant unit of the Nansen Formation is succeeded by a more recessive, greenish weathering, thinly- to medium-bedded, silty limestone of the Raanes Formation at a break in slope.

Proximal to the basin margin, the Raanes Formation is conformably overlain by the Great Bear Cape Formation. This contact is gradational and occurs where the greenish-weathering, shaly-silty wackestone to packstone of the Raanes Formation is succeeded by a yellowish-weathering, variably cherty, resistant, crinoid-bryozoan packstone to grainstone of the Great Bear Cape Formation. However, two anomalies regarding this transition exist in the Otto Fiord area. For example, at location 7 (Figure 4A; Appendix 2) the Trappers Cove Formation separates the Raanes and Great Bear Cape Formations. The contact between the Raanes and the Trappers Cove Formation is conformable and sharp with recessive, shaly-silty limestone of the Raanes Formation succeeded by dark, resistant spiculitic chert of the Trappers Cove Formation. This transition has only been documented at this location in the Otto Fiord area. The second anomaly involves an unconformable contact between the Raanes and the Great Bear Cape formations at location 6 (Figure 4A;

Appendix 2). Evidence suggesting an unconformity includes the presence of an erosional surface truncating bedding, in addition to hematite staining, pyrite, and rip-up clasts incorporated in the basal Great Bear Cape Formation. At this location the Raanes Formation is argillaceous, medium bedded, cherty, and contains *Zoophycos* and brachiopods. This is unconformably overlain by pink-weathering, finely- to medium-bedded, coarse-grained crinoidal grainstone with pyrite and rip-up clasts up to 1.5 cm.

The age of the Raanes Formation in the Otto Fiord area is loosely constrained as early to mid-Artinskian (Irginian to lower Sarginian substages) based on the presence of the following conodonts: *Neogondolella bisselli* and *Hindeodus* (C. Henderson, pers. comm.; Beauchamp et al., 1989a).

### *2.1.2 Great Bear Cape Formation*

#### *Blind Fiord Area*

The type section of the Great Bear Cape Formation is located on the Raanes Peninsula, seven kilometres northeast of the head of Blind Fiord, southwestern Ellesmere Island. This formation was defined by Beauchamp and Henderson (1994) as a resistant, cliff-forming, yellowish-weathering unit that is variably cherty, locally sandy and highly fossiliferous. Beauchamp and Henderson (1994) subdivided the Great Bear Cape Formation into three units based on lithologic character and position within the sequence: a lower, middle and upper unit. The lowest unit consists of large carbonate bryozoan-sponge mudmounds. These bioherms are 50 to 100 m thick and occur locally at the base of the Great Bear Cape Formation (Beauchamp and Henderson, 1994). The middle unit is a yellowish-weathering, thick succession of medium-bedded, silty and cherty, spiculitic wackestone to packstone also beginning at the base of the Great Bear Cape Formation and grading upward into medium- to thickly-bedded, locally cherty, highly fossiliferous packstone with abundant echinoderms, bryozoans, brachiopods and sponge spicules. The top of this succession is dominantly a medium- to very thickly-bedded, locally cross-stratified, calcareous grainstone with abundant bryozoans, echinoderms, brachiopods, common to scarce nodosariid foraminifers and scarce fusulinaceans (Beauchamp and Henderson, 1994). The third unit occurs at the top of the Great Bear Cape Formation and is represented by a few meters of red-weathering, silty wackestones and floatstones with large ramose bryozoans. However, this unit also occurs as yellowish-weathering, cherty limestone and calcareous chert. The Great Bear Cape Formation becomes locally very sandy near the margins of the basin (Beauchamp and Henderson, 1994).

The Great Bear Cape Formation is underlain by the Raanes or Trappers Cove formations and is overlain by the Van Hauen, Trold Fiord, Assistance, Sabine Bay or Esayoo formations (Figure 2). The lower contact of the Great Bear Cape with the Raanes Formation is sharp and usually conformable, but locally non-conformable where erosion preceded deposition of the Great Bear Cape Formation. The conformable contact between the Great Bear Cape Formation and the underlying Trappers Cove Formation is gradational, as dark, cherty beds of the Trappers Cove Formation are interbedded with light-coloured carbonate beds of the Great Bear Cape Formation. The lateral relationship between the Great Bear Cape Formation and the Trappers Cove Formation is also gradational (Beauchamp and Henderson, 1994). The top of the Great Bear Cape Formation, in the type area, is a widespread unconformity which becomes conformable in distal sections (Beauchamp and Henderson, 1994).

The Great Bear Cape Formation in the type area has yielded fourteen species of conodonts, including *Adentognathus paralautus, Sweetognathus inornatus, Sweetognathus whitei, Sweetognathus adjunctus, Sweetognathus bogoslovskajae, Neostreptognathodus clarki, Neostreptognathodus pequopensis, Neostreptognathodus ruzhencevi, Neostreptognathodus prayi, Neogondolella bisselli, Neogondolella gujioensis, and Neogondolella intermedia* indicating an Artinskian age (Beauchamp and Henderson,1994).

***Otto Fiord Area***

Spectacular exposures of the Great Bear Cape Formation are present in the Otto Fiord area and adjacent areas of northwestern Ellesmere Island. In this region, the Great Bear Cape Formation generally ranges from a few meters thick (section 12) at the basin margin to more than 300 m in mid-shelf (section 5; Figures 4A and 5A; Appendix 2), the latter being related to the infilling of an embayment (see below). This formation is identical to that described by Beauchamp and Henderson (1994) in the Blind Fiord area of southwestern Ellesmere Island in that it is a yellowish-weathering, cliff-forming, medium- to very-thickly bedded, packstone to grainstone (Plate 1), with abundant echinoderms, bryozoans, brachiopods, sponges and various amounts of chert. Disseminated chert is abundant in the lower part of the formation but less so in the upper part, where it is commonly in nodular form, and eventually disappears toward the top. The middle and upper units of the Great Bear Cape Formation described by Beauchamp and Henderson (1994) in the Blind Fiord area are recognized in the Otto Fiord area. The lowest unit recognized in the Great Bear Cape Formation of the Blind Fiord area, was not recognized in the Otto Fiord area. Instead the upper portion of the Raanes Formation in the Otto Fiord area is coeval with the lowest unit of the Great Bear Cape Formation of the Blind Fiord region (discussed further in the Sequence Stratigraphy section of Chapter 2). However, the basal part of the Great Bear Cape Formation described in the Otto Fiord Area is similar to the middle unit of the Great Bear Cape Formation in the Blind Fiord area discussed above. The top of the Great Bear Cape Formation, where present, is very similar to the upper unit of Beauchamp and Henderson (1994) in that it is a yellowish-weathering, slightly recessive, medium- to thinly-bedded, cherty wackestone to packstone and calcareous chert. This part of the Great Bear Cape Formation, however, represents the transgressive systems tract of the overlying sequence and will be discussed in greater detail later in the chapter.

In the Otto Fiord area, the Great Bear Cape Formation is underlain by Raanes or Trappers Cove formations and, in both cases, the contact is conformable and gradational. The contact between the Raanes Formation and the Great Bear Cape Formation occurs where greenish-weathering, shaly-silty wackestone to packstone of the Raanes Formation is overlain by a yellowish-weathering, variably cherty, resistant, crinoid-bryozoan packstone to grainstone of the Great Bear Cape Formation. However, this contact is unconformable at location 6 (Figure 4A; Appendix 2) and is evident from hematite staining, and the presence of pyrite and rip-up clasts (up to 1.5 cm) within the basal unit of the Great Bear Cape Formation.

The contact between the Great Bear Cape and Trappers Cove formations is gradational and conformable at all locations as black, spiculitic chert of the Trappers Cove Formation eventually becomes fossiliferous near the top of the formation (Figures 4A and 5A). The Trappers Cove Formation becomes the Great Bear Cape Formation where carbonate becomes the predominant lithology. The same lithological change occurs in the lateral transition from the Great Bear Cape Formation to the Trappers Cove Formation. Glauconitic fine-grained sandstone of the Assistance Formation unconformably overlies the Great Bear Cape Formation in sections proximal to the basin margin in the Otto Fiord area (locations 11 and 12; Figures 4A and 5A; Appendix 2). In more distal sections (Sections 3, 4, 5, 6, 7, 10) the Great Bear Cape Formation is conformably overlain by the black spiculitic chert of the Van Hauen Formation.

The Great Bear Cape Formation in the study area yielded the conodonts *Adetognathus paralautus, Hindeodus*, various neogondolellids including *Neogondolella bisselli, Neostreptognathodus clarki*??, *N. prayi, Sweetognathus inornatus, S. whitei*? indicating an early Artinskian (Irginian substage) to late Kungurian age (C. Henderson, pers. comm; Beauchamp et al., 1989a).

### *2.1.3 Trappers Cove Formation*

#### *Blind Fiord Area*

The type section of the Trappers Cove Formation is located on the Raanes Peninsula, southwestern Ellesmere Island, approximately 1.5 km west of the head of Blind Fiord (Beauchamp and Henderson, 1994). This formation is predominantly composed of chert, however, carbonate or shale accompany the chert, depending on proximity to the basin margin or centre, respectively. The shale:chert ratio increases basinward while the carbonate:chert ratio increases toward the basin margin (Beauchamp and Henderson, 1994).

Beauchamp and Henderson (1994) recognized two units in the Trappers Cove Formation on the Raanes Peninsula: a) a lower unit and b) an upper unit. The lower unit, is a succession of spiculitic chert rhythmically interbedded with shale-siltstone and interfingering with minor lenses of limestone. The shale:chert ratio decreases upward in this succession. The dark-brown, dark-grey or black chert is thinly- to thickly-bedded and interbedded with thin layers of black siliceous shale and siltstone. Bioturbation, dark organic matter, dolomite rhombs and silt-sized quartz grains are also present (Beauchamp and Henderson, 1994). Carbonate lenses make up part of the lower unit. These lenses are yellowish-weathering, medium- to very thickly-bedded, fine- to very coarse-grained, graded, locally dolomitic and variably cherty, fossiliferous limestone (Beauchamp and Henderson, 1994). The biotic elements of these carbonates include echinoderms, bryozoans, brachiopods and sponge spicules. The lenses pinch out laterally and range in thickness from 10 cm to more than 3 m. Some larger lenses comprise stacked smaller lenses (Beauchamp and Henderson, 1994).

The upper unit of the Trappers Cove Formation is spiculitic chert interbedded with shale and siltstone. The shale:chert ratio increases upward within this unit and carbonate lenses occur rarely (Beauchamp and Henderson, 1994).

The Trappers Cove Formation conformably overlies the Nansen, Raanes or Hare Fiord formations and is overlain by the Van Hauen Formation or the Great Bear Cape Formation (Beauchamp and Henderson, 1994). The contact between the Raanes and Trappers Cove Formation is sharp and conformable where black chert overlies the greenish silty limestone of the Raanes Formation. In distal sections the base of the Trappers Cove is a highly condensed section that is correlative with the Raanes Formation and conformably overlies the Hare Fiord Formation (Beauchamp and Henderson, 1994). In sections proximal to the basin margin, the upper contact of the Trappers Cove Formation with the Great Bear Cape is conformable and gradational where dark cherty beds of the Trappers Cove Formation are interbedded with light-coloured carbonate of the Great Bear Cape Formation. In distal sections the resistant black chert of the Trappers Cove Formation is conformably overlain by the recessive, black shales of the Van Hauen Formation.

The age of the Trappers Cove Formation is based on stratigraphic correlation as well as conodonts found within this formation. The Trappers Cove Formation is correlative with the Great Bear Cape Formation and is therefore Early Permian in age. The following conodonts yielded by the Trappers Cove Formation indicate an Artinskian age for the formation: *Sweetognathus whitei, S. bogoslovskajae, Neostreptognathodus pequopensis, N. ruzhencevi, Neogondolella gujioensis,* and *N. intermedia* (Beauchamp and Henderson, 1994). The Trappers Cove Formation has also yielded the ammonoid *Paragastrioceras* which also indicates an Artinskian age (Nassichuk et al., 1965).

*Otto Fiord Area*

The Trappers Cove Formation is well exposed in the Otto Fiord area and ranges from a few metres thick at section 7 (Appendix 2) in the east of the study area to almost 1000 m thick at Degerbols Island (section 3; Plate 2; Figures 4A and 5A; Appendix 2).

The Trappers Cove Formation in the Otto Fiord area is very similar to the Trappers Cove Formation described by Beauchamp and Henderson (1994) in the Blind Fiord area. The formation is predominantly composed of medium- to thickly-bedded, black to dark gray, spiculitic chert that is interbedded with thinly-bedded, black recessive shales and siltstones. As in the Blind Fiord area the shale:chert ratio decreases up-section and closer to the margin of the basin. The chert becomes more pure and gravity-driven deposits of carbonate appear and become more frequent upsection. The fossil content of the chert also increases with the introduction of brachiopods followed by bryozoans. The lenses of carbonate range from 1 cm to 2 m in thickness by 3 to 4 m wide. Near the base of the Trappers Cove Formation and near the top of the formation where transgressive units are present, the shale:chert ratio increases and carbonate lenses become less common and disappear.

In the Otto Fiord area the Trappers Cove Formation conformably overlies the Raanes, Nansen, and Hare Fiord formations (Figure 2). The Trappers Cove Formation is overlain in proximal to basin margin sections by the Great Bear Cape Formation and in distal areas by the Van Hauen Formation.

In the Otto Fiord area, the age of the Trappers Cove Formation is based on stratigraphic correlation as well as the conodont fauna. The Trappers Cove Formation is correlative with the Great Bear Cape Formation and is therefore early Artinskian (Irginian substage) to Kungurian in age. Two conodonts yielded by the Trappers Cove Formation indicate an Artinskian age for the formation in the study area: *i) Neogondolella*, represents a deeper water biofacies, as the characteristic *Sweetognathus* was not present, and ii*)* *Diplognathodus stevens*, typically associated with *S. inornatus* in mid-west USA, represents the first occurrence of this species in arctic North America (C. Henderson, pers. comm.; Beauchamp et al., 1989a).

## 2.2 Conodont Biostratigraphy

The biostratigraphy used in this study is based on the conodont zonation that was formally defined and documented for the Canadian Arctic by Beauchamp and Henderson (1994) using conodonts from type sections of the Great Bear Cape, Raanes and Trappers Cove formations in the Blind Fiord area. Conodonts in the present study area were identified by Dr. Charles Henderson at the University of Calgary. The definitions and detailed descriptions of conodont assemblages can be found in Beauchamp and Henderson (1994; see Table 1).

*Conodont Data - Blind Fiord*

In the Blind Fiord area several assemblages have been identified within the Great Bear Cape, Raanes and Trappers Cove formations and are summarized in Table 2 (Beauchamp et al., 1989a; Beauchamp and Henderson, 1994).

*Conodont Data- Otto Fiord Area*

In the Otto Fiord area the conodont assemblages P5, P6a, P6b, P7, P8, and P10 have been identified within the strata encompassing the Nansen, Hare Fiord, Great Bear Cape, Raanes and Trappers Cove formations (Figures 4B and 5B; Appendix 4). Corresponding ages are assigned to the assemblages and presented in Table 3.

In the study area, two conodont species previously unrecognized in arctic North America are reported for the first time: *S. sulcatus* (zone P5b) and *Diplognathodus stevens* (zone P6; C. Henderson, pers.comm.).

*Comparison of Blind Fiord Area with Otto Fiord Area*

The conodont assemblages established first in the Blind Fiord area for the Raanes, Great Bear Cape and Trappers Cove formations are quite similar to those of the Otto Fiord area. The conodont assemblages that are present in both areas, occur at comparable stratigraphic levels within the various formations. The assemblages P6b, P7, P8, and P10 are consistently in the lower, mid-, upper and uppermost Great Bear Cape Formation, respectively, in both areas.

Table 1 Age ranges for conodont assemblages - Sverdrup Basin (from Beauchamp et al., 1989a).

| AGE[3] (Ma) | NORTH AMERICAN REFERENCE SECTIONS | | COMPOSITE U.S.S.R./U.S.A./CHINA REFERENCE SECTIONS | | | | CONODONT ASSEMBLAGES OF SVERDRUP BASIN | | SAMPLED STRATIGRAPHIC UNITS |
|---|---|---|---|---|---|---|---|---|---|
| 245 | UPPER PERMIAN | OCHOAN | UPPER PERMIAN | CHANGHSINGIAN | | | barren | UNFOSSILIFEROUS PERMIAN | DEGERBOLS TROLD FIORD |
| | | | | DZHULFIAN | | | | | |
| | | | | CAPITANIAN | | | | | |
| 253 | | GUADALUPIAN | | WORDIAN | | | P14 | *Neogondolella rosenkrantzi*-*N. bitteri* | |
| | | | | | | | P13 | *Neogondolella phosphoriensis*-*N.* sp. A | DEGERBOLS, "UNIT-A", TROLD FIORD |
| | LOWER PERMIAN | LEONARDIAN | LOWER PERMIAN | ROADIAN | | | P12 | *Neogondolella* sp | ASSISTANCE |
| 258 | | | | | | | P11 | *Neogondolella idahoensis* | |
| | | | | KUNGURIAN | | | P10 | *Neogondolella idahoensis*-*Neostreptognathodus prayi* | SABINE BAY(?) |
| 263 | | | | ARTINSKIAN | BAIGENDZHINIAN | SARANINIAN | P9 | *Neostreptognathodus prayi*-*N. ruzhencevi* | UNNAMED-A UNNAMED-B |
| | | | | | | SARGINIAN | P8 | *Neostreptognathodus pequopensis*-*N. clarki* | |
| | | | | | | | P7 | *Neogondolella bisselli*-*Sweetognathus whitei* | |
| | | | | | AKTASTINIAN | IRGINIAN | P6b | *Sweetognathus inornatus*-*A. paralautus* | |
| 268 | | | | | | BURTSEVIAN | P6a | *Neogondolella bisselli*-*Adetognathus paralautus* | |
| | | WOLFCAMPIAN | | SAKMARIAN | STERLITAMAKIAN | | P5 | *Streptognathodus elongatus* | NANSEN BELCHER CHANNEL CANYON FIORD HARE FIORD |
| | | | | | TASTUBIAN | | P4 | *Adetognathodus* n sp C | |
| | | | | ASSELIAN | KURMAIKIAN | | P3 | *Streptognathodus barskovi*-*S. constrictus* | |
| | | | | | USKALIKIAN | | | | |
| | | | | | SURENIAN | | P2 | *Idiognathodus ellisoni*-*Streptognathodus nodulinearis* | |
| | | | ? | | | ORENBURGIAN | P1 | *Adetognathus lautus* | |
| 286 | PENNSYLVANIAN | VIRGILIAN | UPPER CARBONIFEROUS | GZHELIAN | | | C6b | *Streptognathodus elegantulus*-*Idiognathodus delicatus* | |
| 296 | | MISSOURIAN | | KASIMOVIAN | | | C6a | *Streptognathodus simulator*-*S. oppletus* | |
| | | DESMOINESIAN | | MOSCOVIAN | | | C5b | *Neognathodus medadultimus* | |
| | | ATOKAN | | | | | C5a | *Idiognathoides marginodosus* | |
| | | | | | | | C4 | *Diplognathodus* spp. | |
| | | MORROWAN | | BASHKIRIAN | | | C3 | *Idiognathodus sinuatus* [1,2] | |
| 320 | | | | | | | C2 | *Declinognathodus noduliferus* [1,2] | NANSEN |
| 333 | MISS. (part) | CHESTERIAN | L. CARBON. (part) | SERPUKHOVIAN | | | C1 | *Adetognathus lautus*- [1] *Paragnathodus commutatus* [2] | NANSEN/EMMA FIORD(?) |
| 352 | | VALMEYERAN (part) | | VISÉAN | | | barren | NOT ZONED | EMMA FIORD |

Table 2 Conodont assemblages - Blind Fiord area: assemblages from the Great Bear Cape, Raanes and Trappers Cove formations (after Beauchamp and Henderson, 1994).

| Assemblage | Assemblage Name | Location of Assemblage | Age Assignment |
|---|---|---|---|
| P10 | *Neogondolella idahoensis - Neostreptognathodus prayi* | uppermost Great Bear Cape Formation | upper Kungurian |
| P9 | *Neostreptognathodus prayi - N. ruzhencevi* | uppermost Great Bear Cape and mid-upper Trappers Cove Formation | upper Baigendzhinian to Kungurian |
| P8 | *Neostreptognathodus pequopensis - N. clarki* | upper Great Bear Cape and mid-Trappers Cove formation | lower Baigendzhinian |
| P7 | *Neogondolella bisselli-Sweetognathus whitei* | mid-Great Bear Cape Formation and carbonate tongue of Trappers Cove Formation | lower Baigendzhinian |
| P6b | *Sweetognathus inornatus - Adetognathus paralautus* | upper Raanes and lower Great Bear Cape formations | upper Aktastinian |
| P6a | *Neogondolella bisselli - Adetognathus paralautus* | lower to mid-Raanes Formation | lower Aktastinian |

Table 3 Conodont assemblages - Otto Fiord area: assemblages from the Great Bear Cape, Raanes, Hare Fiord and Trappers Cove formations (Appendix 4).

| Assemblage | Assemblage Name | Location of Assemblage | Age Assignment |
|---|---|---|---|
| P10 | *Neogondolella idahoensis - Neostreptognathodus prayi* | uppermost Great Bear Cape Formation | upper Kungurian |
| P8 | *Neostreptognathodus pequopensis - N. clarki* | upper Great Bear Cape Formation | lower Baigendzhinian |
| P7-P8* | various *Neogondollelids - N. clarki?* | mid-Great Bear Cape Formation | lower Baigendzhinian |
| P7 | *Neogondolella bisselli- Sweetognathus whitei* | mid-Great Bear Cape Formation lower Trappers Cove | lower Baigendzhinian |
| P6 -P7* | *Neogondolella bisselli- Hindeodus minutus* | upper Hare Fiord and mid-Raanes formations (lower Trappers Cove) | upper Aktastinian to lower Baigendzhinian |
| P6b | *Sweetognathus inornatus - Adetognathus paralautus* | lower Great Bear Cape Formation | upper Aktastinian |
| P6a | *Neogondolella bisselli - Adetognathus paralautus* | upper Hare Fiord Formation | lower Aktastinian |
| P5 | *Streptognathodus Elongatus* | mid- to upper Hare Fiord Formation | Sterlitamakian |

* Not a recognized assemblage but a combination of two. In this case the 'Assemblage Name' section of the table will indicate only the range of conodonts present.

## 2.3 Sequence Stratigraphy

The Artinskian to Kungurian Sequence of the Otto Fiord area, best resembles and therefore has been defined using the Transgressive-Regressive (T-R) sequence stratigraphic model by Embry (1993). This sequence stratigraphic model consists of five main components, which are as follows (Plate 3): lower sequence boundary (LSB), transgressive systems tract (TST), maximum flooding surface (MFS), regressive systems tract (RST), and upper sequence boundary (USB). In contrast to the depositional sequence stratigraphic model (Posamentier et al., 1988; Van Wagoner et al., 1990) which uses subaerial unconformities and their correlative conformities as the sequence boundaries, the T-R Model uses transgressive surfaces as sequence boundaries (that may or may not coincide with subaerial unconformities). This type of boundary is preferred as it has lithologic character and therefore can be objectively determined, whereas, sequence boundaries for the Depositional Model (Posamentier et al., 1988) cannot be objectively determined as they do not always have distinct lithologic character (Embry, 1993).

The upper Paleozoic succession of the Sverdrup Basin is characterized by eight, long-term, transgressive-regressive sequences bounded at the basin margin by major unconformities that pass basinward into their equivalent conformities (Figure 2; Beauchamp et al., 1989b; Beauchamp and Henderson, 1994). This study focuses exclusively on the Artinskian to Kungurian Sequence in the Otto Fiord area. This sequence, that was described earlier on southern Ellesmere Island (Beauchamp et al., 1989b; Beauchamp and Henderson, 1994), represents a 5 to 10 million year duration, spanning the latest Sakmarian and Kungurian. The Artinskian to Kungurian Sequence is represented by the following formations: the uppermost Nansen and Hare Fiord formations; the entire Raanes and most of the Great Bear Cape and Trappers Cove formations (Beauchamp and Henderson,1994).

In the Otto Fiord area, major sequence stratigraphic surfaces, such as the upper and lower sequence boundaries and the maximum flooding surface, are easily recognizable (Figures 4C and 5C; Plates 3, 4). Unconformities are present and represent the upper and lower sequence boundaries of the Artinskian to Kungurian Sequence in sections proximal to the basin margin (sections 4, 6, 11, 12; Appendix 2) while the more basinal equivalent strata are bounded by conformable contacts (Sections 1, 2, 3, 5, 8, 9, 10; Appendix 2). The internal transgressive and regressive packages that have been identified by Beauchamp et al. (1989a) on southern Ellesmere Island, are also recognized in the Otto Fiord area. The transgressive phase of the sequence in the Otto Fiord area is represented by greenish weathering, deepening-upward shales and mixed siliciclastic-carbonate facies of the Raanes Formation in sections proximal to the basin margin (Plate 3) and by the Hare Fiord Formation in more basinal sections (Plate 4). The regressive phase of the sequence is represented by the fossiliferous limestone of the Great Bear Cape Formation in sections proximal to the basin margin (Plate 3) and by correlative black chert and shale of the Trappers Cove Formation in the more basinal sections (Plate 4; Beauchamp et al., 1989b; Scott et al., 1991; Beauchamp and Harrison, 1994).

The following sections discuss in detail the criteria and characteristics of the lower sequence boundary, upper sequence boundary, maximum flooding surface, transgressive systems tract and regressive systems tract of the Artinskian to Kungurian Sequence of the Otto Fiord area.

### *2.3.1 Lower Sequence Boundary (LSB)*

Close to the margin of the Sverdrup Basin and at locations of paleohighs, the LSB is a subaerial unconformity within the uppermost Nansen Formation (locations 4, 6, 11, 12; Appendix 2; Plates 3, 4), except at location 12 where the sequence boundary coincides with the lithostratigraphic contact between the Great Bear Cape and Nansen formations. The unconformity separates shallow water grainstones of the Nansen Formation below from slightly recessive, muddier packstones of the Nansen Formation above (Figures 4C and 5C). Field evidence for subaerial exposure at these sections includes: sharp erosional surfaces that truncate beds, predominantly thin zones of terra rosa material at the unconformity and terra rosa material incorporated of into the basal part of the overlying strata (Plate 4). The magnitude of the unconformity at the LSB is not known as samples collected for age dating were barren of conodonts. The unconformity representing the LSB at the basin margin and at paleohighs changes to a correlative conformity toward the basin centre (locations 1, 2, 3, 5, 8, 9, 10; Appendix 2). This sequence boundary occurs in the basin within the uppermost Hare Fiord Formation at the top of a shallowing upward succession. This succession is often capped by a very thickly-bedded debris flow (Plate 4).

The shallowest water facies in the basin is represented by medium-bedded, calcareous mudrock to slightly fossiliferous, thickly-bedded wackestone lying directly below the debris flow. The thick debris flow is overlain by a deepening-upward succession of mudstone and shale representing the basal part of the transgressive systems tract of the Artinskian Sequence.

### *2.3.2 Upper Sequence Boundary (USB)*

The upper sequence boundary (USB) is manifested in two ways: i) as a subaerial unconformity on the shelf in a proximal position, and ii) as a conformable surface on the outer shelf and in a distal position. In proximity to the shelf margin, the USB is a regional subaerial unconformity occurring within the uppermost Great Bear Cape Formation in the easternmost part of the study area (locations 4, 6, 11, 12; Appendix 2). Evidence for subaerial exposure includes: i) erosional nature of the contact at locations 11 and 12, ii) incorporation of soil derived materials into the rocks lying above and below the unconformable surface (locations 4, 6, 11, 12), and iii) the presence of terra rosa clay at location 12.

Below the subaerial unconformity, at locations 11 and 12, is a shallowing-upward succession of carbonates that is capped by coarse-grained, crinoidal limestone of the Great Bear Cape Formation. Above this surface a deepening-upward succession (i.e. transgressive systems tract of the overlying sequence) of finer grained, crinoidal packstone to wackestone of the Great Bear Cape Formation succeeds the grainstones.

In the outer shelf section, within the Great Bear Cape Formation, the USB becomes a conformable surface basinward, as evidence for subaerial exposure disappears (locations 3, 5, 7, 10; Appendix 2; Plate 4). The trend below the sequence boundary is of shallowing to a coarse-grained crinoidal grainstone that is overlain by finer grained wackestone to packstone, recording the initial stages of a deepening trend.

In the distal basin the USB is a conformable surface and can be traced from the Great Bear Cape Formation into the correlative basinal facies of the Trappers Cove Formation (Figures 4C and 5C). Below the sequence boundary are the chert-dominated facies of the Trappers Cove Formation. Above the sequence boundary the lithologic units are dominated by the shaly chert facies of the Trappers Cove Formation, representing deepening (locations 1, 2, 8, 9; Appendix 2), and the initial stages of the transgressive systems tract of the overlying sequence.

Depositional facies present in strata between these sequence boundaries will be described in greater detail in a later section.

### *2.3.3 Maximum Flooding Surface (MFS)*

The Maximum Flooding Surface (MFS) is the surface in the rock representing the deepest water facies of the sequence and separates the transgressive systems tract from the regressive systems tract (Embry, 1993). In the Otto Fiord area, concentrations of pyrite, rare phosphate and silty to shaly sediment characterize the MFS.

In sections proximal to the basin margin (locations 4, 5, 6, 7, 11; Appendix 2) the MFS coincides with the lithostratigraphic boundary separating the Great Bear Cape (or basinal equivalent Trappers Cove Formation) from the underlying Raanes Formation (Plate 3). At these localities, the MFS is a silty wackestone unit that is rich in pyrite and silt-sized quartz grains, indicating that slow deposition occurred in a reducing environment associated with deeper-water environments. At the feather edge of the basin margin (location 12), finely laminated, and bioturbated facies immediately above the basal sequence boundary show a shallowing-upward trend into fossiliferous grainstone to the USB, indicating that the MFS and the transgressive systems tract has been eroded and the regressive systems tract juxtaposes the LSB (Figures 4C and 5C). In areas of paleohighs (location 6) more than one episode of subaerial exposure occurred during the deposition of the Artinskian to Kungurian Sequence, eroding most of the strata deposited prior to the MFS event (Plate 3a).

In the areas of the slope and basinal facies (locations 1, 2, 3, 8, 9, 10; Plate 4) the deepest water facies is represented by an abrupt change from green shales of the Hare Fiord Formation to "papery" black shales of the base of the Trappers Cove Formation, accompanied by high concentrations of pyrite and locally of phosphate. Conodonts present indicate that the age of the MFS ranges from late Aktastinian to early Baigendzhinian (*i.e.* mid- to late Artinskian, see Table 1).

*2.3.4 Transgressive Systems Tract (TST)*

The stratigraphic succession between the LSB and the MFS is the Transgressive Systems Tract (TST) and represents the deepening-upward succession resulting from a relative rise of sea level (Embry, 1993). This systems tract is represented by the uppermost Nansen and correlative Hare Fiord formations and by the entire Raanes Formation (Figures 4C and 5C; Plate 3). The TST is a deepening-upward succession that onlaps the subaerial unconformity at the basin margin and locally at areas of paleohighs, and thins into a condensed interval basinward. The TST is subdivided into two parts: a) an Early Transgressive Systems Tract (ETST) and b) a Late Transgressive Systems Tract (LTST; Figures 4C and 5C). Conodonts from samples collected in the study area are from zones P5b to P7, indicating that the age of the TST is late Sterlitamakian to early Baigendzhinian (see Table 1).

The ETST represents the initial deepening phase with relative rise of sea-level. This episode of deepening was gradual and is represented by subtle changes that occur upsection in the uppermost Nansen and Hare Fiord formations. Shallow-water grainstones grade upward into slightly muddier packstones and eventually wackestones. The ETST lies between the lower sequence boundary and a flooding surface which corresponds to the sharp Nansen-Raanes contact at the basin margin (locations 4, 5, 6, 11; Appendix 2; Figures 4C and 5C). Toward the basin centre evidence of gradual deepening is more difficult to distinguish in the field, however it is expressed by an increase in green shale within the Hare Fiord Formation (locations 3, 8, 9, 10; Appendix 2; Plate 4).

The LTST represents a period of significant deepening and is only present in sections proximal to the basin margin (locations 4, 5, 6, 7, 11; Appendix 2; Figures 4C and 5C). An extremely sharp flooding surface, corresponding to the Nansen-Raanes formations contact, represents the start of the extreme deepening phase recorded in the LTST. The deepening terminated at the MFS, and the LTST encompasses the entire Raanes Formation and equivalent condensed basinal strata of the Hare Fiord Formation (Figures 4C and 5C).

Beauchamp and Henderson (1994) concluded that the TST of the Artinskian to Kungurian Sequence in the Blind Fiord area contains a number of higher-order, shallowing-upward cycles which could be grouped into four subdivisions, documenting distinct stages of the transgression. These subdivisions are based upon differential thickness of strata, conodonts, and lithostratigraphic relationships. Within the study area, based on lithostratigraphic relationships only, packages of higher order T-R cycles are also recognized in the TST of the Artinskian to Kungurian Sequence in the Otto Fiord area and are discussed in Chapter 3.

### *2.3.5 Regressive Systems Tract (RST)*

The stratigraphic succession between the MFS and the USB is the regressive systems tract (RST) (Figures 4C and 5C; Plates 3, 4). This package of rock records progressive relative sea-level fall (Embry, 1993). This systems tract is represented by: i) shallowing upward, progradational, temperate shelf carbonates of the Great Bear Cape Formation, and ii) laterally equivalent slope and basin deposits of black shale and chert of the Trappers Cove Formation (Figures 4 and 5). Samples collected from the RST in the study area yielded conodonts from zones P6b to P8 indicating that the age of the RST is late Aktastinian to late Baigendzhinian (see Table 1).

The regressive systems tract of the Artinskian sequence in the Blind Fiord area was documented by Beauchamp and Henderson (1994) to contain a number of higher-order T-R cycles within the Great Bear Cape Formation. Similar higher order T-R cycles are also recognized in the Great Bear Cape Formation of the Otto Fiord area and are discussed in Chapter 3.

### *2.3.6 Comparison: Blind Fiord - Otto Fiord Areas*

Prior to this study, extensive geologic work was carried out by Beauchamp and Henderson (1994) in the Blind Fiord area of west-central Ellesmere Island. They documented a low-order, transgressive-regressive sequence of latest Sakmarian to earliest Kungurian age in this area. This sequence can be compared directly to the low-order latest Sakmarian to earliest Kungurian Sequence presently being studied in the Otto Fiord area (referred to as the Artinskian to Kungurian Sequence throughout this study for reasons of simplicity).

The lower sequence boundary of the Artinskian to Kungurian Sequence in the Otto Fiord area is similar to that in the Blind Fiord area in its relation to the surrounding lithostratigraphy. In both the Blind Fiord and Otto Fiord areas, the LSB is usually within the uppermost Nansen Formation at the basin margin, and in the uppermost Hare Fiord

Formation in the more basinward areas. However, locally in the Otto Fiord area (location 12; Figure 5), the LSB corresponds with the Nansen-Great Bear Cape formational contact. The LSB in both the Blind Fiord and Otto Fiord areas shows significant evidence for subaerial exposure at the basin margin, and basinward the LSB becomes a correlative conformity. However, the magnitudes of the unconformities in both areas cannot be compared as the magnitude of the sequence boundary in the Otto Fiord area is not yet determined.

Like the LSB, the USB in each area is a significant unconformity at the basin margin and passes laterally into a correlative conformity basinward. However, the unconformity in the Otto Fiord area is not as widespread and profound as the unconformity documented in the Blind Fiord area, which extends to the Great-Bear Cape-Trappers Cove transition (Beauchamp and Henderson, 1994). The lithostratigraphic position of the USB is similar in both areas and coincides with the Great Bear Cape-Assistance lithostratigraphic contact at the basin margin. Toward the outer shelf and basin centre the USB is contained within the Great Bear Cape and Trappers Cove formations, respectively. Conodont evidence indicates that the age of the USB is Baigendzhinian (see Table 1) in both areas.

The MFS is similar in the Blind Fiord and Otto Fiord areas, coinciding with the Raanes-Great Bear Cape lithologic contact near the basin margin. Further basinward in the Blind Fiord area, the Raanes Formation is believed, by Beauchamp and Henderson (1994), to become a highly condensed, thin interval of pyritic shale and siltstone. In the Otto Fiord area the MFS, however, is coincident with the lithologic contact between the uppermost Hare Fiord green shales and the black shales of the Trappers Cove Formation. At this contact an abundance of pyrite and occasionally of phosphate resembles that described in the Blind Fiord area by Beauchamp and Henderson (1994). Locally (location 7; Appendix 2) in the Otto Fiord area, the MFS is coincident with the lithologic contact between the Trappers Cove Formation and the underlying Raanes Formation which has also been documented in the Blind Fiord area (Beauchamp and Henderson, 1994). Conodont evidence indicates that the age of the MFS ranges from late Aktastinian to early Baigendzhinian in the Otto Fiord area, whereas in the Blind Fiord area the age is better defined to late Aktastinian.

The TST in both the Blind Fiord and Otto Fiord areas is composed of a number of higher order T-R cycles. However, four subdivisions of the TST were recognized in the Blind Fiord area and not in the Otto Fiord area. The difference in the frequency of the subtidal cycles between the two locations is possibly due to differential subsidence of the basin margin or autocyclic processes acting on the shelf (discussed further in Chapter 3). Samples collected in the Blind Fiord area yielded conodonts that indicate an age of Aktastinian (assemblages P6a-P6b) whereas conodont assemblages from the TST of the Otto Fiord area (assemblages P6-P7) provide a less well constrained age of Aktastinian to early Baigendzhinian.

The RST of the Artinskian to Kungurian Sequence is very similar in both the Blind Fiord and Otto Fiord areas, containing a number of higher-order T-R cycles within the Great Bear Cape Formation. Conodonts from both areas belong to assemblages P6b to P8, indicating a late Akastinian to Baigendzhinian age (see Table 1).

# CHAPTER 3: SEDIMENTOLOGY AND DEPOSITIONAL ENVIRONMENTS

## 3.1 Terminology

### *3.1.1 Modern Setting*

In modern settings, carbonate environments are found in a variety of geographic locations and under a variety of environmental conditions in both tropical and temperate waters (Chave, 1967; Lees and Buller, 1972; Lees, 1975). As a first order division, reflecting the tropical and temperate and polar climates of growth, carbonates are divided into the following four groups, based on differences in biotic associations: a) the Chlorozoan Association, b) the Chloralgal Association, c) the Foramol Association and d) the Hyalosponge Association (Lees and Buller, 1972; Lees, 1975; Beauchamp, 1994). These divisions are based upon the main biotic components present and represent warm-water, hypersaline warm-water, cool-water, and cold-water conditions, respectively. The following is a description of each association:

a) *The Chlorozoan Association*, dominated by hermatypic corals, calcareous green algae, and a non-skeletal grain association (pellets, ooids and aggregates), mainly occurs between the 30th parallels (30° N and 30° S), in normal to hypersaline, carbonate-saturated to supersaturated waters that have mean temperatures greater than 23°C. Aragonite is the dominant mineralogy and dominant lithotypes include a complete textural spectrum ranging from mudstone through to boundstone (Lees and Buller, 1972; Lees, 1975; Nelson, 1988; Nelson et al., 1988).

b) *The Chloralgal Association* is similar to the Chlorozoan Association in most aspects. It differs primarily in having a skeletal association dominated by calcareous green algae and lacking corals. This association occurs in hypersaline environments where corals cannot exist (Lees, 1975).

c) *The Foramol Association (also called Bryomol Association)*, dominated by molluscs, benthic foraminifer, echinoderms, and bryozoans, mainly occurs at latitudes higher than 30° N and 30° S, in waters that are saturated to undersaturated with respect to carbonate, have normal to reduced salinities, and exhibit a mean temperature of less than 20°C. Low-Mg and high-Mg calcite are the dominant mineralogies with common glauconite grains. The dominant textural lithotype is grainstone to packstone with micrite being less common (Lees and Buller, 1972; Lees, 1975; Nelson, 1978; Nelson et al., 1988).

d) *The Hyalosponge Association*, dominated by siliceous sponge spicules and minor components of the foramol association, occurs in polar regions and in deep and very cold water below the photic zone. The mineralogy dominating this association includes biogenic silica with minor amounts of low-Mg calcite, glauconite, manganese, and iron oxides (Beauchamp, 1994; Van Wagoner et al., 1989)

The geographic distribution of these sediments is mainly dependent on water temperature and to a lesser degree salinity (Lees, 1975). Since temperature is the dominant factor, the distribution of the associations changes not only with latitude but also with depth. Consequently shelf sediments with the Chlorozoan Assemblage are likely to dominate in the warm- and shallow-waters of the shelf and yield to the Foramol Association at greater depths where water temperatures are lower (Tait, 1981; Brookfield, 1988; Beauchamp, 1994). Siliciclastic influx also controls the distribution of carbonate development. Where siliciclastic influx is high, carbonate sediments are absent. In the absence of high siliciclastic input carbonate sediments may be formed even at mid- to high latitudes (Chave, 1967).

### *3.1.2 Late Paleozoic Setting*

In the late Paleozoic, five distinct biotic associations have been identified, described and named by Beauchamp (1994). These associations include: a) the Chloroforam Association, b) the Chlorosponge Association, c) the Bryonoderm Association, d) the Bryonoderm-Extended Association and e) the Hyalosponge Association (Figure 6). The following is a description of each association:

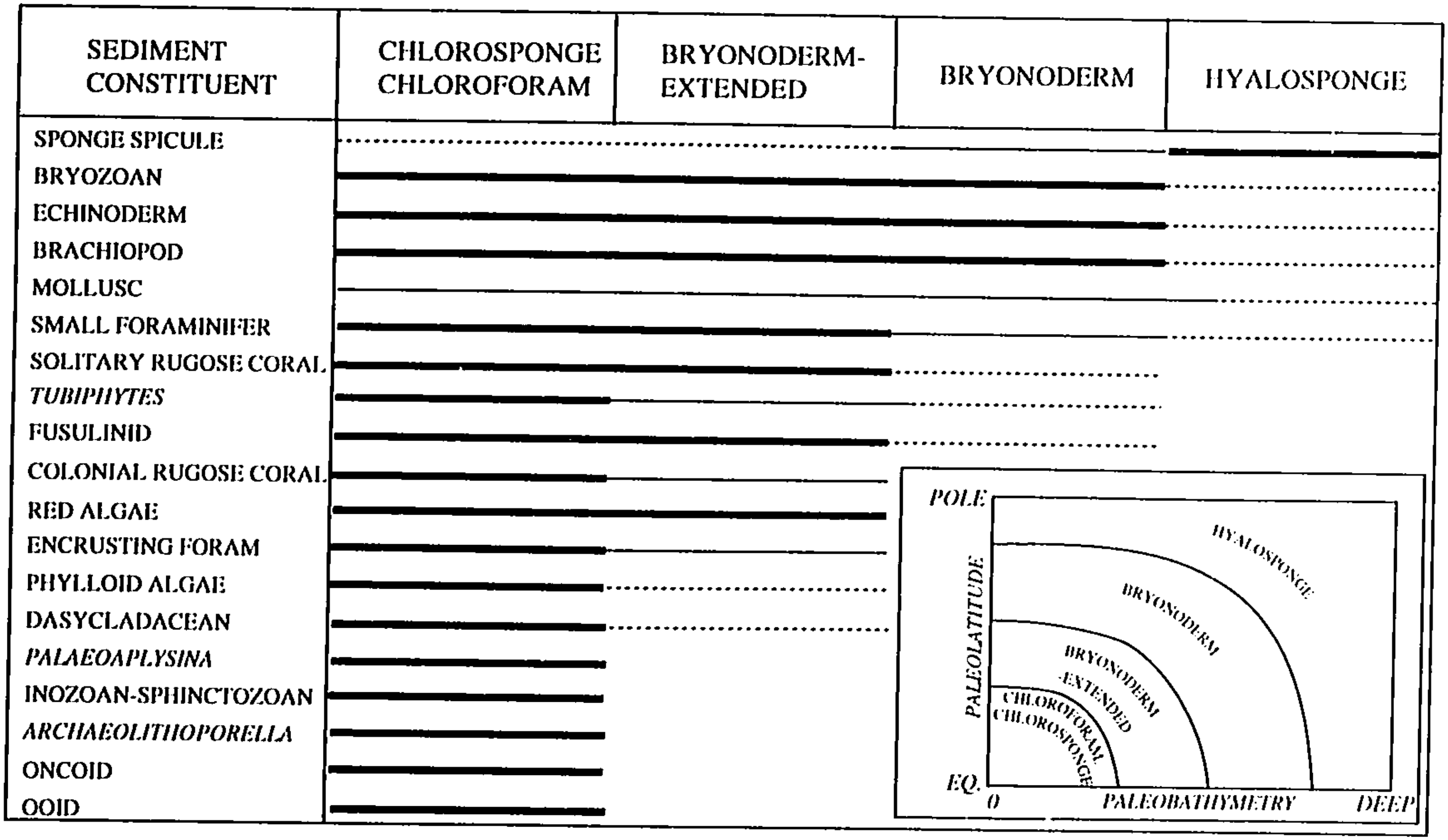
a) *The Chloroforam Association* is similar in character to modern-day, tropical assemblages in that it has a highly diverse biotic assemblage, dominated by phylloid and dasycladacean algae, benthic and epibiotic foraminifers and fusulinaceans; and an abiotic assemblage including ooids, peloids, oncoids and micrite. The mineralogy is dominated by aragonite and high-Mg calcite and early marine cements are present.

b) *The Chlorosponge Association* includes the biotic components of the Chloroforam Association in addition to calcisponges (inozoans and sphinctozoans), making it a more diverse association. An example of this association is present in the Permian Reef Tract of West Texas (Wahlman, 1985).

c) *The Bryonoderm Association* is similar to modern, cool-water associations, as follows: i) it is dominated by a sparse biota comprising bryozoans, echinoderms, brachiopods and spicules; ii) it lacks an abiotic assemblage and lime mud; iii) the mineralogy is dominated by low-Mg calcite with abundant biogenic silica and glauconite; and d) it lacks early marine cements.

d) *The Bryonoderm-Extended Association* is more diverse than the Bryonoderm Association as it additionally contains solitary and colonial rugose corals, small benthic

**Figure 6** Components of facies associations: Chlorosponge, Chloroforam, Bryonoderm-Extended, Bryonoderm and Hyalosponge. Inset (bottom right) shows the relative positions of these associations with paleolatitude and paleobathymetry (from Beauchamp and Desrochers, in press).


SEDIMENT CONSTITUENT
CHLOROSPONGE CHLOROFORAM
BRYONODERM-EXTENDED
BRYONODERM
HYALOSPONGE
SPONGE SPICULE
BRYOZOAN
ECHINODERM
BRACHIOPOD
MOLLUSC
SMALL FORAMINIFER
SOLITARY RUGOSE CORAL
TUBIPHYTES
FUSULINID
COLONIAL RUGOSE CORAL
RED ALGAE
ENCRUSTING FORAM
PHYLLOID ALGAE
DASYCLADACEAN
PALAEOAPLYSINA
INOZOAN-SPHINCTOZOAN
ARCHAEOLITHOPORELLA
ONCOID
OOID
POLE
PALEOLATITUDE
EQ.
0
PALEOBATHYMETRY
DEEP
HYALOSPONGE
BRYONODERM
BRYONODERM -EXTENDED
CHLOROFORAM CHLOROSPONGE

foraminifers, and fusulinaceans. Nevertheless, this association is distinct from the Chloroforam Association as it is less diverse and lacks green algae and the abiotic component (ooids, peloids and oncoids) that are an important part of the Chloroforam Association.

e) *The Hyalosponge Association* is dominated by sponge spicules with rarely occurring bryozoans, echinoderms, brachiopods and molluscs. The mineralogy of this association is dominated by biogenic silica with glauconite and low Mg-calcite present. This association is similar to the modern Hyalosponge Association, representing a cold-water, polar environment.

Beauchamp (1994) suggested that the change in grain associations, in the late Paleozoic, from the Chloroforam Association to the Hyalosponge Association was a direct result of temperature change (Figure 6), similar to the transition from the modern Chlorozoan/Chloralgal Association to the Hyalosponge Association, as a result of decreasing temperatures due to either climatic cooling or increasing water depths (Lees, 1975; Tait, 1981; Brookfield, 1988; Beauchamp, 1994).

A note of caution must be issued about using biotic facies associations alone to determine climatic conditions at the time of deposition, since fluctuating water levels also result in fluctuating temperatures that can alter facies associations (Rao, 1981, 1988). Therefore, in determining climatic conditions, other paleoclimatic indicators must be considered in addition to observing the biotic components. For example, the biotic association of the shallowest water grainstones are a reliable climatic indicator since the biotic components would not have been affected by temperature changes associated with depth.

### 3.2 Facies Description

The different facies of the Artinskian to Kungurian Sequence exposed in the Otto Fiord and adjacent areas are defined, described and interpreted in the following section. The facies are grouped into four distinct facies associations, identified on the basis of the biotic associations, namely: The Chloroforam Facies Association; The Bryonoderm-Extended Facies Association; The Bryonoderm Facies Association; and the Hyalosponge Facies Association. The individual facies within these facies associations are distinguished on the basis of the dominant depositional texture. Tables 4 and 5 summarize various attributes of each facies, including the main biotic and abiotic components, lithotype, bedding,

**Table 4** Components and textures of facies of the Otto Fiord area: main biotic and abiotic elements, depositional textures and siliciclastic components in the Artinskian to Kungurian Sequence, Otto Fiord area.

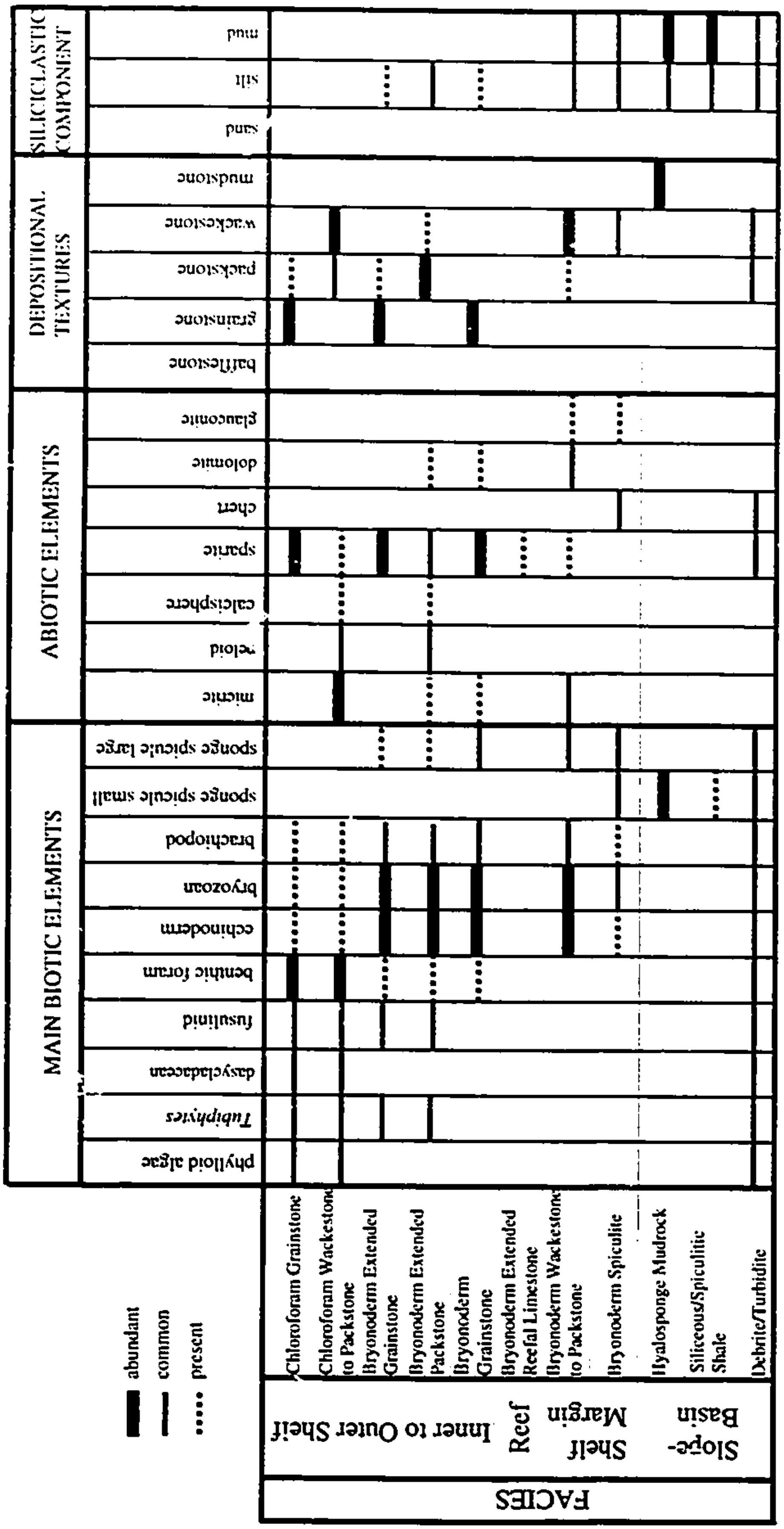

MAIN BIOTIC ELEMENTS
phylloid algae
Tubiphytes
dasycladacean
fusulinid
benthic foram
echinoderm
bryozoan
brachiopod
sponge spicule small
sponge spicule large
ABIOTIC ELEMENTS
micrite
peloid
calcisphere
sparite
chert
dolomite
glauconite
DEPOSITIONAL TEXTURES
bafflestone
grainstone
packstone
wackestone
mudstone
SILICICLASTIC COMPONENT
sand
silt
mud
FACIES
Inner to Outer Shelf
Reef
Shelf Margin
Slope-Basin
Chloroforam Grainstone
Chloroforam Wackestone to Packstone
Bryonoderm Extended Grainstone
Bryonoderm Extended Packstone
Bryonoderm Grainstone
Bryonoderm Extended Reefal Limestone
Bryonoderm Wackestone to Packstone
Bryonoderm Spiculite
Hyalosponge Mudrock
Siliceous/Spiculitic Shale
Debrite/Turbidite
abundant
common
present

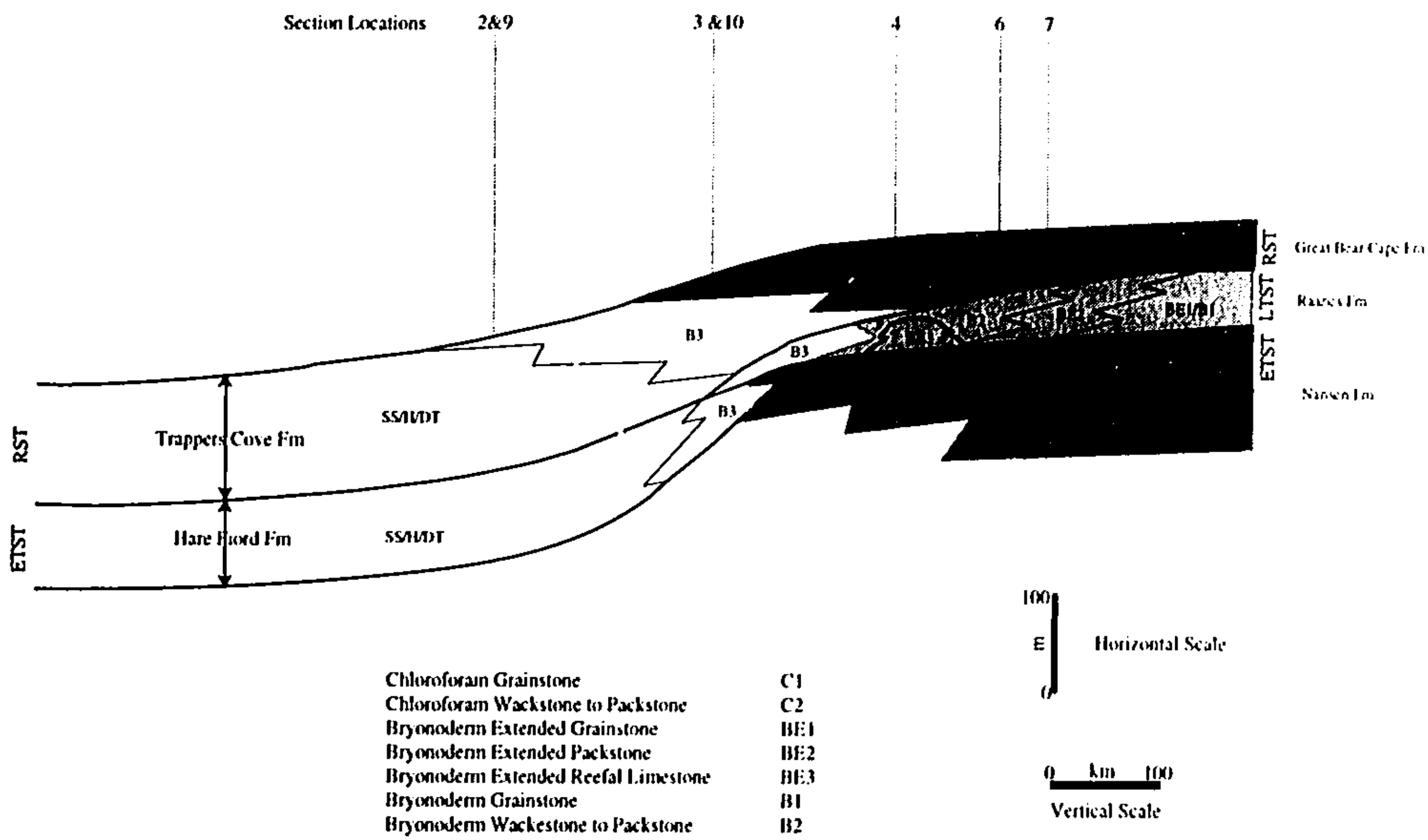
Table 5 Facies summary chart the Artinskian to Kungurian Sequence, Otto Fiord area. The table summarizes the following aspects of the facies: the lithotype, bedding style, main biotic component, bioturbation and sequence stratigraphic context.

## Facies Summary Chart

| Facies | Rock Types | Bedding | Main Biota | Other Constituents | Bioturbation | Sequence Stratigraphic Context |
|---|---|---|---|---|---|---|
| ***Chloroforam Grainstone*** | Fossiliferous Grainstone | Thick - Massive | phylloid algae, dasycladacean algae, *Tubiphytes*, benthic forams, fusulinid | | present? | early to late TST |
| ***Chloroforam Wackestone to Packstone*** | Fossiliferous Wackestone - Packstone | Thick - Very Thick | phylloid algae, dasycladacean algae, *Tubiphytes*, benthic forams, fusulinid | micrite, peloid calcisphere | present? | early TST |
| ***Bryonoderm-Extended Grainstone*** | Fossiliferous Grainstone | Medium - Very Thick | echinoderm, bryozoan, brachiopods, *Tubiphytes*, fusulinid | | present | RST/early to late TST |
| ***Bryonoderm-Extended Packstone*** | Fossiliferous Packstone | Medium - Very Thick | echinoderm, bryozoan, brachiopods, *Tubiphytes*, fusulinid | micrite, peloid, silt, dolomite rhombs | present | RST/early to late TST |
| ***Bryonoderm-Extended Reefal Limestone*** | Bryozoan-*Tubiphytes* Wackestone<br>Crinoid-Spicule Wackestone | Massive | *Tubiphytes*, bryozoan, fusulinids, echinoderm, sponge spicules | micrite, peloid<br>micrite | present | late TST |
| ***Bryonoderm Grainstone*** | Fossiliferous Grainstone | Medium - Thick | echinoderm, bryozoan, brachiopod, sponge spicules | silt | present | RST/early to late TST |
| ***Bryonoderm Wackstone to-Packstone*** | Argillaceous, Cherty Wackestone-Packstone | Thin - Medium | echinoderm, bryozoan, sponge spicules (large), brachiopods | clay, micrite, silt | present | RST/late TST |
| ***Bryonoderm Spiculite*** | Argillaceous, Cherty Wackestone | Thin - Medium | bryozoan, large and small sponge spicules | clay, micrite, silt, glauconite | abundant | RST/late TST |
| ***Hyalosponge Mudrock*** | Homogeneous Mudrock | Thin to medium | sponge spicules (small) | clay, silt | abundant | RST/TST |
| ***Debrite/Turbidite*** | Breccia, Conglomerate Turbidite | Very Thin - Massive | various clasts | crinoid, spicule, siliceous matrix | rare | RST/TST |
| ***Siliceous/ Spiculitic Shale*** | Shale | Very Thin - Thin | | clay, silt | abundant | RST/TST |

**Figure 7** Idealized facies distribution across the Artinskian to Kungurian shelf, slope and basin in the TST and RST of the Otto Fiord area. Relative locations of measured sections used to construct this figure are indicated.

# Distribution of Facies




| | |
|---|---|
| Chloroforam Grainstone | C1 |
| Chloroforam Wackstone to Packstone | C2 |
| Bryonoderm Extended Grainstone | BE1 |
| Bryonoderm Extended Packstone | BE2 |
| Bryonoderm Extended Reefal Limestone | BE3 |
| Bryonoderm Grainstone | B1 |
| Bryonoderm Wackestone to Packstone | B2 |
| Bryonoderm Spiculite | B3 |
| Hyalosponge Mudrock | H |
| Debrite/Turbidite | DT |
| Siliceous/Spiculitic Shale | SS |

bioturbation, cyclicity, and sequence stratigraphic context. Figure 7 summarizes the distribution of facies from shelf to basin.

### *3.2.1 Chloroforam Facies Association*

The Chloroforam Facies Association is characterized by a highly diverse biotic assemblage dominated by green calcareous algae and foraminifers. This association occurs only in the early parts of the TST of the Artinskian to Kungurian Sequence and is present within the uppermost Nansen and lowermost Raanes formations. In the study area, this facies association has been divided into two distinct facies based on their depositional textures: the Chloroforam Grainstone and the Chloroforam Wackestone to Packstone (Plate 5).

#### *Chloroforam Grainstone*

This facies consists of light to medium gray, thickly- to massively-bedded grainstone. The predominant biotic components of this facies include phylloid algae, dasycladacean algae, *Tubiphytes*, small benthic foraminifers, and fusulinids. Other biotic components present include *Palaeoaplysina*, red algae, bryozoans, echinoderms, brachiopods, solitary and colonial rugose corals and ostracods. These allochems are subangular to subrounded yet abraded and broken (Plate 5 c, d). Grains are poorly sorted and range from 0.01 to 0.5 cm in size. Primary porosity is occluded by iron-poor equant spar and ferroan saddle dolomite

This facies has two distinct stratigraphic occurrences: i) in the uppermost Nansen Formation forming the early parts of the TST in the shelf section (Table 6; section 7; Appendix 2); and ii) in the Raanes Formation forming the later parts of the TST in the shelf sections. This facies is typically present within decameter-scale subtidal carbonate cycles forming the bulk of the Nansen cycles (i.e. mid-/upper portions) but thinner caps in the Raanes cycles (sections 4, 7, 13; Appendix 2).

#### *Interpretation*

The Chloroforam Grainstone represents sediments deposited in a high energy environment and under relatively warm-water and open marine conditions. A relatively high-energy and inner to mid-shelf environment above wave base is evidenced by the well-winnowed depositional texture, and abundant evidence of grain fragmentation and abrasion. Water restriction was low as shown by the abundant and diverse, stenohaline biotic assemblage (Flugel, 1982). In addition, the conspicuous presence of biotic elements associated with the Chloroforam Facies Association here indicated that relatively warm-

**Table 6** Inner to outer shelf facies in the TST and RST of the Artinskian to Kungurian Sequence, Otto Fiord area.

## Inner to Outer Shelf Facies - TST

| Facies | Bedding | Rock Type | Major Grain Types | Minor Grain Types | Main Diagenetic Features | Depositional Environment | Max. Grain Size (cm) | Min. Grain Size (cm) |
|---|---|---|---|---|---|---|---|---|
| **Chloroforam Grainstone** | thick to massive | grainstone | phylloid algae, *Tubiphytes*,benthic forams, | dasycladacean algae, fusulinids, bryozoans, crinoids | iron-poor equant spar and saddle dolomite | high energy tropical shelf | 0.5 | 0.01 |
| **Chloroforam Wackestone to Packstone** | thick to very thick | wackestone to packstone | phylloid algae, *Tubiphytes*,benthic forams, micrite | dasycladacean algae, fusulinids, bryozoans, crinoids | iron-poor equant spar and saddle dolomite | medium to low energy tropical shelf | 0.5 | 0.01 |
| **Bryonoderm - Extended Grainstone** | med. - very thick | grainstone | echinoderms, bryozoans, brachipods | fusulinids, *Tubiphytes* spicules, gastropods | iron-poor bladed and equant spar | high-energy shallow cool-water shelf | 0.5 | 0.01 |
| **Bryonoderm - Extended Packstone** | med. - very thick | packstone | echinoderms, bryozoans, brachipods | fusulinids, *Tubiphytes* spicules, gastropods, micrite | iron-poor bladed and equant spar | medium energy cool-water shelf | 0.5 | 0.01 |
| **Bryonoderm Grainstone** | med - thick | grainstone | echinoderm, bryozoans, brachiopods | spicules, gastropods | iron-poor bladed and equant spar | high-energy shallow cool-water shelf | 0.5 | 0.1 |

## Inner to Outer Shelf Facies - RST

| Facies | Bedding | Rock Type | Major Grain Types | Minor Grain Types | Main Diagenetic Features | Depositional Environment | Max Grain Size (cm) | Min Grain Size (cm) |
|---|---|---|---|---|---|---|---|---|
| **Bryonoderm - Extended Grainstone** | med. - very thick | packstone - grainstone | echinoderms, bryozoans, brachipods | fusulinids, *Tubiphytes* spicules, gastropods | iron-poor bladed and equant spar | high energy cool-water shelf | 0.5 | 0.01 |
| **Bryonoderm - Extended Packtone** | med. - very thick | packstone | echinoderms, bryozoans, brachipods | fusulinids, *Tubiphytes* spicules, gastropods, micrite | iron-poor bladed and equant spar | medium energy cool-water shelf | 0.5 | 0.01 |
| **Bryonoderm Grainstone** | med - thick | grainstone | echinoderms, bryozoans, brachiopods | spicules, gastropods | iron-poor bladed and equant spar | high-energy shallow cool-water shelf | 0.5 | 0.1 |

water tropical conditions (Beauchamp, 1994) existed in shelf environments above wave base during the early parts of the TST.

*Chloroforam Wackestone to Packstone*

The Chloroforam Wackestone to Packstone consists of light to medium gray, thickly- to very-thickly bedded wackestone to packstone. The biotic assemblage of this facies is identical to that in the Chloroforam Grainstone facies. The biotic fragments are subangular, poorly sorted, unabraded and range from 0.01 to 0.5 cm in size (Plate 5 a, b). In addition, this facies comprises abiotic components including micrite, peloids, and calcispheres. Primary porosity, mainly intragranular, is occluded by iron-poor equant spar and ferroan saddle dolomite.

This facies has two distinct stratigraphic occurrences: i) in the uppermost Nansen Formation forming the early portion of the TST in the shelf sections (Table 6; section 4, 7, 13; Appendix 2); and ii) in the Raanes Formation forming the lower portion of the TST and becoming scarce in upper portions (sections 7, 13; Appendix 2). This facies is typically present within decameter-scale subtidal carbonate cycles forming the bulk of the lower to mid-portion of the Nansen shelf cycles and the mid- to upper portion of Raanes shelf cycles. This facies also occurs in grabens in block-faulted regions of the Nansen shelf.

*Interpretation*

The Chloroforam Wackestone to Packstone represents sediments deposited in a relatively quiet environment below wave base but within the photic zone under relatively warm-water and open marine conditions. This shelf environment is evidenced by the muddy and poorly-winnowed depositional texture, lack of evidence of grain fragmentation and abrasion and the presence of calcareous algae. This facies has a stenohaline biotic assemblage similar to that in the Chloroforam Grainstone indicating that water restriction was low (Flugel, 1982) and that relatively warm-water, tropical conditions (Beauchamp, 1994) existed in the mid- to outer shelf environments below wave base during the early TST.

### *3.2.2 Bryonoderm-Extended Facies Association*

The Bryonoderm-Extended Facies Association is characterized by a less diverse biotic assemblage than the Chloroforam Association, dominated by bryozoans, echinoderms and brachiopods together with fusulinids and *Tubiphytes*. This association occurs within the uppermost Nansen and entire Raanes formations, forming the later parts of the TST of the Artinskian to Kungurian Sequence. In the study area, this facies association has been divided into three distinct facies based on depositional textures: the Bryonoderm-Extended Grainstone, the Bryonoderm-Extended Packstone and the Bryonoderm-Extended Reefal Limestone.

*Bryonoderm-Extended Grainstone*

The Bryonoderm-Extended Grainstone Facies consists of buff to yellowish weathering, medium- to very thickly-bedded fossiliferous grainstone. The main biotic elements in this facies include echinoderms, fenestellid and ramose bryozoans, and brachiopods. Subordinate allochems include *Tubiphytes* (encrusting bryozoan fragments), fusulinids, large sponge spicules, gastropods, dasycladacean algae, solitary and colonial rugose corals, red algae and ostracods. The bioclastic grains are typically subangular to subrounded, disarticulated, abraded, moderately sorted, and range from 0.01 to 0.5 cm in size. In addition, these grains, especially bryozoans, fusulinids and *Tubiphytes*, display evidence of post-burial mechanical compaction (i.e. fragmentation) indicating that the compaction occurred prior to any significant pore-filling cementation (Plate 6 a, b). Primary porosity is occluded by i) syntaxial overgrowth cement, and ii) iron-poor bladed and equant spar with the bladed spar adjoining the bryozoan zooecia, and the equant spar infilling the remaining intergranular porosity.

This facies has two distinct stratigraphic occurrences: i) in the Raanes Formation, throughout the TST in shelf sections (Table 5; sections 4, 7, 13; Appendix 2); and ii) in the Great Bear Cape Formation forming the lower portion of the RST in shelf sections (sections 3, 5, 11). This facies is typically present and forms the mid- to upper portion of decameter-scale carbonate shelf cycles within both formations.

*Interpretation*

The Bryonoderm-Extended Grainstone represents sediments deposited in a high energy environment and under relatively temperate and open marine conditions. A relatively high-energy, most likely inner- to mid-shelf environment above wave base is evidenced by the well-winnowed depositional texture, and abundant evidence of grain fragmentation and abrasion (Jones and Desrochers, 1992). Water restriction was low as shown by a relatively diverse stenohaline biotic assemblage (Flugel, 1982). In addition, the decrease in fossil diversity and the change in nature of biotic elements from the Chloroforam Association to the Bryonoderm-Extended Association indicate that relatively cool-water, temperate conditions existed in shelf environments above wave base during the late TST and early RST (Beauchamp, 1994). Although the change in temperature was significant enough to eliminate the majority of the tropical biota, the presence of

*Tubiphytes*, fusulinids and calcareous algae indicates that conditions were most likely transitional between warm and cold conditions (Beauchamp, 1994).

## Bryonoderm-Extended Packstone

The Bryonoderm-Extended Packstone is very similar in biotic composition, bedding and colour to the Bryonoderm-Extended Grainstone but differs by the presence of a lime mud matrix and other abiotic components, including iron-poor dolomite rhombs, peloids, and silt-size quartz grains. The allochems are subangular to subrounded but show little sign of abrasion; they are moderately sorted and range from 0.01-0.5 cm in size. The presence of peloids and well defined burrows indicates some bioturbation. Primary porosity is occluded by iron-poor bladed and equant spar with the bladed spar adjoining the bryozoan zooecia and the equant spar infilling the remaining intergranular porosity.

This facies has three distinct stratigraphic occurrences: i) in the Nansen Formation, in the early TST in shelf sections (Table 5; section 7, 11, 12, Appendix 2); ii) in the Raanes Formation, throughout the TST in shelf sections (sections 4, 7, 13; Appendix 2); and iii) in the Great Bear Cape Formation, in the RST in shelf sections (sections 3, 5, 13; Appendix 2). This facies typically occurs in the mid- to upper portion of decameter-scale subtidal carbonate shelf cycles in the three formations.

### *Interpretation*

The Bryonoderm-Extended Packstone represents sediments deposited in a lower energy environment than the related grainstone and under relatively temperate and open marine conditions. A relatively low-energy and mid- to outer-shelf environment below wave base for this facies is evidenced by the muddy depositional texture, and minimal grain fragmentation and abrasion (Jones and Desrochers, 1992). Similar to the Bryonoderm-Extended Grainstone, water restriction was low as shown by the abundant stenohaline biotic assemblage (Flugel, 1982), and relatively cool-water, temperate conditions (Beauchamp, 1994) existed in shelf environments below wave base, but within the photic zone, during the TST and RST, as is evidenced by the biota.

## Bryonoderm-Extended Reefal Limestone

The Bryonoderm-Extended Reefal Limestone occurs in skeletal mounds (James and Bourque, 1992) that are 10 m to 366 m thick within the study area (Plate 7). The mounds tend to be roughly circular in section. These skeletal mounds are present within the Raanes Formation in the lower portion of the TST in mid- to outer-shelf environments (Table 7; sections 4, 7, 13; Appendix 2). The Bryonoderm-Extended Reefal Limestone

**Table 7 Shelf margin facies in the TST and RST of the Artinskian to Kungurian Sequence, Otto Fiord area.**

## Shelf Margin Facies - TST

| Facies | Bedding | Rock Type | Major Grain Types | Minor Grain Types | Main Diagenetic Features | Depositional Environment | Max. Grain Size (cm) | Min. Grain Size (cm) |
|---|---|---|---|---|---|---|---|---|
| **Bryonoderm Wackestone to Packstone** | thin - med | wackestone-packstone | crinoids, bryozoans, large sponge spicules | small sponge spicules | iron - rich equant spar, microcrystalline chert | low - energy, deep water, below fair weather wave base | 0.4 | 0.05 |
| **Bryonoderm - Extended Reefal Limestone** | massive | wackestone | bryozoans, *Tubiphytes*, crinoid, large sponge spicules | small sponge spicules, benthic forams | iron - poor equant spar | Reef Mound | 1.5 | 0.05 |
| **Bryonoderm Spiculite** | thin - med | wackestone | bryozoans large and small sponge spicules | crinoid, brachiopod | iron - rich equant spar, microcrystalline chert | low - energy, deep water, below fair weather wave base | 0.5 | 0.01 |

## Shelf Margin Facies - RST

| Facies | Bedding | Rock Type | Major Grain Types | Minor Grain Types | Main Diagenetic Features | Depositional Environment | Max Grain Size (cm) | Min Grain Size (cm) |
|---|---|---|---|---|---|---|---|---|
| **Bryonoderm Wackestone to Packstone** | thin - med | wackestone-packstone | crinoids, bryozoans, large sponge spicules | small sponge spicules | iron - rich equant spar, microcrystalline chert | low - energy, deep water, below fair weather wave base | 0.4 | 0.05 |
| **Bryonoderm Spiculite** | thin - med | wackestone | bryozoans large and small sponge spicules | crinoid, brachiopod | iron - rich equant spar, microcrystalline chert | low - energy, deep water, below fair weather wave base | 0.5 | 0.01 |

Facies, occurring within the Raanes Formation (late TST), is divided into the genetically related Core and Flank Subfacies.

The Core Subfacies is a massive, light gray weathering, boundstone-bafflestone composed mainly of abundant micrite, with fenestellid and ramose bryozoans in life position, encrusting *Tubiphytes*, rare sponge spicules, benthic foraminifers, silt-sized quartz and open-space stromatactoid? cavities. The allochems are angular, showing no signs of abrasion. Poorly sorted grains range from 1.5 to 0.5 cm in size. Primary porosity is eliminated by i) early marine fibrous cements rimming pore spaces and ii) low-iron equant spar occluding remaining porosity. This facies dominates and comprises the cores of the reef mounds (Plate 8a, b).

The Flank Subfacies is a light gray weathering, medium- to thickly-bedded wackestone composed of abundant micrite, crinoid plates, large sponge spicules (up to 20 cm long), and silt-sized quartz grains. The allochems are angular to subangular and rarely show sign of abrasion. The grains range from 0.1 to 20.0 cm in size. Primary porosity is occluded by iron-poor equant spar. This facies is subordinate to the core facies, is distributed preferentially on the sides of the mounds and dominates near the base (Plate 8c, d).

*Interpretation*

The Bryonoderm-Extended Reefal Limestone facies represents sediment deposition in a low energy environment under cool-water, temperate and open marine conditions where delicate reef builders acted as baffling agents during reef growth. A low energy, below wave base, mid-shelf environment is demonstrated by the abundance of mud and the lack of evidence of grain abrasion and fragmentation within these mounds. In addition, the presence of biotic elements associated with the Bryonoderm-Extended Association indicates that deposition occurred in relatively cool-water, temperate conditions on the outer shelf environments below wave base during the TST.

The shape of the mounds and the fact that these mounds survived in the early TST and not in the late TST suggests that vertical growth dominated over lateral growth and that they grew as accommodation space was provided (*i.e.* analogous to keep-up reefs; James and Bourque, 1992). Eventually the water depth was too great for the mound constructors to survive and the bioherms drowned (*i.e.* give-up reefs; James and Bourque, 1992).

### *3.2.3 Bryonoderm Facies Association*

The Bryonoderm Facies Association, is characterized by a less diverse biotic assemblage than the Chloroforam Association or even the Bryonoderm-Extended Association, and is dominated by bryozoans, echinoderms, brachiopods and sponge spicules. This facies association is dominant in the late TST of the Raanes Formation and the RST of the Great Bear Cape Formation in the Artinskian to Kungurian Sequence. In the study area, the Bryonoderm Facies Association has been divided into two distinct facies based on their depositional textures: the Bryonoderm Grainstone and the Bryonoderm Wackestone to Packstone.

*Bryonoderm Grainstone*

The Bryonoderm Grainstone is a yellowish to buff weathering, medium- to thickly-bedded grainstone. The abundant biotic components include echinoderms and bryozoans with common brachiopods and large sponge spicules (Plate 9a, b). Gastropods, small foraminifers, solitary rugose corals and ostracods are present but scarce. The bioclastic grains are subangular to subrounded, commonly disarticulated, and show signs of abrasion. Grains are moderately well sorted ranging from 0.01 to 0.5 cm in size. Primary porosity is occluded by syntaxial overgrowths, and iron-poor bladed and equant spar. The bladed spar dominantly occurs in the bryozoan zooecia and equant spar occludes intergranular porosity.

This facies occurs in three stratigraphic positions: i) in the Nansen Formation, in the early TST in shelf sections (Table 6; sections 6, 11, 12; Appendix 2); ii) in the Raanes Formation, in the upper portion of the TST in shelf sections (sections 4, 7, 13; Appendix 2); and iii) in the Great Bear Cape Formation, dominating the upper portion of the RST in shelf sections (sections 3, 5, 11; Appendix 2). This facies typically occurs in the upper portion of decameter-scale subtidal shelf cycles in the three formations.

*Interpretation*

The Bryonoderm Grainstone represents sediment deposition in a high energy environment and under relatively cool-water and open marine conditions. A relatively high-energy, inner- to mid-shelf environment above wave base for this facies is demonstrated by the well-winnowed depositional texture, and abundant evidence of grain fragmentation and abrasion (Jones and Desrochers, 1992). Water restriction was low as shown by the abundant stenohaline biotic assemblage. The greatly reduced diversity of biota and the obvious similarity to the modern Foramol/Bryomol (Nelson, 1988) Association indicate that temperate-cool and temperate-cold conditions existed on the shelf above wave base during the TST and RST (Beauchamp, 1994).

*Bryonoderm Wackestone-Packstone*

The Bryonoderm Wackestone-Packstone Facies is a greenish-gray weathering, thinly to medium bedded, argillaceous cherty wackestone to packstone. The dominant allochems are identical to those of the Bryonoderm Grainstone Facies with the addition of abundant large and small sponge spicules. In addition to the abundant micritic matrix, the abiotic elements present in this facies which are not present in the Bryonoderm Grainstone, include green clay, chert, silt-sized quartz, and local iron-free dolomite rhombs (Plate 9). These grains are angular to subangular and show little sign of abrasion, however, some are broken. Grains are poorly sorted and range from 0.05 to 0.4 cm in size. Original porosity, although limited, appears to have been occluded by post-depositional chertification, and iron-rich equant spar diagenetically replaces all large and some small sponge spicules. Evidence of intense bioturbation can be seen in the outcrop as *Thalassinoides*-like burrows are preserved by preferential silicification (Plate 9c).

This facies occurs in two stratigraphic positions: i) in the Raanes Formation throughout late TST in shelf sections (Table 7; sections 4, 5, 7, 13; Appendix 2); and ii) in the Great Bear Cape Formation within the RST in shelf sections (sections 3, 4, 5, 10, 11; Appendix 2). This facies typically dominates the lower portion of subtidal decameter-scale shelf cycles in both formations.

*Interpretation*

The Bryonoderm Wackestone to Packstone represents sediments deposited in a low energy environment under cool-water and open marine conditions. A low-energy and outer-shelf/shelf margin environment below wave base for this facies is demonstrated by the presence of fine-grained material, and lack of grain fragmentation and abrasion or sedimentary structures indicative of agitation (Jones and Desrochers, 1992). Open shelf conditions and therefore normal salinities are indicated by various stenohaline biotic elements (Nelson, 1988). The greatly reduced diversity of biota and nature of biota associated with the Bryonoderm Association indicate that cool-water conditions (Beauchamp, 1994) existed on the outer shelf/shelf margin below wave base during the TST and RST. This facies, however, being deposited in the outer shelf/shelf margin setting, may reflect cooling associated with a greater water depth rather than climatic cooling (Tait, 1981; Brookfield, 1988), especially its occurrence within the Raanes Formation.

*3.2.4 Hyalosponge Facies Association*

The Hyalosponge Facies Association, is characterized by a greatly reduced biotic assemblage of sponge spicules with rare bryozoans, echinoderms and brachiopods. This facies association occurs in the TST of the Hare Fiord Formation but dominates in the RST of the Trappers Cove Formation. This facies association comprises two distinct facies including: i) Hyalosponge Mudrock and ii) Siliceous/Spiculitic Shale (Plate 10).

*The Hyalosponge Mudrock*

This facies is a dark-gray to black, yellowish-weathering, thinly- to medium-bedded, resistant mudrock composed of calcareous to cherty fine-grained material, mainly siliceous shale, with sparse bioclastic material but abundant sponge spicules (Plate 10a, b). Cement is limited to the biomoldic filling of former opaline sponge spicules by iron-poor calcite cement and/or microcrystalline chert giving the mudrock its calcareous or cherty nature, respectively. This facies is thoroughly bioturbated, with the *Nereites* trace fossil assemblage abundant in outcrop. Abundant metre-scale truncation features observed in outcrop are also identified with this association.

This facies occurs in two stratigraphic positions: i) in the Hare Fiord Formation, dominating throughout TST in slope sections (Table 8; sections 8, 9, 10; Appendix 2); and ii) in the Trappers Cove Formation, throughout the RST in slope sections (sections 1, 2, 3, 8, 9, 10; Appendix 2). Within the Trappers Cove Formation, this facies is interbedded on a centimeter scale with the Siliceous Shale Facies.

*Interpretation*

The Hyalosponge Mudrock represents sediments deposited in a low energy, deep-water environment under cold and open marine conditions. A deep-water, low-energy environment well below the photic zone for this facies is demonstrated by the presence of fine-grained material with monospecific sponge spicules, and the general absence of other biota. Further evidence to support this interpretation includes the abundance of metre- to decameter-scale truncation features. The prolific growth of siliceous sponges is commonly favoured by a combination of cold temperatures, absence of light (Beauchamp, 1994) and nutrient-rich environments (Van Wagoner et al., 1989). This supports the fact that cool-water and likely very cold conditions (Beauchamp, 1994) existed on the deeper shelf margin / lower slope during the TST and RST.

Table 8 Slope/basin facies in the TST and RST of the Artinskian to Kungurian Sequence, Otto Fiord area.

## Slope/Basin Facies - TST

| Facies | Bedding | Rock Type | Major Grain Types | Minor Grain Types | Main Diagenetic Features | Depositional Environment | Max. Grain Size (cm) | Min. Grain Size (cm) |
|---|---|---|---|---|---|---|---|---|
| **Hyalosponge** | very thin - medium | mudstone | sponge spicules | siliceous shale, silt-size quartz, crinoid and bryozoan fragments | microcrystalline chert | slope - basin | silt | clay |
| **Siliceous/ Spiculitic Shale** | very thin - thin | shale | siliceous shale | sponge spicules, silt-size sand | microcrystalline chert | basin | silt | clay |
| **Debrite/ Turbidite** | thick - very thick | breccia - conglomerate | various pebbles | crinoids, bryozoans | microcrystalline chert | slope - basin | 15.0 | 0.5 |

## Slope/Basin Facies - RST

| Facies | Bedding | Rock Type | Major Grain Types | Minor Grain Types | Main Diagenetic Features | Depositional Environment | Max. Grain Size (cm) | Min. Grain Size (cm) |
|---|---|---|---|---|---|---|---|---|
| **Hyalosponge** | very thin - medium | mudstone | sponge spicules | siliceous shale, silt-size quartz | microcrystalline chert | slope - basin | silt | clay |
| **Siliceous/ Spiculitic Shale** | very thin - thin | shale | siliceous shale | sponge spicules, silt-size sand | microcrystalline chert | basin | silt | clay |
| **Debrite/ Turbidite** | very thin - thick | wackestone-packstone | crinoid | bryozoan, sponge spicules | microcrystalline chert | basin | 1.0 | 0.5 |

*Siliceous/Spiculitic Shale*

This facies is a dark gray to black, siliceous, commonly fissile shale that weathers recessively. It is composed dominantly of siliceous shale with minor sponge spicules and silt-sized quartz (Plate 10c, d). This facies is moderately bioturbated with distinct *Nereites* horizontal burrows evident in outcrop.

This facies occurs in two stratigraphic positions: i) in the Hare Fiord Formation, late in the TST in basinal sections (Table 8; sections 3, 8, 9, 10; Appendix 2); and ii) in the Trappers Cove Formation, in the lower portion of the RST in the basin (sections 2, 3, 8, 9, 10; Appendix 2). Within the Trappers Cove Formation, this facies is interbedded on a centimeter scale with the Hyalosponge Mudrock.

*Interpretation*

This facies represents the deep-water background sedimentation that existed in the basin well below storm wave base and the photic zone. A deep-water, low-energy and lower slope/basinal environment is suggested by the dominance of finer grained siliciclastic material and the absence of most biota except for a few organisms able to survive under dysaerobic conditions. This sedimentation was intermittently interrupted by shelf-derived sediment gravity flow deposits.

***3.2.5 Mixed Facies Association***

The Mixed Facies Association includes facies that combine the characteristics of two or more previously described facies. In the study area, this association includes two distinct facies that show characteristics from two or more of the above mentioned facies. These facies are: i) the Bryonoderm Spiculite facies, that is clearly transitional in composition with the Hyalosponge Mudrock; and ii) the Debrite/Turbidite Facies. Both of these facies are found within the TST and the RST of the Artinskian-Kungurian Sequence in the Otto Fiord area (Plates 11, 12).

*Bryonoderm Spiculite*

The Bryonoderm Spiculite Facies is greenish-gray weathering, thinly- to medium-bedded, argillaceous to calcareous chert. Major components of this facies include bryozoan fragments, large sponge spicules ranging from 0.5 - 1.0 cm in size, and small sponge spicules ranging from 0.01 to 0.05 cm in size (Plate 11). Minor components include sparse brachiopods and echinoderms. The biotic grains are subangular to subrounded and show little sign of abrasion and fragmentation. Abiotic elements include green clay, silt-sized quartz, and rarely occurring iron-free dolomite rhombs. Grains are poorly sorted and range from 0.02 cm to 0.4 cm in size. Cement includes iron-rich calcite (equant spar), replacing usually large and some small sponge spicules. Chert fills the original porosity in the bryozoan zooecia. Burrows have been preserved by preferential silicification. Grain flows with scoured bases are common in this facies (section 15; Appendix 2).

This facies occurs in both the TST and RST of the Hare Fiord and Trappers Cove formations forming part of the upper slope (Table 7; sections 2, 3, 8, 9, 10, 15; Appendix 2).

*Interpretation*

The Bryonoderm Spiculite, with its mixed Bryonoderm-Hyalosponge biotic association, represents sediments deposited in a low energy environment under cool and open marine conditions on the upper slope. An upper-slope environment of deposition is evidenced by the presence of limestone debris flow beds having irregular basal contacts truncating the underlying beds. A low-energy environment below wave base for this facies is demonstrated by the presence of fine-grained material, angular to subangular texture of the grains and lack of grain fragmentation and abrasion (Jones and Desrochers, 1992). Open shelf conditions and therefore low water restriction, is indicated by the stenohaline biotic assemblage. The greatly reduced diversity of biota indicates that cool-water conditions existed on the upper slope below wave base during the RST (Beauchamp, 1994). This facies developed on the upper slope, therefore the cool, possibly very cold temperatures may have been a function of the water depth rather than climatic cooling (Tait, 1981 ; Brookfield, 1988).

Using the modern cool-water Otway Shelf, southeastern Australia (Boreen and James, 1993) as an analog for the Artinskian to Kungurian Sequence, the Bryonoderm Spiculite Facies would be equivalent to the extensive bryozoan/sponge sediment blanket that occurs in the deep outer shelf/upper slope setting of the Otway Shelf.

Debrite/Turbidite Facies

This facies includes all the gravity driven deposits that are present in the study area from massive polymictic breccias to classical crinoidal turbidites (Plate 12). These deposits vary in thickness from 2 cm to 0.5 m, are laterally discontinuous and can occur in amalgamated units up to 20 m thick.

The breccia is typically composed of a crinoid-bryozoan grainstone matrix with various clasts, including: a) green laminated siltstone, b) dark-grey to black carbonate mudstone to wackestone containing small echinoderm fragments, and c) spiculitic chert. The clasts range from 3 to 6 cm but can reach up to 15 cm in size. Large-scale, low-angle cross-stratification is locally present. In general these deposits are laterally discontinuous, occurring within the TST of the Hare Fiord Formation (Table 8; sections 8, 9, 10; Appendix 2).

Two distinct types of turbidites exist in the study area including: a) crinoidal turbidite, early in the RST of the Trappers Cove Formation (Plate 12), and b) carbonate turbidite, in the early TST of the Hare Fiord Formation. The crinoidal turbidites predominantly include crinoidal material and sponge spicules. The turbidites consist of packstone at the base and grade upward into wackestone and mudstone that contains a spiculitic matrix. The echinoderm grains are angular and locally broken and range from 0.1 to 1.0 cm in size. These deposits range from 2 cm to more than 30 cm thick. The bases of these crinoidal deposits locally fill scours into the siliceous shale. From the base, these deposits fine upward. They are laterally discontinuous and occur at the base of the RST within the Trappers Cove Formation. The carbonate turbidites are dark-coloured, greyish-green weathering, resistant, with sharp erosional bases and grade into siliceous shale and aphanitic cherty limestone. These turbidites consist of a variety of cool- and warm-water biota in a calcareous matrix and range from packstone at the base to mudstone at the top. These deposits are generally medium-bedded ranging from 5 cm to 40 cm thick and are laterally continuous. Packages of these turbidites up to 20 m thick occur in the early TST of the Hare Fiord Formation.

*Interpretation*

The Debrite/Turbidite Facies, with its mixed Chloroforam-Bryonoderm-Hyalosponge biotic assemblages, represents gravity-driven, shelf-derived sediments deposited on the lower slope and in the basin. The scoured bases and normal grading within these deposits indicate that they were gravity driven (Walker, 1992), interrupting ambient basinal sedimentation (Hyalosponge Association) and forming discontinuous sheets. The sediments were derived from the adjacent shelf and therefore provide a window to shelf margin sedimentation at the time of the gravity flow, essentially recording temporal change in biota living at or near the shelf margin, throughout the Artinskian to Kungurian time interval in the study area. That is, the Chloroforam Association is more common in the Debrite/Turbidite Facies within the ETST, while during the RST, the Bryonoderm Association dominates this facies.

## 3.3 Depositional Model

The facies defined and interpreted in the above section represent inner-to-outer shelf, shelf margin, and slope-to-basin depositional settings. The majority of the inner shelf facies are not present as they were removed, by erosion, especially along the basin margin, following uplift during the Melvillian Disturbance (Beauchamp et al., 1989a). The distribution of facies across the shelf and slope is quite complex as not only did the facies change with water depth but they also changed through time.

The following section describes a depositional model in terms of the spatial and temporal distribution of the facies on the shelf. Spatial distribution addresses the controls affecting the position of facies on the shelf at a particular point in time and temporal distribution addresses the change in the location of the facies on the shelf through time. Figures 8, 9, and 10 provide models showing diagrammatically the distribution of facies across the Nansen, Raanes and Great Bear Cape shelves (ETST to RST).

### *3.3.1 Spatial Facies Distribution*

The spatial distribution of facies is dependent on several interrelated factors that include: i) biologically-driven sediment production and extrabasinal sediment influx, ii) oceanographic conditions such as water depth, restriction, photic levels, temperature, agitation and upwelling, iii) tectonics, involving block faulting of the shelf, and iv) initial depositional profile. As mentioned above, the facies of the Artinskian to Kungurian Sequence characterize three distinct zones: the inner to outer shelf, the shelf margin, and the slope-to-basin region. The following section discusses the spatial facies distribution across these zones.

#### *Inner to Outer Shelf*

Throughout the Artinskian to Kungurian Sequence, abundant sediment was deposited in the inner, mid- and outer regions of the shelf. The spatial distribution of sediment on the shelf is affected by all the elements mentioned above and is discussed in detail in the following sections.

The first element controlling spatial facies distribution on the shelf was the type of sediment production and/or the influx of sediment delivered to the shelf. The Artinskian to Kungurian shelf was carbonate-dominated and hosted a wide array of biotic facies ranging from the warm-water Chloroforam through to the cool-water Bryonoderm associations. The association dominating the shelf at any one time depended on the ambient climate and/or ocean temperature. Through the majority of the Artinskian to Kungurian Sequence

Figure 8 Schematic block diagram illustrating the position of facies on the shelf during the early transgressive systems tract of the Artinskian to Kungurian Sequence, Otto Fiord area. Note the interpreted upwelling at the shelf margin that would explain the coexistence of cool and warm-water facies associations on the shelf. At this time part of the shelf was block faulted, resulting in the change to packstones and wackestones in down-dropped areas. The facies represented are: C1-Chloroforam Grainstone, C2-Chloroforam Wackestone to Packstone, BE1-Bryonoderm-Extended Grainstone, BE2-Bryonoderm-Extended Wackestone to Packstone, B1-Bryonoderm Grainstone, B3-Bryonoderm Spiculite, H-Hyalosponge Mudstone, SS-Siliceous/Spiculitic Shale, DT-Debrite/Turbidite.

# T1 Early Transgressive Systems Tract
# Nansen Shelf

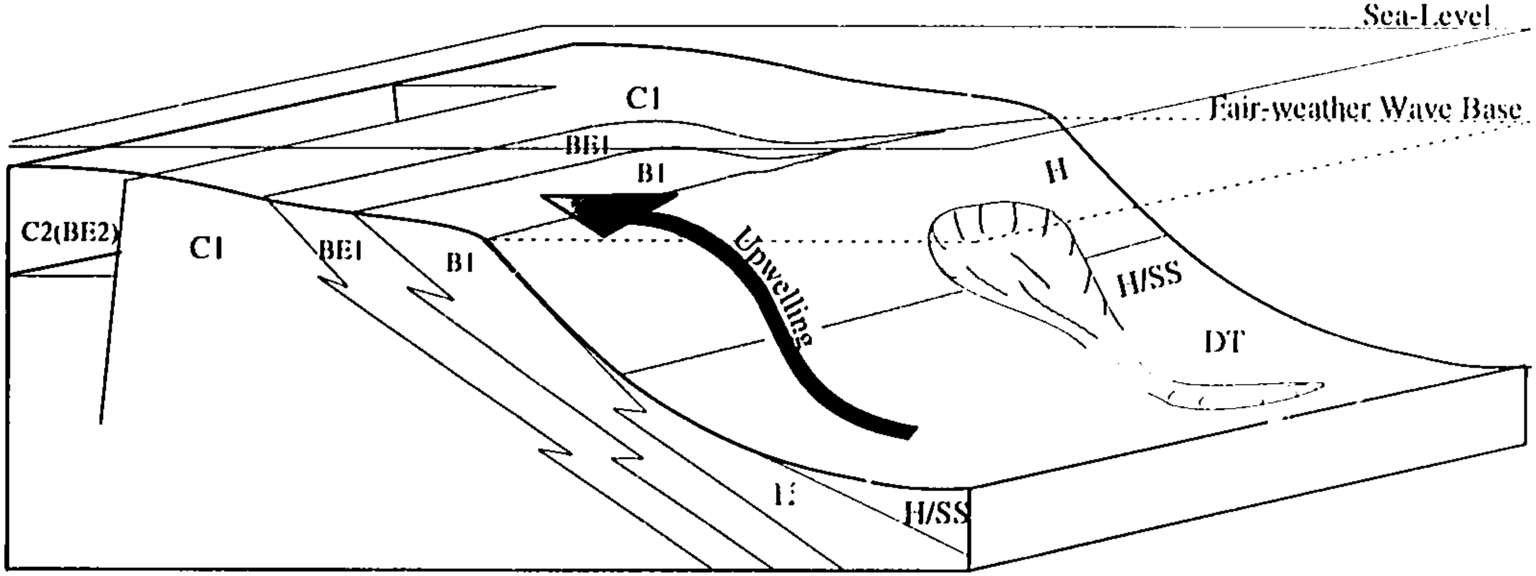


Figure 9 Schematic block diagram illustrating the position of the facies on the shelf during the late transgressive systems tract of the Artinskian to Kungurian Sequence, Otto Fiord area. Note the backstep of the facies in the LTST compared to the ETST. At this time the shelf was largely dominated by the temperate-warm Bryonoderm-Extended Facies Association while the shelf margin was dominated by the temperate-cool Bryonoderm Facies Association. The facies are represented as follows: C1-Chloroforam Grainstone, C2-Chloroforam Wackestone to Packstone, BE1-Bryonoderm-Extended Grainstone, BE2-Bryonoderm-Extended Wackestone to Packstone, BE3-Bryonoderm-Extended Reefal Limestone, B1-Bryonoderm Grainstone, B2-Bryonoderm-Extended Wackestone to Packstone, B3-Bryonoderm Spiculite, H-Hyalosponge Mudstone, SS-Siliceous/Spiculitic Shale, DT-Debrite/Turbidite.

# T2 Transgressive Systems Tract
# Raanes Shelf

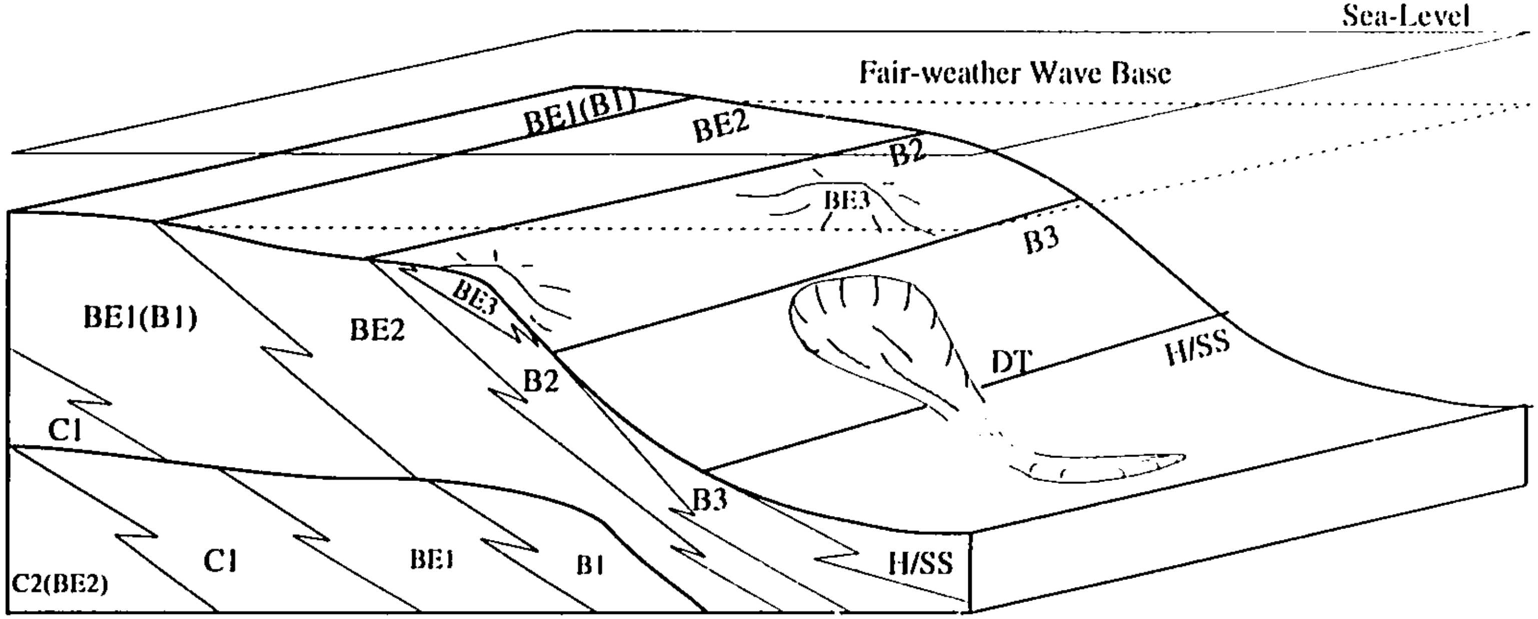
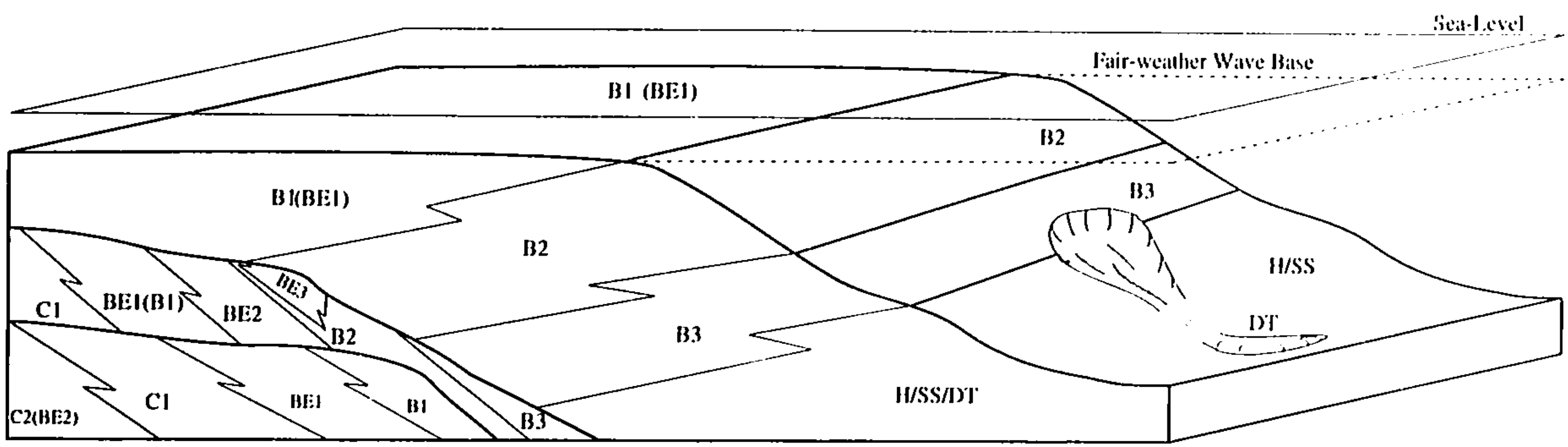


Figure 10 Schematic block diagram illustrating the position of facies on the shelf during the regressive systems tract of the Artinskian to Kungurian Sequence, Otto Fiord area. Note that the shelf and shelf margin are dominated by the temperate-cool Bryonoderm Association. The slope and basin are dominated by the Hyalosponge Association. The facies are represented as follows: C1-Chloroforam Grainstone, C2-Chloroforam Wackestone to Packstone, BE1-Bryonoderm-Extended Grainstone, BE2-Bryonoderm-Extended Wackestone to Packstone, BE3-Bryonoderm-Extended Reefal Limestone, B1-Bryonoderm Grainstone, B2-Bryonoderm-Extended Wackestone to Packstone, B3-Bryonoderm Spiculite, H-Hyalosponge Mudstone, SS-Siliceous/Spiculitic Shale, DT-Debrite/Turbidite.

# T3 Regressive Systems Tract
# Great Bear Cape Shelf



the temperate-warm Bryonoderm-Extended and temperate-cool Bryonoderm associations prevailed in shallow-water shelf grainstones, indicative of a cooling climate. Throughout this time, siliciclastic input to the shelf was minor and periodic, with the maximum siliciclastic influx occurring during the TST comprising approximately 10% in volume of the sediment. It is postulated that siliciclastic influx was relatively higher during this period, compared to the other periods, due to tectonic uplift of the adjacent land creating a source of siliciclastic sediment while at the same time the shelf was submerged during relative rise in sea-level. The hinge zone of this tectonic tilt is presumed to be at or near the basin margin. Another possible cause for the relative increase in siliciclastic sediments during the TST could have been sea-level rise, resulting in decreased production of carbonate sediment and a decreased carbonate:siliciclastic ratio. Therefore, the increase in siliciclastic sedimentation may be only apparent and the absolute influx could have remained the same or decreased slightly.

The second control on spatial facies distribution on the shelf was oceanographic conditions, including water depth, restriction, photic levels, temperature, agitation and upwelling. The array of facies existing on the shelf throughout the Artinskian to Kungurian time period ranged from the Chloroforam to the Bryonoderm facies associations. The presence of the Chloroforam Association, including calcareous green algae, suggests that the sea floor was within the photic zone. The continual occupation of the shelf by a stenohaline biotic assemblage attests to unrestricted circulation. The majority of the shelf was above or very close to the fair-weather wavebase. The abundance of abraded grainstones and packstone in shelf areas, indicates that energy levels were moderate to high on the shelf, agitating the bioclasts and winnowing away fines. Upwelling of cool waters onto the outer shelf apparently occurred in the early part of the Artinskian to Kungurian Sequence, altering biotic associations on the shelf and resulting locally in the coexistence of the cool-water Bryonoderm Grainstone Facies with the warm-water Chloroforam Grainstone and Wackestone to Packstone Facies (*e.g.* Otto Fiord Embayment). In regions of upwelling, the Bryonoderm Association (B1) became established (sections 2, 10, 14) on the outer shelf where cool and nutrient-rich waters from the deep invaded the warmer waters of the shelf. The influx of nutrient-rich, cool waters to the shelf would have inhibited the development (Hallock and Schlager, 1986) of the typically warm-water Chloroforam Association by: i) substantially decreasing the temperature (<20°C), and/or ii) increasing the nutrient availability, thereby inhibiting the growth of the Chloroforam Association by decreasing clarity and the photic zone. As a result, the facies existed as 'haloes' around regions of upwelling. At distances farther from the upwelling is gained, the facies associations became more diverse as warmer temperatures prevailed and nutrient levels decreased. For example the Bryonoderm Grainstone Facies (B1) in an area of upwelling would grade laterally into the Bryonoderm-Extended Grainstone Facies (BE1), and in turn into the more diverse Chloroforam Grainstone Facies (C1) farther away from the upwelling (Figure 8). The presence or absence of the Chloroforam Association (C1/C2) at mid-shelf locations, early in the sequence, would have been a result of upwelling of cooler, nutrient-rich waters along the Nansen shelf edge at this time altering the faunal associations. A modern analog illustrating the response of biota to upwelling is provided by the Otway continental margin of southeastern Australia. Boreen et al. (1993) documented nutrient-rich, upwelling currents along the Australian shelf margin that support the 'prolific growth of deep-water organisms dominated by bryozoan, sponges and azooxanthellate corals'. In addition, in regions of upwelling primary warm-water carbonate-sediment producers (zooxanthellate corals and calcareous algae) are unable to survive as they only flourish in nutrient-deficient waters. Any increase in available nutrients due to upwelling i) inhibits the growth of the chlorozoan carbonate factory by reducing water clarity and depth of the photic zone, and ii) stimulates the growth of competitive aphotic organisms, displacing hermatypic algae and corals (Hallock and Schlager, 1986).

Complicating the spatial distribution of facies, block faulting of the shelf early in the sequence, resulted in regions of the sea-floor dropping below the fair-weather wavebase. Therefore, in addition to the abundance of grainstones on the shelf, deeper locations of the shelf were dominated by packstones and wackestones. In regions of block faulting (section 15), the Chloroforam Wackestone to Packstone (C2) or the Bryonoderm-Extended Wackestone to Packstone (BE2) facies prevailed in the tectonic lows, below fair-weather wave base where energy levels were substantially less (Jones and Desrochers, 1992), while Chloroforam Grainstone (C1) or Bryonoderm-Extended Grainstone (BE1) facies dominated the highs where energy levels were greater. Anomalously thick successions of shelf strata dominated by packstones and wackestones (section 15) corroborate this.

The underlying Nansen shelf and slope acted as a template partially controlling the spatial facies distribution of the sediment deposited early in the Artinskian to Kungurian Sequence. The underlying Nansen Shelf was highly sinuous (Beauchamp et al., 1995) and the sedimentation of the early Artinskian to Kungurian Sequence mimicked the geographical positioning of the Nansen shelf. That is, the Raanes shelf very closely matches the paleogeography of the Nansen Formation. However, by the end of the Artinskian the shelf of the Great Bear Cape Formation extended far beyond the progradational extent of the Nansen Formation.

*Shelf Margin*

The shelf margin lay in an open marine setting, below fair-weather wave base, in moderate to low energy conditions extending below the photic zone. Carbonate sediment production was restricted to the Bryonoderm Association or a combination of the Bryonoderm-Hyalosponge associations throughout the Artinskian to Kungurian Sequence. Fine-grained siliciclastic material and micrite combined with bioclastic elements (mainly bryozoan, echinoderm and sponge spicule) dominated this setting with the addition of bryozoan-*Tubiphytes* skeletal mudmounds present at the shelf margin during the TST. These mounds grew as accommodation space was provided.

The second control on spatial facies distribution on the shelf margin was the oceanographic conditions, including water depth, restriction, photic levels, temperature, agitation and upwelling. The facies occupying the shelf margin throughout the Artinskian to Kungurian Sequence ranged from the Bryonoderm to the Hyalosponge associations. The presence of these associations suggests that the shelf margin extended below the photic zone and that cool-water temperatures existed on the sea-floor at the shelf margin. The shelf margin lay below fair-weather wavebase, and as a result, facies (B2, B3, H) are dominated by fine materials. The only buildups present at the margin were sparsely occurring relatively small skeletal mounds of bryozoans and *Tubiphytes*. The bryozoa behaved as baffling and trapping instruments, collecting lime mud and bioclastic debris. The mounds were the only buildups present on the outer shelf and at the shelf margin and were relatively small and discontinuous. With few buildups at the shelf margin, the shelf took on an open-shelf morphology (Jones and Desrochers, 1992), with the shelf margin characterized mainly by a change in the angle of slope. Therefore the shelf was subjected to unimpeded wave energies and unrestricted circulation. Upwelling of cool waters onto the outer shelf occurred in the early part of the Artinskian to Kungurian Sequence altering biotic associations on the shelf and maintaining cool-, to cold-water assemblages (facies B2, B3, H) at the shelf margin and on the upper slope.

The third factor controlling the distribution of facies at the shelf margin was the underlying Nansen shelf edge. The underlying Nansen Shelf edge was highly sinuous, with a massive reef tract that included a number of deeper-water embayments with a more gradational shelf-to-basin transition (Beauchamp et al., 1995). As mentioned above it appears as though the early shelf edge of the Artinskian to Kungurian Sequence mimicked the geographical positioning of the Nansen shelf edge (Chapter 4). However, by the end of the Artinskian the shelf edge had prograded into the basin 10 km to 30 km beyond the Nansen shelf edge. The Otto Fiord Embayment, present in the Nansen shelf edge and still present in the Raanes shelf edge was later infilled by the progradation of the Great Bear Cape Formation (section 5) at the end of the Artinskian.

*Slope/Basin*

Sedimentation in the slope/basin environment was largely dominated by gravity flow sediments interrupting the ambient basinal sedimentation. During the early portion of the Artinskian to Kungurian Sequence, slope/basin sedimentation was dominated by biogenic siliceous material on the upper slope and fine grained siliciclastic material interrupted by debris flows (DT facies) on the lower slope and basin. In the late Artinskian, sedimentation was largely controlled by sponges (Hyalosponge Mudrock) providing abundant spicules to the slope and basin within turbidites and debris flows. The lower slope and basinal sedimentation was dominated by fine materials (Spiculitic/Siliceous Shale Facies) settling out of suspension, punctuated by frequent spiculitic turbidites originating from the upper slope. As a result, the slope/basin setting is dominated by calcareous shale / shaly limestone and spiculitic chert

The slope/basin environment was well below the photic zone and cool temperatures prevailed on the upper slope, resulting in the occurrence of the Bryonoderm Association (Facies B2) in this region. The cool temperatures were the result of greater water depth in addition to upwelling along the slope during the late Sakmarian to early Artinskian. By the end of the Artinskian the temperatures were relatively cold and the upper slope was dominated by bryozoans and sponges producing the Bryonoderm Spiculite Facies (a combination of the Bryonoderm and Hyalosponge associations). In the lower slope-to-basin setting the conditions were dysaerobic and cold inhibiting the growth of all biota except sponges and producers of the *Nereites* Ichnofacies (Hyalosponge Association).

A slope setting is indicated by the presence of slump-related features, carbonate debris flows with sharp erosional bases, and incomplete turbidites exhibiting graded bedding. The slope setting onto which sediments of the Artinskian to Kungurian Sequence were deposited was relatively steep, resulting from the massive phylloid algal buildups rimming the edge of the Nansen shelf. This is evidenced by clinoforms averaging 20° to 40°, representing the Nansen-Hare Fiord transition (Beauchamp et al., 1995). As a result, slope sedimentation of the Artinskian to Kungurian Sequence was influenced by this early gradient resulting in numerous turbidites and debris flows throughout this time period. This slope gradient, was considerably less by the end of the Artinskian to Kungurian Sequence, a result of prolific sedimentation on the slope and lowered sedimentation rates on the shelf (further discussed in the *Sediment Production/Accumulation* section of this chapter).

### *3.3.2 Temporal Facies Distribution*

Temporal facies distribution addresses the response of facies to: i) climatic deterioration, ii) sediment productivity, iii) local oceanographic conditions, and iv) changes in shelfal accommodation governed by changes in sea-level and styles of tectonic subsidence, through time. The following section discusses the temporal facies distribution on the shelf and slope and how facies change in response to the above-mentioned variables throughout the Artinskian to Kungurian Sequence.

<u>*Climatic Deterioration*</u>

During the Artinskian to Kungurian, climatic deterioration in the Sverdrup Basin altered the existence and distribution of biotic associations on the shelf, as evidenced by the biota present in the shallow-water shelf grainstones. In the early portion of the sequence the shallow-water shelf grainstones are dominated by the Chloroforam Facies Association, indicating a tropical climate (Beauchamp, 1994). At the end of the sequence, however, the Bryonoderm Facies Association dominated, indicating that the climate had considerably cooled (Beauchamp, 1994). The following section describes the facies changes from the ETST, ETST to LTST, and LTST to RST of the Artinskian to Kungurian Sequence of the northeastern shore of the Sverdrup Basin, as a result of changing climate. To eliminate the possibility that temperature changes were related to increasing depth, thereby altering the facies associations, only the shallowest water shelf grainstones were examined (Figures 8, 9, 10).

The ETST (upper Nansen Formation) is dominated by the tropical Chloroforam Association (sections 4, 7; Appendix 2). The shelf of the ETST was dominated by the Chloroforam Grainstone (C1), above fair-weather wave base, and by the Chloroforam Wackestone to Packstone (C2) facies below fair-weather wave base, indicating that the ambient climate was tropical (Beauchamp, 1994).

A change of facies in the shallow-water shelf grainstones occurred across the ETST/LTST surface implying that the climate had cooled. Evidence of the climatic deterioration is found by comparing the shallow-water grainstones below and above this surface. The ETST Chloroforam Association is succeeded by the Bryonoderm-Extended Grainstone in the LTST where crinoids, bryozoans, infrequent *Tubiphytes* and fusulinids existed for the majority of the LTST in the inner to mid-shelf environment. The absence of the diverse Chloroforam Facies Association on the mid-shelf and the presence of the less diverse Bryonoderm-Extended Facies Association indicate that the climate had become temperate throughout the LTST (sections 4, 5, 6, 7, 11, 13; Appendix 2).

The less diverse Bryonoderm Assemblage dominated late in the RST, replacing the Bryonoderm-Extended Association that dominated the shallow waters of the LTST and early RST on the shelf. This is evidence that climatic cooling continued throughout the RST.

*Sediment Productivity/Accumulation*

This section addresses the sediment productivity of, and accumulation from, the biogenic carbonate and silica factories forming the open shelf, slope and basin during deposition of the Artinskian to Kungurian Sequence. The shelf was initially dominated very briefly by the warm-water carbonate factory and subsequently mainly by the cool-water carbonate factory during deposition of the mid- and latter parts of the sequence. The slope/basin environment was largely dominated by the silica factory throughout, although more so during the RST. Precise production rates for the shelf carbonate factory and the slope/basin silica factory are difficult to establish, however, accumulation rates can be estimated when averaged over the scale of the sequence.

Nelson (1978) estimated that the rate of accretion for cool-water carbonates is approximately 5 cm $kyr^{-1}$ in contrast to some warm-water carbonates within the photic zone which accrete at 100 cm $kyr^{-1}$ (Schlager, 1981). Cool-water carbonate shelf sedimentation rates for the Artinskian to Kungurian Sequence are estimated to have been less than half of the accretion rate for modern cool-water carbonates. This estimation is based on: i) the average thickness of the Great Bear Cape Formation across the shelf between the MFS and the USB, representing the average thickness of the RST on the shelf (85 m); and ii) the average thickness of the Nansen, Raanes and Great Bear Cape formations within the USB and LSB, representing the average thickness of the whole Artinskian to Kungurian Sequence on the shelf (200m). Both of these values, 85 m for the RST and 200 m for the whole sequence, were then divided by various sedimentation rates to obtain the corresponding lengths of time required to deposit 85 m and 200 m of sediment on the shelf assuming continuous deposition. The results are outlined in the table below:

| Sedimentation Rate (cm $kyr^{-1}$) | Time Interval Required (Ma) for Entire Sequence (200 m) | Time Interval Required (Ma) for RST (85 m) |
|---|---|---|
| 1 | 20 | 8.5 |
| **2** | **10** | **4.25** |
| 3 | 6.7 | 2.8 |
| 4 | 5 | 2.1 |
| 5 | 4 | 1.7 |

According to the geologic time scale (Harland et al., 1990), the Artinskian Stage spanned approximately 9 Ma. Conodont assemblages collected in the study area, P5 through P8 inclusive, indicate that the Artinskian to Kungurian Sequence spans roughly the same period of time. In addition, the RST represented by conodont assemblages P6 through to P8 inclusive, indicate that deposition of the regressive systems tract spanned roughly 5 million years. Based on this, the sedimentation rate on the shelf for both the whole Artinskian to Kungurian Sequence and the RST is estimated to be at least 2 cm $kyr^{-1}$. It must be noted that this rate is a minimum value as strata have been removed by erosion at the sequence boundaries and in some instances within the systems tracts. Additionally, embayments such as the Otto Fiord embayment were sinks for sediment deposition especially during the RST, indicating that the average estimated sedimentation rate was higher locally. Other factors to consider in estimating sedimentation rates include i) compaction, ii) time intervals of non-deposition, and iii) resedimentation. Considerable thicknesses of strata are potentially lost through compaction while intervals of non-deposition or resedimentation common to open shelves represent periods of unrecorded time. When considering these factors, in addition to the estimated sedimentation rate of 2 cm $kyr^{-1}$, the sedimentation rate of the Artinskian to Kungurian Sequence would approximate the sedimentation rate of modern cool-water shelves.

However, regardless of the above-estimated sedimentation rate, the production rate of sediment on the shelf during Great Bear Cape time was high enough to cause progradation of the bioclastic sediments toward the outer shelf and also into offshore areas, as is evidenced by the complete filling of the Otto Fiord Embayment.

In the slope-to-basin environment, sediment production and accumulation rates from the silica factory greatly exceeded the cool-water carbonate sediment production and accumulation rates on the shelf. This is evident in the thicknesses of the slope-to-basin sections containing up to 800 m of siliceous shale and spiculitic chert. This supports the point made by Wright (1986) that sediment accumulation rates below storm wave base are much higher than on the shelf, a consequence of relative sea-level fluctuations decreasing shelfal accommodation space, lowering wave base and eroding sediment. In contrast, sea-level fluctuations do not affect the deeper water environments, therefore resulting in greater rates of accumulation and thicker deeper-water successions. Overall, this style of sedimentation dominated during accumulation of the latter part of the Artinskian to Kungurian Sequence and resulted in extensive progradation of the Great Bear Cape shelf and slope, 10 km to 30 km into the basin (see Chapter 4).

This style of sedimentation resulting in open-shelf progradation can be contrasted to the sedimentation style of rimmed shelves where rapid sediment accretion within the shallow water areas results in the steepening of the shelf edge (Wright and Faulkner, 1990). Perhaps it was this style of sediment accumulation that occurred in the upper Nansen Formation of the previous sequence, resulting in a less extensive progradation of the shelf edge than that of the Great Bear Cape shelf edge.

*Local Oceanographic Conditions*

Superimposed on the long-term, sequence-scale migration of facies belts due to climatic deterioration, shown by the lithologic change from the Nansen Formation to the Great Bear Cape Formation, a shorter-term facies migration is locally evident through the Raanes and Great Bear Cape Formations. This is similar in scale to metre- to decametre-scale cyclicity, resulting from high-order relative sea-level fluctuations. However, the short-term facies migration discussed here was not a result of relative sea-level changes, since the depositional textures remain the same. Only the biota changed and this is thought to have been due to shorter term oceanographic processes. For example, the following facies changes are noted locally within the Raanes and Great Bear Cape Formations (sections 4, 5, 7; Appendix 2): i) Bryonoderm-Extended Wackestone to Packstone, a temperate-warm water assemblage is succeeded by the Chloroforam Wackestone to Packstone, a warm-water assemblage; ii) the Bryonoderm-Extended Grainstone, a temperate-warm assemblage, is succeeded by the Bryonoderm Grainstone, a temperate-cool assemblage; and iii) the Bryonoderm Packstone, a temperate-cool assemblage is succeeded by the Bryonoderm-Extended Packstone, a temperate-warm assemblage. In each example, only the biotic elements change, while the depositional textures remain the same, indicating that relative changes in sea-level were not the cause. Such changes in facies, throughout the Artinskian to Kungurian time period, may reflect periodic fluctuations in i) light penetration and ii) temperature that could have locally altered the distributions of facies, as discussed below. Other factors affecting carbonate production, including oxygen stratification, circulation, and salinity fluctuations, are not considered here as it is expected that they would affect a broader area of the shelf, whereas, such facies changes observed in this study are only local occurrences.

The presence or absence of key biotic elements of the Chloroforam Association was dependent on light penetrating to the sea-floor. If enough light became available at the sea-floor this association may have replaced other associations. Conversely, reduction in light penetration, associated with a reduction in water clarity, would have had the opposite effect with light-independent associations succeeding associations that are light-dependent.

Changes in temperatures at the sea-floor, caused by the initiation or cessation of upwelling currents and/or temperature stratification, may have allowed warm-water associations to be replaced by temperate-warm or temperate-cool associations and vice versa, without changing depositional textures.

An analog, supporting these observations, is provided from research on the Abrakurrie Limestone of southern Australia. James and Bone (1991) stated that cool-water and warm-water carbonates do not exist in isolation. These two provinces may i) coexist as laterally adjacent facies on the shelf, and/or ii) vertically change from warm-water to cool-water biota and vice versa, resulting from subtle variations in ocean water temperature brought about by laterally shifting water masses of different temperature or upwelling of cooler waters onto the shelf (James and Bone, 1991).

*Shelf Accommodation Space*

Major changes in shelf accommodation space occurred through the Artinskian to Kungurian Sequence, as indicated by the changing depositional style of sediments on the shelf. During deposition of the early portion of the TST, an overall increase in shelf accommodation space occurred while during RST deposition, in the later portion of the sequence, shelf accommodation space decreased. Such variation in accommodation space is evidenced by the i) facies successions, ii) stacking patterns of decametre-scale cycles and iii) internal cycle facies organization (cyclicity is further discussed at the end of this chapter). A relative sea-level model for the deposition of the Artinskian to Kungurian Sequence is provided in Figure 11.

During deposition of the TST there was a marked increase in accommodation space on the shelf. The most obvious and immediate evidence of this is the fact that the clean, light gray resistant carbonate of the Nansen Formation (ETST), dominated by packstones and grainstones, is succeeded by the greenish-gray, argillaceous, and silty carbonate of the Raanes Formation (LTST), dominated by wackestones to packstones.

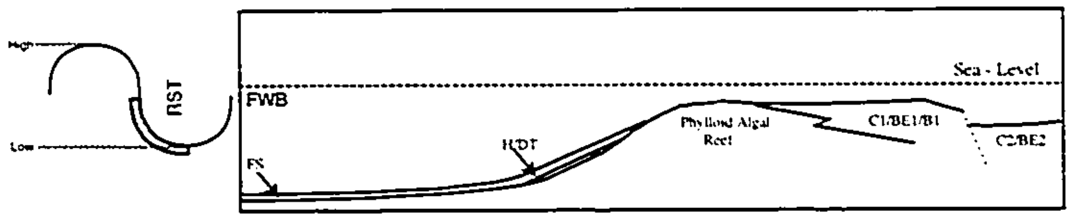
Further evidence of increased shelf accommodation space includes the stacking patterns of the cycles. Within the TST, at least four decametre-scale subtidal cycles developed in the shelf environment. Of these cycles, in the early portion of the TST, the average cycle is 10 m thick and consists of medium- to thickly-bedded wackestones to grainstones.

**Figure 11** Relative sea-level model for deposition on the Artinskian to Kungurian shelf. The model indicates relative sea-level position during: Time1 ) the RST of the previous sequence (Sakmarian); Time 2a,b) the ETST, LTST of the Artinskian to Kungurian Sequence; and Time 3) the RST of the Artinskian to Kungurian Sequence. The model illustrates the deposition of the facies through time in response to relative sea-level fluctuation.

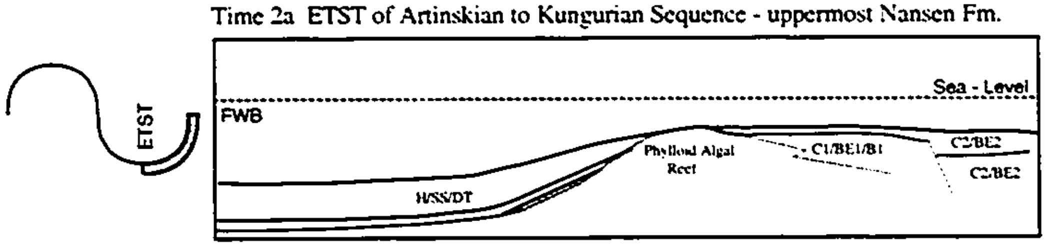
# Relative Sea-Level model for deposition on the Artinskian to Kungurian shelf

Relative Sea-Level

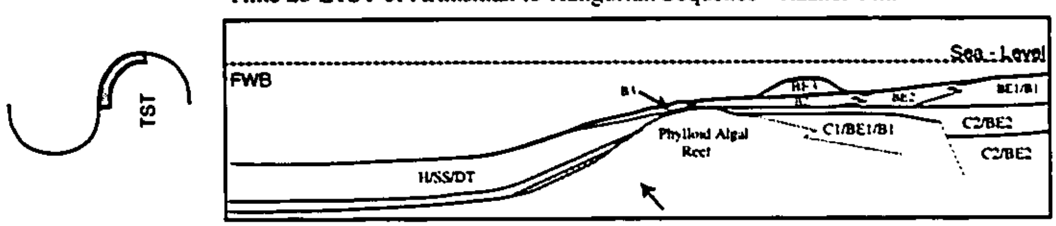
Time 1 Late RST of the preceding sequence (Sakmarian) - Nansen Fm.



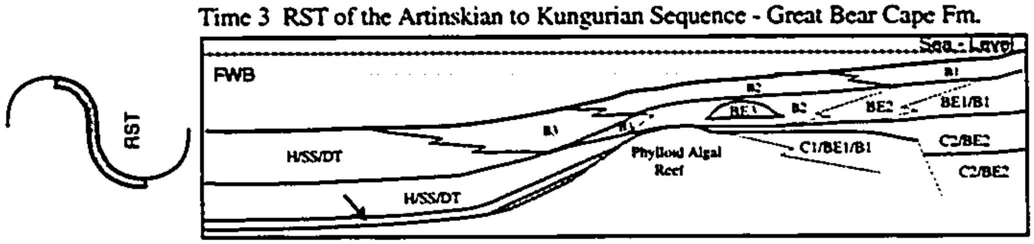

Time 2a ETST of Artinskian to Kungurian Sequence - uppermost Nansen Fm.




Time 2b LTST of Artinskian to Kungurian Sequence - Raanes Fm.




Time 3 RST of the Artinskian to Kungurian Sequence - Great Bear Cape Fm.



Upsection the individual cycles reach thicknesses of 45 m and the individual cycles shoal from very thinly- to medium-bedded wackestone to packstone (Figure 12).

Within each cycle, the internal facies organization also documents the increasing accommodation space from the base to the top of the TST. In the shelf environment early in the LTST, the intracycle facies range from the Bryonoderm Spiculite at the base of the cycle to the Bryonoderm Wackestone to Packstone in the middle portion to the Bryonoderm-Extended Grainstone or the Chloroforam Grainstone capping the subtidal cycle. Higher in the section, and more commonly, the cycles lack the Bryonoderm Spiculite Facies at the base and commence with the Bryonoderm Wackestone to Packstone (sections 4 and 13; Appendix 2). Higher in the vertical section and still within the LTST, the shallow water grainstones of the Chloroforam Association (C1) and the Bryonoderm-Extended Association (BE1) disappear entirely and the subtidal cycles are dominated by the Bryonoderm Wackestone to Packstone. Each cycle is now defined by the change from wackestone at the base to packstone capping the cycle (section 5, 7, 13; Appendix 2). This type of cyclicity is ubiquitous across the shelf and dominates the late portion of the LTST and the early portion of the RST (sections 4, 7, 5, 11, 13; Appendix 2).

In block faulted regions (section 7) the intracycle facies changes differ from those on other regions of the shelf, in that the subtidal cycles shoal from the Bryonoderm Wackestone to the Bryonoderm-Extended Packstone and/or the Chloroforam Packstone and not to grainstones (sections 4, 13; Appendix 2).

During the RST there was a significant decrease in accommodation space across the shelf. Evidence of this includes the continual shoaling within the Great Bear Cape Formation from a variably cherty slightly argillaceous carbonate dominated by packstones at the base of the RST to a highly fossiliferous limestone dominated by grainstones toward the end of the RST.

Further evidence of decreased shelf accommodation space includes the stacking patterns of the subtidal decametre-scale cycles. Within the RST, subtidal cycles exist but are very difficult to distinguish in the shelf environment near the top of the RST. Due to limited accommodation space, the cycles are dominantly grainstones with minor packstone components near the base of each cycle. Most cycles are amalgamated, as the packstone portion of the cycle is very thin or absent (Figure 13).

Within each cycle, the internal facies organization records the decreasing accommodation space from the base of the RST to the top, a result of falling relative sea-level. In the shelf environment early in the RST, the intracycle facies range from the Bryonoderm Packstone at the base of the cycle to the Bryonoderm Grainstone capping the

Figure 12 Typical subtidal carbonate cycles within the TST of the Artinskian to Kungurian Sequence from selected sections in the Otto Fiord Area. Various locations across the platform are shown including: A. block-faulted and subsiding region on the mid-shelf; B. outer shelf; C. embayment in the shelf edge; and D. basin. Note the differences in cycle thickness between the various locations. Arrows denote shallowing-upward facies successions within the individual cycles. Refer to Appendix 2 for symbol legend.

# Short -Term Cyclicity of the TST

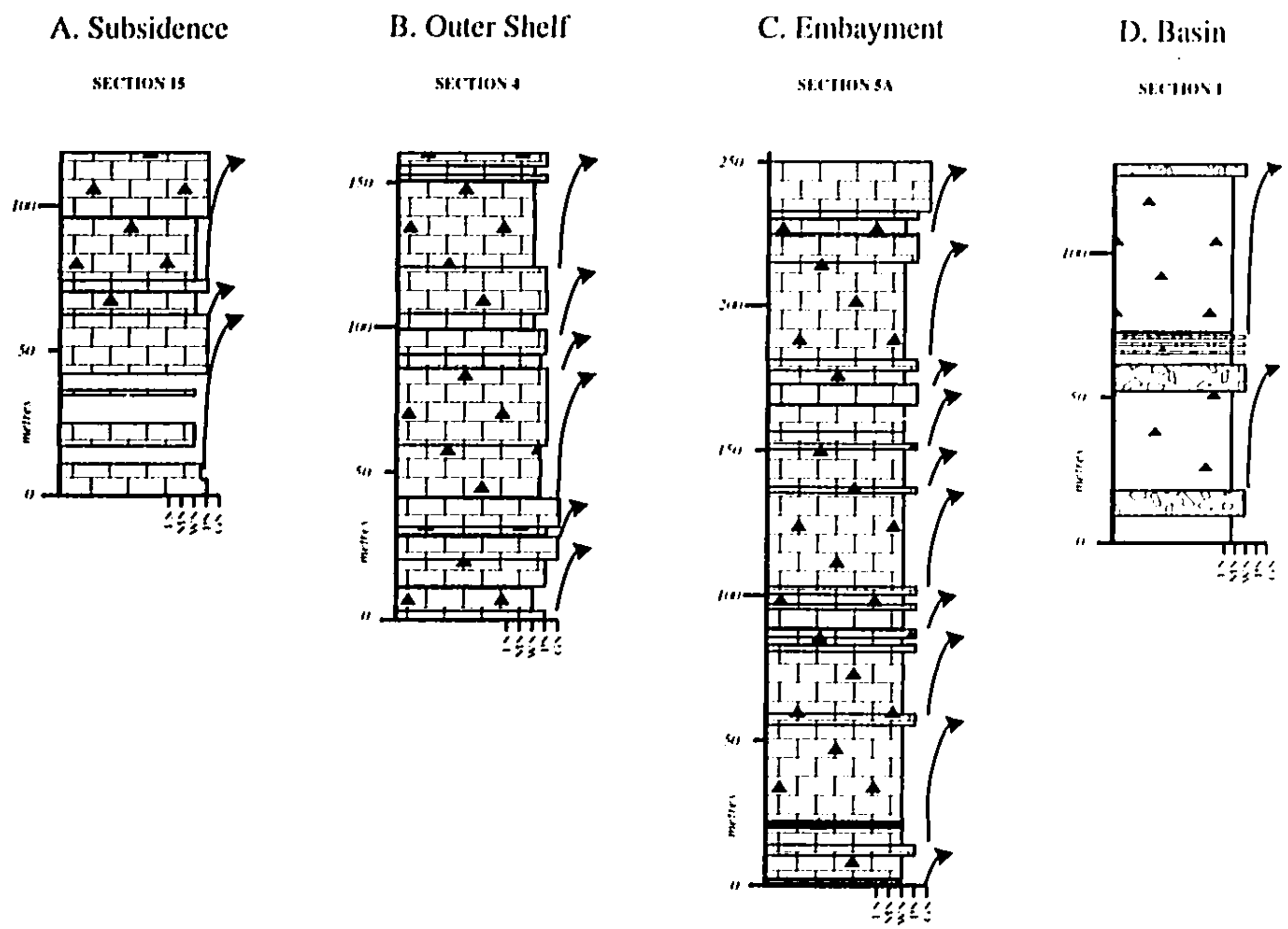
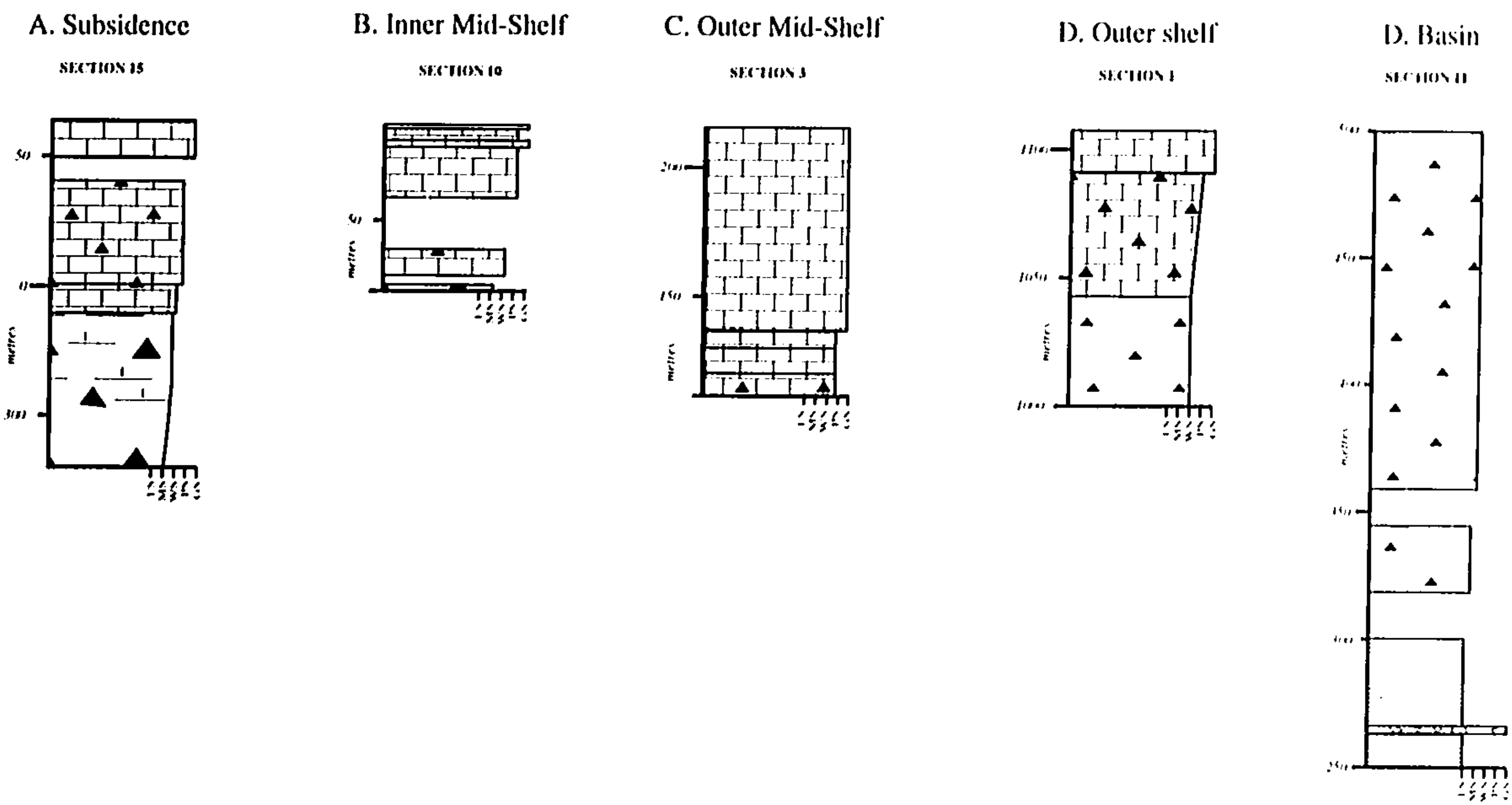


Figure 13 Typical subtidal carbonate cycles within the RST of the Artinskian to Kungurian Sequence from selected sections in the Otto Fiord area. Various locations across the platform are shown including: A. block-faulted and subsiding region on the mid-shelf; B. inner mid-shelf; C. outer mid-shelf; D. outer shelf; and E. basin. Decametre-scale cyclicity is not obvious as the cycles are amalgamated. However, an overall upward shoaling is apparent. Refer to Appendix 2 for symbol legend.

# Short -Term Cyclicity of the RST



subtidal cycle. Higher in the section, the majority of the cycles are dominated by the Bryonoderm Grainstone, some with a basal packstone.

*Mechanism*

Beauchamp (1993) suggested that the long term fluctuation in accommodation space was largely tectonically driven. His model suggests that 80 Ma of intermittent rifting occurred from the Tournaisian until the late Artinskian, at which time a regime of passive subsidence ensued. The Artinskian to Kungurian Sequence has been attributed to one of these rifting pulses that was active from the Serpukhovian to the Artinskian, creating long-term (5-10 Ma) fluctuations in relative sea-level (Beauchamp et. al., 1989a).

*Cyclicity*

In the Otto Fiord area, superimposed on the long-term T-R sequence, are decametre-scale subtidal cycles (Figures 12, 13). The subtidal cycles, shoaling to below intertidal levels as defined by Osleger (1991), represent mid- to outer shelf, subtidal environments that were present across the majority of the shelf. The cyclicity is irregular, ranging from metre to decametre scales, and not correlatable across the study area due to amalgamation or removal of the cycles by erosion in some areas. These subtidal cycles within the Artinskian to Kungurian Sequence are present in other areas of the Sverdrup Basin and are interpreted as the results of fourth and fifth order sea-level fluctuations (500 000 to 1 000 000 years) of possibly glacio-eustatic origin (Beauchamp et al., 1989a).

Osleger (1991) summarized three mechanisms by which subtidal carbonate cycles may form, including: 1) variations in sediment redistribution, ii) episodic tectonism, and iii) eustatic oscillations of sea-level. Osleger (1991) favoured eustatic oscillations in sea-level as the main mechanism for subtidal cycle formation and explained that sea-level fluctuation due to tectonism is too slow to produce shorter term cyclicity, and sediment redistribution does not account for the ability to correlate cycles between widely spaced outcrops. However, it is believed by the author that all three mechanisms are responsible to some degree for the occurrence of subtidal carbonate cycles present in the Artinskian to Kungurian Sequence in the Otto Fiord area.

Sea-level fluctuations due to oscillations in sea-level were most likely the dominant control creating the subtidal carbonate cycles that are observed all across the Artinskian to Kungurian platform in the Otto Fiord area. The observed distribution of cycles across the platform ubiquitously required a control that would have affected the entire platform simultaneously. The simplest explanation would be eustatic oscillation of sea-level, likely due to remnants of a world-wide glaciation during late Paleozoic time (Eyles and Eyles, 1992).

Osleger (1991) stated that oscillations in relative sea-level due to tectonics are too slow to produce high-frequency carbonate cycles. Tectonism, however, is considered a possible mechanism for the formation of subtidal carbonate cycles within the Artinskian to Kungurian Sequence now exposed in the Otto Fiord area. During this time, the basin was exposed to phases of tectonism (B. Beauchamp, pers. comm.) and it is quite conceivable that each of these phases proceeded in an intermittent and irregular fashion, causing short term fluctuations in relative sea-level that overprinted the eustatic signature.

Variations in sediment redistribution as a mechanism for the formation of subtidal carbonate cycles was dismissed by Osleger as a minor variable in the formation of subtidal cycles, as it does not explain the persistent lateral and vertical rhythmicity of subtidal carbonates. According to Osleger, the subtidal cycles could be 'correlated in outcrops more than 45 km apart', and stacked subtidal cycles 'show virtually the same repetition of lithofacies in 16 shallow subtidal and 34 deep subtidal successive cycles'(Osleger, 1991). However, the subtidal carbonate cycles of the Artinskian to Kungurian Sequence in the Otto Fiord area cannot be correlated, as the number of vertically stacked subtidal cycles and lithofacies composing each cycle differs from section to section. The fact that the subtidal cycles cannot be correlated between sections, and that the lithofacies comprising each cycle change frequently upsection, suggests that the loci of carbonate sedimentation on the Artinskian to Kungurian Shelf were consistently shifting, playing a major role in the formation of subtidal cycles. As a result, lateral and offshore sediment redistribution as a possible mechanism creating subtidal cycles cannot be ruled out. However, amalgamation of cycles may be responsible for the variations in the number of vertically stacked cycles recognized from section to section. This needs further research.

It is concluded that the higher-order carbonate cycles present in the Artinskian to Kungurian Sequence in the Otto Fiord area were predominantly due to eustatic oscillations in sea-level. However, eustatic sea-level oscillation was possibly overprinted by relative sea-level fluctuation due to tectonism occurring in the Sverdrup Basin region at this time. In addition, variations in sediment redistribution cannot be ruled out as a local control on subtidal carbonate cycle formation in the Artinskian to Kungurian Sequence of the Otto Fiord area.

# CHAPTER 4: DISCUSSION

This chapter discusses the paleogeography and paleoclimatology of the Artinskian to Kungurian Sequence, addressing it in three parts: the late Sakmarian, early Artinskian and late Artinskian. It discusses the relative positions of, and changes of biotic associations within the Nansen, Raanes and Great Bear Cape formations throughout the sequence. The second part of the chapter reviews selected studies on cool-water carbonate shelves from the Ordovician, Tertiary and the Holocene and briefly compares aspects such as shelf morphology, biota, and sediment production with the Permian cool-water carbonate shelf in the Otto Fiord area.

## 4.1 Paleogeography/Paleoclimatology

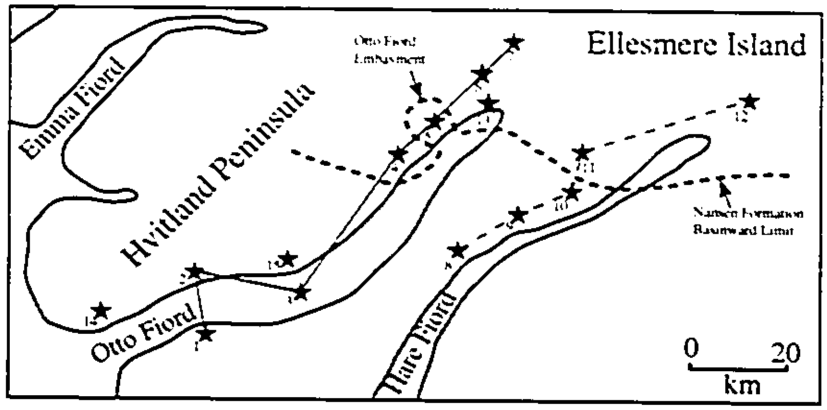
### *4.1.1 Late Sakmarian*

The paleogeography interpreted for the late Sakmarian is defined by the progradational extent of the Nansen Shelf in the Otto Fiord area. The Nansen Shelf prograded no more than approximately 15 km southward from the heads of the present day Otto and Hare fiords (Figure 14 A). The Nansen Shelf Edge was formed by a meandering, incomplete reef tract that was interrupted by embayments. One such embayment, the Otto Fiord Embayment (Figure 14 A; Beauchamp et al., 1995), existed within the study area. This embayment contains an anomalously thick succession of Hare Fiord mudrock, grading directly into the overlying Raanes Formation, without indication of Nansen shelf deposits (section 5; Appendix 2). These deep water embayments were most likely the vestiges of rift-related block faulting from the Carboniferous (Beauchamp et al., 1995). It is postulated in this study that these embayments were the foci for upwelling waters from deeper water environments onto the late Sakmarian Nansen Shelf, thus altering shelf biotic associations (Chapter 3).

The late Sakmarian time interval represents the earliest transgressional phase of the Artinskian to Kungurian Sequence. During this time spiculitic mudrock, represented by the Hare Fiord Formation, was infilling the accommodation space newly created in the basin, onlapping the correlative conformity representing the sequence boundary. At the same time, the Nansen shelf was exposed, as is indicated by the subaerial unconformity at the sequence boundary; it was later progressively flooded yet remained within the photic zone toward the end of the ETST. Carbonate production was reintroduced on the Nansen shelf and deposits onlapped the unconformity (Figures 4 and 5).

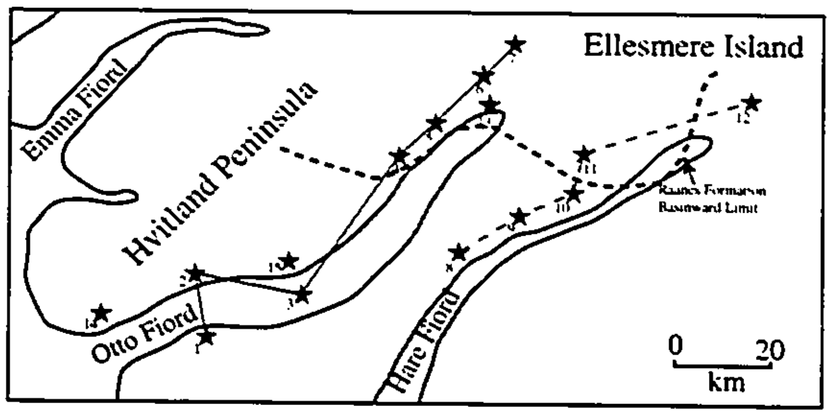
Figure 14 Paleogeography map of the Otto Fiord area showing the relative extent of the Nansen, Raanes and Great Bear Cape shelves in late Sakmarian, early Artinskian and late Artinskian times.

A.



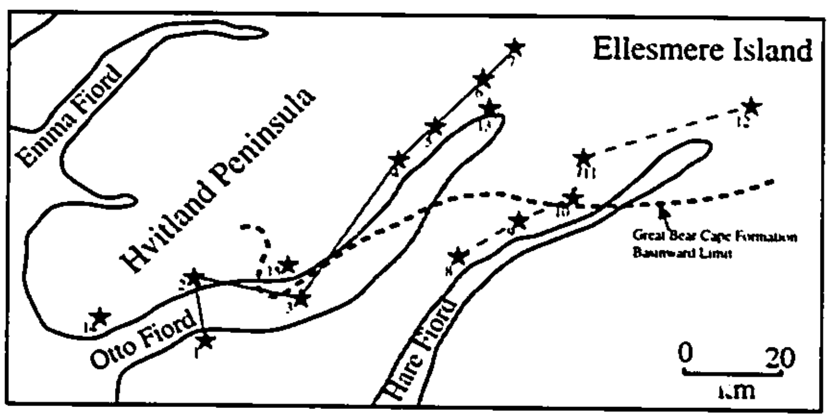

Nansen Shelf Edge

B.




Raanes Shelf Edge

C.




Great Bear Cape Shelf Edge

★ measured sections
——— northern cross-section
- - - - southern cross-section

During the late Sakmarian, not only had sea-level begun to rise to form the ETST, presently exposed in the Nansen and Hare Fiord formations in the Otto Fiord area, but also at that time a warm-water carbonate factory, represented by the limestone of the Nansen Formation, dominated the shelf, indicated by the tropical Chloroforam Association. A cool-water carbonate factory existed on the upper slope while in deeper waters a cold water silica factory was present (Figure 15) but carbonate and siliciclastic mud still dominated basinal sedimentation resulting in variably cherty mudstone of the Hare Fiord Formation, presently outcropping in the Otto Fiord area.

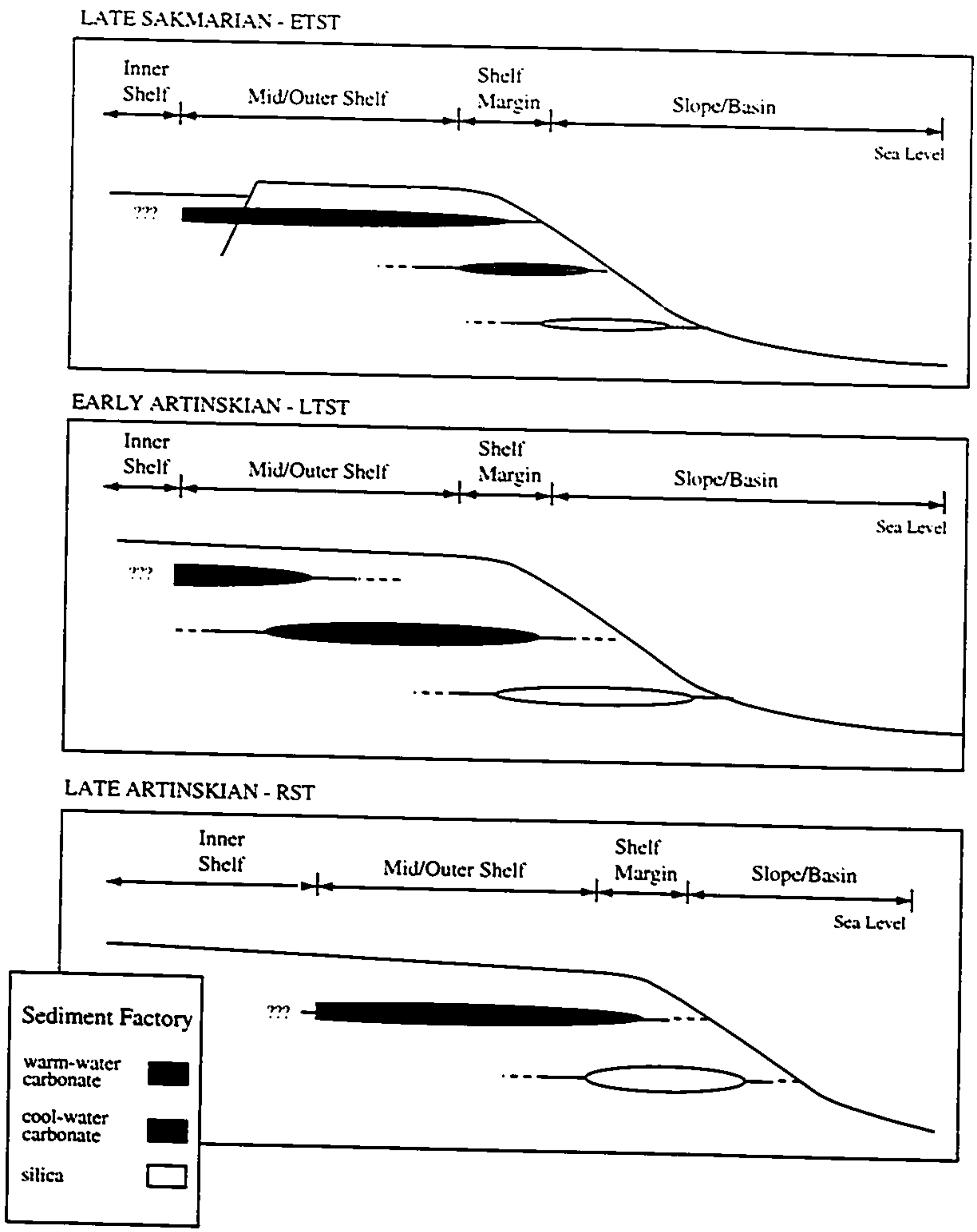
### *4.1.2 Early Artinskian*

Early Artinskian paleogeography is defined by the extent of the variably cherty, argillaceous and silty limestone of the Raanes Formation, formed during the LTST of the Artinskian to Kungurian Sequence. The paleogeographic level of the Raanes Formation was almost coincident with that of the underlying Nansen Formation shelf edge with the exception of the Otto Fiord embayment where the Raanes Formation is present and the Nansen Formation is not (Figure 14 B). The thickness of the Raanes Formation varies across the study area. The formation is mostly relatively thin, averaging 50 m (Sections 4, 5, 6, 11) although it thickens dramatically to 225 m in the northeastern quadrant of the study area, between sections 6 and 7 (Figure 4; section 7; Appendix 2). This thickening is attributed to syntectonic rift-related block faulting, evidence of which was previously recognized by Beauchamp and Henderson (1994) in southwestern Ellesmere Island. In addition to the block faulting, evidence of rapid subsidence is also present. The presence of numerous reef mounds as well as relatively deep-water spiculitic chert (Figure 4; section 7; Appendix 2) associated with the Trappers Cove Formation indicates that the area was subsiding, creating accommodation space for the 'keep-up' mounds (Chapter 3). The termination of mound growth and the presence of the spiculitic chert stratigraphically higher than the mounds, indicate that water depth had increased substantially and the mounds 'gave-up'.

The early Artinskian, late transgressional phase of the Artinskian to Kungurian Sequence, represents a significant flooding event in the Sverdrup Basin, indicated by a major facies shift shoreward (Figures 4, 5, 9, 11). During this time the Raanes Formation was infilling the accommodation space created on the shelf, onlapping the Nansen Formation. The flooding surface is represented by the Nansen-Raanes formational contact.

Figure 15 Diagram illustrating the the extent of sediment factories in shelf, shelf margin, and slope/basin settings in the late Sakmarian, early Artinskian and late Artinskian times. Note in the late Sakmarian, the warm-water factory dominated and by the end of the Artinskian, the cool-water factory dominated.

# The Sediment Factories



This time interval marks not only a significant flooding event for both the shelf and basin but also a significant climatic change. The previously shallow, warm-water carbonate factory of the late Sakmarian had been replaced by a dominantly cool-water carbonate factory represented by the argillaceous and silty limestone of the Raanes Formation presently outcropping in the Otto Fiord area. The tropical Chloroforam Facies Association of the late Sakmarian had been replaced by the temperate-warm Bryonoderm-Extended Facies Association dominating the shelf by the end of the early Artinskian. At the shelf margin and on the upper slope, the temperate-cool Bryonoderm Facies Association dominated. The lower slope and basin were largely starved at this time, just receiving fine particles from suspension, now constituting the papery black shales marking the Maximum Flooding Surface. The increased siliciclastic component of the Raanes Formation may indicate that i) carbonate sediment production was low at this time allowing the siliciclastic sediment to accumulate, and/or ii) the basin margin was tectonically uplifted during this period thereby increasing the supply of siliciclastic sediment to the basin.

*4.1.3 Late Artinskian*

The paleogeography of the cool-water carbonate shelf of the late Artinskian is defined by the basinward extent of the Great Bear Cape Formation. The Great Bear Cape Formation extends 10 km to 30 km beyond the paleogeographic limits of the underlying Nansen and Raanes shelves (Figure 14 C). The overall thickness of the Great Bear Cape Formation is consistent across the study area, averaging 200 m on the mid-shelf and becoming progressively thinner toward its progradational limits in the basin (Figures 4 and 5). However, the influence of the Otto Fiord Embayment is evident as the Great Bear Cape Formation at this location reaches thicknesses of 400m (Figure 4: section 5: Appendix 2). The greater thickness of Great Bear Cape Formation at this location is a result of the increased accommodation space due to the Otto Fiord Embayment.

The presence and the immense thickness of the Trappers Cove Formation (Figure 4: section 3: Appendix 2), the basinal equivalent to the Great Bear Cape Formation, indicates that the preceding transgression created substantial accommodation space, that was filled by the Trappers Cove Formation. The Great Bear Cape Formation interfingered with and prograded basinward over the Trappers Cove Formation (Figures 4 and 5).

The late Artinskian represents the regressive phase of the Artinskian to Kungurian Sequence. Apparently rifting had ceased in the area, by the time of the Maximum Flooding Surface, as the regressive Great Bear Cape Formation appears to have been deposited in a passively subsiding setting allowing simple basinward progradation of the cool-water shelf to occur. Progradation of the Great Bear Cape Formation was most likely the result of a combination of autocyclic and allocyclic controls, with high-order sea-level fluctuations decreasing accommodation space, and sediment being swept off the shelf between fair-weather and storm wave bases.

The late Artinskian marks not only a regressive phase of sea-level change but also a completely temperate climate influencing the shelf. A shallow, cool-water carbonate factory, represented by the highly fossiliferous, variably cherty and sandy Great Bear Cape Formation presently outcropping in the Otto Fiord area, dominated the shelf at this time. This temperate-cool Bryonoderm Facies Association completely replaced the temperate-warm Bryonoderm-Extended Facies Association that dominated the shelf during the early Artinskian. The shelf margin was also dominated by the cool-water carbonate factory while on the upper slope both the cool-water carbonate factory and the silica factory prevailed simultaneously. The lower slope and basin, at this time, were dominated by the silica factory (Figure 15), represented by the Hyalosponge Facies Association presently outcropping in the study area.

## 4.2 Comparison

The second part of the chapter will examine selected studies of other cool-water carbonate shelves from the Ordovician, Tertiary and Holocene. Various depositional aspects and facies distribution across the mid- to outer shelf, shelf edge and slope-to-basin environments, will be briefly compared with those of the Lower Permian cool-water carbonate shelf of the Sverdrup Basin presently outcropping in the Otto Fiord area.

### *4.2.1 Ordovician Deschambault cool-water carbonate shelf*

The late Ordovician, temperate-water, open carbonate shelf of southern Quebec (Lavoie, 1995) is described as gently sloping and having three major sedimentation belts delimited by fair-weather and storm wave bases. Lavoie (1995) identified, described and documented six lithofacies, each confined to one of the three belts on the Deschambault shelf.

Above fair-weather wave base, medium- to thickly-bedded grainstones to rudstones with bryozoans, brachiopods, molluscs, red algae, trilobites, *Vermiporella*, and abundant intraclasts were deposited as carbonate shoals in a high energy environment. Abundant discontinuous hardgrounds are also present.

Facies associations occurring between fair-weather and storm wave bases include i) mud mounds, and ii) storm deposits displaying hummocky cross stratification. The mudmounds consist of ramose bryozoan bafflestones that include minor brachiopods, molluscs, crinoids and void-filling peloids. The storm beds are subdivided into proximal and distal, grain- and mud-supported deposits, with limy shale interbeds containing the following biota: bryozoans (massive colonial and ramose) brachiopods, molluscs, crinoids, trilobites, *Vermiporella* and peloids in the proximal deposits and a similar biota with the addition of sponges and local chert nodules in the distal deposits. Below storm wave base, deep water environments were dominated by the deposition of carbonate mud and clay.

*4.2.2 Tertiary cool-water carbonate shelf*

Various mid-Tertiary limestones from the Otway, Murray, Gippsland and Bass basins of southeastern Australia have been described by Boreen and James (1995) as originating on cool-water shelves. It has been noted that all sediments on the shelves are bioclastic dominated by bryozoans, echinoderms, benthic foraminifers, brachiopods, and molluscs while deep muddy facies include ahermatypic corals, ostracods, sponge spicules, planktic foraminifers, and terrigenous clays.

Shallow shelf environments are characterized by massively bedded and trough cross-bedded grainstones including the following biota: bryozoans and echinoids with minor foraminifers, coralline algal fragments, brachiopods, bivalves, gastropods and quartz. Burrows are present in the form of *Scolicia* and minor *Thalassinoides*. Marine cemented hardgrounds or quartz granule lags are common capping cosets of bryozoan/echinoid grainstone (Boreen and James, 1995).

In mid- to deep shelf environments, between fair-weather wave base and storm wave base, cross-bedded and locally burrowed grainstone/packstone cycles occur that include the following biota: bryozoans, small serpulids, echinoids, foraminifers, coralline algae and molluscs. Irregular firmgrounds, skeletal lag beds and HCS are present and sediment is well sorted. This facies grades basinward into interbedded grainstone and wackestone cycles that include bryozoans, echinoids, serpulids, brachiopods, quartz, calcareous clay, foraminifers and glauconitic pellets. Local HCS, cross lamination and mud rip-up clasts, thin skeletal lag concentrates, and graded tempestites are common. These facies are interpreted to represent both mid- and deep shelf storm and fair-weather deposits (Boreen and James, 1995).

Deep shelf environments, below storm wave base, are represented by interbedded bryozoan mudstone, calcareous clays and a bryozoan bioherm facies. The bryozoan marl is a packstone to wackestone that is thinly- to medium-bedded and interbedded with the calcareous clay facies. This facies is dominated by bryozoans with less abundant gastropods, infaunal bivalves, scaphopods, brachiopods and solitary corals. The calcareous clay facies is massive to bedded clay and silt with scarce large skeletal particles and various bioclasts except spicules and calcispheres. The bryozoan bioherm is internally bedded, alternating bryozoan bafflestone and packstone layers containing various bryozoans, bivalves, brachiopods, gastropods, scaphopods, solitary corals, echinoids, benthic and planktic foraminifers, sponge spicules and ostracods. These bioherms have a low synoptic relief and are up to 15 m high and 100's m in length (Boreen and James, 1995). Shelf edge and slope environments were not described in this study area.

### *4.2.3 Modern Otway cool-water carbonate shelf*

An example of a modern, cool-water carbonate shelf is the Otway continental margin, southeastern Australia, and has been described by Boreen et. al., (1993) as an open, swell-dominated, cool-water carbonate platform that is partitioned into three hydrodynamic zones controlling sediment production and accumulation. These zones include: i) zone of abrasion (0 - 70 m); ii) swell wavebase zone (70 - 130m); and iii) zone below storm wavebase (> 250m) (Boreen et al., 1993).

The shallow shelf lies within the zone of abrasion and is subject to high energy conditions. The seafloor biota is characterized by molluscs, sponges, bryozoans and red algae. Patchy loose sediment accumules as a thin, quartz-rich, palimpsest gravel veneer (Boreen et al., 1993). The mid-shelf, lying within the zone of swell wavebase, is dominated by swell wave shoaling, producing two dimensional dunes of bryozoan sands. Fine foraminifer, echinoid, and bryozoan bioclastic sands accumulate in deep shelf areas and are bioturbated and reworked by storms. Depositional textures are dominated by grainstones and packstones (Boreen et al., 1993). At the shelf edge and on the upper slope, upwelling of nutrient-rich waters support extensive and aphotic development of bryozoan, sponge, and coral skeletal mounds. Upper slope sediment includes bioturbated bioclastic debris and muds. On the upper slope gravity-driven resedimentation is common. The lower slope consists of interbedded, shelf-derived turbidites and pelagic ooze (Boreen et al., 1993).

### *4.2.4 Comparison*

There are many similarities and differences between the three examples described above and the Great Bear Cape Formation cool-water carbonate shelf of the Sverdrup Basin. Comparison of the Ordovician, Tertiary and Holocene cool-water carbonate shelves, with the cool-water carbonate shelf in this study, will be made on the basis of the overall shelf morphology and biotic associations, and facies distribution across the mid- to outer shelf, shelf margin and slope-to-basin settings.

*Shelf Morphology*

In all three examples summarized above, the overall shelf morphology has been described as open-shelf style with some noted differences ranging from the classical ramp to the distally steepened ramp. For example, the Ordovician Deschambault ramp is described as gently sloping whereas the ramp of the modern Otway Shelf is described as distally steepened. Since the platforms are not rimmed, due to the absence of reef building organisms, in all three examples and in the present study the facies distributions on the shelf are largely controlled by the location of fair-weather and storm wavebases. As a result, similar facies are recognized at similar locations on all four shelves. However, the absolute depths of the facies on the shelves are not equal as the locations of the fair-weather and storm wavebases change from basin to basin depending on the size of the depositional basin and local oceanographic conditions, among other factors.

*Biotic Associations*

In comparing the Ordovician Deschambault, mid -Tertiary, Permian Great Bear Cape and the modern Otway shelves in terms of biota, it becomes apparent that the main biotic 'players' dominating the cool-water carbonate factory have remained the same over millions of years. From the Ordovician through to the Holocene, the key biotic elements dominating the cool-water carbonate factory were bryozoans, crinoids, brachiopods, sponges, foraminifers and molluscs. Bryozoans are the principle mound-forming organisms in all examples. However, differences do exist in each example due to local variations in conditions and evolutionary processes throughout time. For example, on the Ordovician Deschambault shelf, trilobites and *Vermiporella* were additional contributors of sediment on the shelf while additional contributors on the modern Otway shelf include azooxanthellate corals, serpulids and pteropods. This is also noted in the mud mounds on the shelf in each example. Mounds of the Ordovician Deschambault shelf included minor brachiopods, molluscs, and crinoids with peloids in voids, whereas mounds of the Permian Great Bear Cape shelf included *Tubiphytes*, fusulinids, sponge spicules and echinoderms. The mid-Tertiary shelf carbonates are internally bedded and contain bivalves, brachiopods, gastropods, scaphopods, solitary corals, echinoids foraminifers, quartz sponge spicules and ostracods while the modern mounds on the Otway shelf include corals and sponges.

In all examples including the study area the shelf sediments grade laterally into mud-dominated slope and basin environments. The slope-to-basin environments are very similar in the Ordovician Deschambault shelf, and the mid-Tertiary and the modern Otway sheves in that carbonate muds, terrigenous clays and sponge spicules dominate. Only the nature of the carbonate muds changes in these examples, with the appearance of pelagic foraminifers in the Jurassic. In contrast, the slope-to-basin environment of the Permian Great Bear Cape shelf is very different from the others in that sponge spicules and siliceous shale were dominant. Tremendous volumes of sponge spicules deposited on the Early Permian slope were frequently delivered to the basin via gravity flows resulting in hundreds of metres of sponge spicules and siliceous shale filling the basin. The volumes of sponge spicules present in this environment is evidence of prolific sponge growth. The only modern analog providing insight into the organisms and processes that created the Great Bear Cape basin fill is the modern Arctic shelf existing below the polar pack ice from western Ellesmere Island to Meighan Island. The Arctic shelf is covered with extensive communities of siliceous sponges and in downslope environments, thick spicule-mud mats with ...liceous sponges exist (Van Wagoner et. al., 1989). This analog suggests that the slope ...e Great Bear Cape shelf were subject to cold-water and aphotic but nutrient-rich c... ...rting the prolific sponge growth.

*Facies Distributions*

*Mid- to Outer Shelf*

The mid- to outer Great Bear Cape Shelf of the Permian is directly comparable to the Ordovician Deschambault, mid-Tertiary and modern Otway shelves in terms of depositional textures. The inner shelves cannot be compared as sediments of this zone have been removed by erosion in the Otto Fiord area. In all of the three examples, the mid- to outer shelf is dominated by thickly to massively bedded grainstones to packstones, a result of deposition on an open shelf, above fair-weather wavebase, in a high energy environment. Similarly, the mid- to outer Great Bear Cape Shelf is dominated by thickly to massively bedded grainstones to packstones, resulting from deposition above fair-weather wavebase. However, unlike the three examples mentioned above, large-scale cross-stratification in storm beds and marine hardgrounds in the landward portion of the shelves are not commonly present in the mid- to outer shelf setting within the study area. The absence of large-scale cross-stratification is thought to be a result of extensive bioturbation and sediment reworking on the shelf above fair-weather wave base. Conditions supporting marine hardground development may or may not have existed. If marine hardgrounds were present, they formed on inner shelf carbonates which were later removed during the Melvillian Disturbance.

*Shelf Margin*

The margins of the Ordovician Deschambault, mid-Tertiary and modern Otway shelves are very similar to the Permian Great Bear Cape shelf margin in that all were i) dominated by muddy bioclastic carbonate sand commonly interbedded with storm deposits, and ii) prevalently supported bryozoan mud mound development. In each case the bryozoans acted as baffling agents collecting and stabilizing fine materials.

The Ordovician Deschambault shelf margin was above storm wavebase, resulting in common storm beds characterized by hummocky cross stratification. These storm beds were grain- to mud-supported and contained limy shale interbeds. On the mid-Tertiary shelves and modern Otway shelf, deep shelf and shelf edge environments were below storm wave base and are represented by interbedded bryozoan mudstone and calcareous clays in the mid-Tertiary and by olive-coloured, bioturbated, fine-grained, and muddy bryozoan sand in the Holocene.

The Permian Great Bear Cape shelf margin is dominated by bioturbated green clay and bioclastic debris. This facies is extremely similar to those on the modern Otway shelf margin, suggesting that the shelf margin of the Permian Great Bear Cape cool-water platform, presently outcropping in the Otto Fiord area, was below storm wave base. Storm deposits, including HCS, graded tempestites, and rip-up clasts, are not common in the Great Bear Cape sediments and this may be a result of the small size and relative isolation of the Sverdrup Basin from the open ocean, during the Artinskian to Kungurian, significantly dampening wave energies on the Great Bear Cape shelf.

*Slope/Basin*

Slope-to-basin environments of the Ordovician Deschambault shelf and modern Otway shelf were similar to that of the Permian Great Bear Cape shelf in the Sverdrup Basin in that these deep environments were dominated by the deposition of fine material. Differences do exist, however, in the composition of that fine material. The mid-Tertiary slope/basin environments were not studied and therefore cannot be compared here. In the Ordovician example deep water environments were dominated by carbonate mud and clay and in the Holocene example the lower slope is dominated by pelagic ooze. This difference can be related to the appearance of pelagic foraminifers in the Jurassic. The pelagic foraminifers settle out of suspension and have dominated basin sedimentation in post-Jurassic times. In contrast, the slope-to-basin environment of the Permian Great Bear Cape shelf was dominated by small sponge spicules in mudrock interbedded with siliceous shales (see above). Evidence of gravity-driven resedimentation is present in the slope deposits in all three settings, commonly in the Permian Great Bear Cape and modern Otway shelf deposits, as they represent distally steepened ramps, but not as commonly in the Ordovician Deschambault shelf deposits, representing a ramp not distally steepened.

## CHAPTER 5: CONCLUSIONS

The Artinskian to Kungurian Sequence of the Otto Fiord area comprises the Great Bear Cape, Raanes and Trappers Cove formations in addition to the upper portions of the Nansen and Hare Fiord formations.

The Great Bear Cape Formation (GBC), in the Otto Fiord area, is a yellowish-weathering, cliff-forming, medium- to very thickly-bedded, packstone to grainstone, with abundant echinoderms, bryozoans, brachiopods, sponges and various amounts of chert. The Raanes Formation consists predominantly of greenish-weathering, dominantly recessive, locally resistant, thinly- to medium-bedded, shaly to silty and variably cherty wackestone to packstone, containing bryozoans, brachiopods, crinoids, and sponge spicules (small and large), as well as resistant, massive, very fine-grained, bryozoan-lime mud wackestone forming biohermal mounds. The Trappers Cove Formation is medium- to thickly-bedded, black to dark gray spiculitic chert that is interbedded with thinly-bedded, black recessive shales and siltstones. Upsection the chert becomes more pure, gravity-driven deposits of carbonate appear and the fossil content of the chert increases with the introduction of brachiopods followed by bryozoans.

The Artinskian to Kungurian Sequence of the Otto Fiord area, best resembles a Transgressive-Regressive (T-R) Sequence consisting of five main components: lower sequence boundary (LSB), transgressive systems tract (TST), maximum flooding surface (MFS), regressive systems tract (RST), and upper sequence boundary (USB).

The LSB in the study area is a subaerial unconformity on the shelf indicated by thin zones of terra rosa material, predominantly occurring between shallow water grainstones of the Nansen Formation below and slightly recessive, muddier packstones of the Nansen Formation above. Toward the basin centre the unconformity becomes a correlative conformity within the uppermost Hare Fiord Formation at the top of a shallowing upward succession often capped by a very thickly-bedded crinoidal turbidite. The USB at the basin margin is a subaerial unconformity within the Great Bear Cape Formation, that becomes a correlative conformity basinward, within the outer shelf sediments of the Great Bear Cape Formation and the basinal sediments of the Trappers Cove Formation. The MFS is characterized by concentrations of pyrite, phosphate, silty sediment and papery black shales. In sections proximal to the basin margin the MFS coincides with the lithostratigraphic boundary separating the Great Bear Cape (or basinal equivalent Trappers Cove Formation) from the underlying Raanes Formation. At the feather edge of the basin margin the MFS and the TST were eroded prior to deposition of the RST. Paleohighs experienced more than one episode of subaerial exposure and erosion. during the deposition of the Artinskian to Kungurian Sequence. In slope and basinal areas the MFS is represented by an abrupt change from green shales of the Hare Fiord Formation to "papery" black shales at the base of the Trappers Cove Formation. accompanied by high concentrations of pyrite and locally of phosphate. The TST is subdivided into an early transgressive systems tract (ETST) and a late transgressive systems tract (LTST). The ETST records the initial deepening phase and is represented by the uppermost Nansen Formation on the shelf and by the Hare Fiord Formation in the basin. The LTST records a phase of significant deepening that is represented by the entire Raanes Formation. In the basin the LTST is a condensed section merging with the MFS at the top of the Hare Fiord Formation. The RST is represented by: i) shallowing upward. progradational. cool-water shelf carbonates of the Great Bear Cape Formation. and ii) laterally equivalent slope and basinal cherts and shales of the Trappers Cove Formation.

The facies of the Artinskian to Kungurian Sequence exposed in the Otto Fiord area are grouped into the following four distinct facies associations. identified on the basis of their biota: Chloroforam Facies Association: Bryonoderm-Extended Facies Association: Bryonoderm Facies Association: and Hyalosponge Facies Association. Eleven individual facies within these associations were distinguished on the basis of the dominant depositional textures. They are the: Chloroforam Grainstone: Chloroforam Wackestone to Packstone: Bryonoderm-Extended Grainstone: Bryonoderm-Extended Packstone: Bryonoderm-Extended Reefal Limestone: Bryonoderm Grainstone: Bryonoderm Wackestone to Packstone: Bryonoderm Spiculite: Hyalosponge Mudrock: Siliceous/Spiculitic Shale: and Debrite/Turbidite. These facies represent inner to outer shelf. shelf margin. and slope-to-basin depositional settings of an open-marine. distally steepened shelf. However. the distribution of facies across the shelf and slope is quite complex as not only did the facies change spatially with water depth but they also changed temporally accompanying climatic deterioration.

The spatial distribution of facies was dependent on several factors including: i) biologically-driven sediment production and extrabasinal sediment influx. ii) oceanographic conditions such as water depth, restriction, photic levels, temperature, agitation and upwelling, iii) tectonics involving block faulting of the shelf, and iv) initial depositional profile. In examining the spatial distribution of the facies on the shelf, it is evident that at any one point in time the inner-to-outer shelf was dominated by grainstones with minor packstones while the shelf margin, slope and basin were dominated by wackestones and mudstones. This was a result of fair-weather wavebase impinging on the shelf creating higher energy conditions that prevented the accumulation of fine material and caused abrasion of skeletal material. Also, the spatial distribution of facies was dependent on temperature changes related to depth of formation or upwelling. The Bryonoderm Association always occupied the deeper water environments or shelf environments exposed to upwelling currents while the more diverse and tropical Chloroforam Association was restricted to shallow, warm-water shelf environments. The very presence of the Chloroforam Association on the shelf indicates that the shelf was within the photic zone.

Temporal facies distribution was dependent on the following factors: i) climatic deterioration, ii) sediment productivity, iii) local oceanographic conditions, and iv) changes in shelf accommodation governed by changes in sea-level and styles of tectonic subsidence, through time. In examining the temporal distribution of facies throughout the Artinskian to Kungurian Sequence it is evident that the facies association dominating the shelf at any one time was dependent on climatic conditions existing at that time. It is obvious from examining the shallow-water shelf grainstones, that early in the sequence the shelf was exposed to tropical conditions, as the Chloroforam Association dominated, while later in the sequence cool-water conditions prevailed, evidenced by the dominance of the Bryonoderm Association.

Shelf sedimentation rates increased from the early portions of the sequence to the later portions as shelf production and sedimentation rates during Great Bear Cape time exceeded sedimentation rates of the older Raanes Formation. Sedimentation rates on the Great Bear Cape shelf were high enough to cause extensive progradation of the bioclastic sediments toward the outer shelf and offshore areas. In the slope-to-basin environment, sediment production and accumulation rates related with the silica factory were important and also contributed to the extensive basinward progradation of the Great Bear Cape/Trappers Cove shelf and slope.

Major changes in shelf accommodation space occurred throughout the Artinskian to Kungurian Sequence, indicated by the changing depositional style of sediments on the shelf. During the TST, in the early portion of the sequence, an overall increase in shelf accommodation space occurred while during the RST, in the later portion of the sequence, shelf accommodation space decreased. The long term fluctuation in relative sea-level and accommodation space was tectonically driven, and caused by intermittent rifting through the Artinskian.

Higher-order carbonate cyclicity is present in the Artinskian to Kungurian Sequence in the Otto Fiord area. These cycles are considered to have resulted from eustatic oscillations in relative sea-level that were overprinted by sea-level fluctuations due to tectonism as the Sverdrup Basin at this time was tectonically active. In addition, variations in sediment redistribution cannot be ruled out as a local control on subtidal carbonate cycle formation in the Artinskian to Kungurian Sequence of the Otto Fiord area.

## REFERENCES

Balkwill . H.R. 1978. Evolution of the Sverdrup Basin. Arctic Canada. American Association of Petroleum Geologists. Bulletin. v. 62. p.1004-1028.

Beauchamp. B. 1993. Tectonic cycles and the origin of Upper Paleozoic low-order sequences in the Sverdrup Basin. Canadian Arctic. Canadian Society of Petroleum Geologists. Annual Convention Program and Abstracts. p.20.

Beauchamp. B. 1994. Permian climatic cooling in the Canadian Arctic. *In*: Pangea: Paleoclimate. Tectonics. and Sedimentation During Accretion. Zenith. and Breakup of a Supercontinent. Boulder. Colorado. Geological Society of America. Special Paper 288. p.229-246.

Beauchamp. B and Desrochers. A. in press. Permian warm- to very cold-water carbonates and cherts in the Sverdrup Basin-Barents Sea area. northwestern Pangea. SEPM Special Publication.

Beauchamp. B.. Harrison. J.C.. and Henderson. C.M. 1989a. Upper Paleozoic stratigraphy and basin analysis of the Sverdrup Basin. Canadian Arctic Archipelago: Part 1. time frame and tectonic evolution. *In*: Current Research. Part G. Geological Survey of Canada. Paper 89-1G. p.105-113.

Beauchamp. B.. Harrison. J.C.. and Henderson. C.M. 1989b. Upper Paleozoic stratigraphy and basin analysis of the Sverdrup Basin. Canadian Arctic Archipelago: Part 2. transgressive-regressive sequences. *In*: Current Research. Part G. Geological Survey of Canada. Paper 89-1G. p.115-124.

Beauchamp. B. and Henderson. C.M. 1994. The Lower Permian Raanes. Great Bear Cape and Trappers Cove formations. Sverdrup Basin. Canadian Arctic: stratigraphy and conodont zonation. Bulletin of Canadian Petroleum Geology. v.42. No.4. p.562-597.

Beauchamp. B. Mayr. U. and Harrison. J.C. 1995. Carboniferous and Permian stratigraphic sequences on Hvitland Peninsula and adjacent areas. northwestern Ellesmere Island. Arctic Canada. *In:* Current Research 1995-B. Geologic Survey of Canada. p.19-28.

Boreen. T.D. and James. N.P. 1993. Holocene sediment dynamics on a cool-water carbonate shelf: Otway. southeastern Australia. Journal of Sedimentary Petrology. v.63. No. 4. p. 574-588.

Boreen. T.D. and James. N.P. 1995. Stratigraphic sedimentology of Tertiary cool-water limestones. SE Australia. Journal of Sedimentary Research. v.B65. No.1. p.142-159.

Boreen. T.D.. James. N.P.. Heggie. D.. and Wilson. C. 1993. Surficial cool-water carbonate sediments on the Otway continental margin. southeastern Australia: Marine Geology. v.112. p.35-36.

Brookfield, M.E. 1988. A mid-Ordovician temperate carbonate shelf-the Black River and Trenton Limestone Groups of southern Ontario, Canada. Sedimentary Geology, v.60, p.137-154.

Chave, K.E. 1967. Recent carbonate sediments-an unconventional view. Journal of Geological Education, v.15, p.200-204.

Dickson, J.A.D. 1966. Carbonate identification and genesis as revealed by staining. Journal of Sedimentary Petrology, v.36, p. 491-505.

Dunbar, C.O. 1955. Permian brachiopod faunas of central East Greenland. Medd. om Grønland, v.110, No.3, p.1-169.

Embry, A.E. 1992. Crockerland-the northwest source area for the Sverdrup Basin, Canadian Arctic Islands. In: Arctic Geology and Petroleum Potential. T.O. Vorren, E. Bergsager, Ø.A. Dahl-Stamnes, E. Holter, B. Johansen, E. Lie and T.B. Lund (eds.). NPF Special Publication 2, p.205-216.

Embry, A.E. 1993. Transgressive-regressive (T-R) sequence analysis of the Jurassic succession of the Sverdrup Basin, Canadian Arctic Archipelago. Canadian Journal of Earth Sciences, v.30, p.301-320.

Eyles, N. and Eyles, C.H. 1992. Glacial depositional systems. *In:* Facies Models: Response to Sea-Level Change. R.G. Walker and N.P. James (eds.). Geological Association of Canada, p.73-100.

Flugel, E. 1982. Microfacies Analysis of Limestones. New York, Springer-Verlag, 633p.

Gobbet, D.J. 1963. Carboniferous and Permian brachiopods of Svalbard. Norsk Polarinstitut Skr., v.127, p.1-201.

Hallock, P. and Schlager, W. 1986. Nutrient excess and the demise of coral reefs and carbonate platforms. Palaios, v.1, p.389-398.

Harland, W.B., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith, A.G. and Smith, D.G. 1990. A Geologic Time Scale. Cambridge University Press, Cambridge, 263p.

James, N.P. and Bone, Y. 1991. Origin of a cool-water, Oligo-Miocene deep shelf limestone, Eucla Platform, southern Australia. Sedimentology, v.38, p.323-341.

James, N.P. and Bourque, P.-A. 1992. Reefs and mounds. *In:* Facies Models: Response to Sea-Level Change. R.G. Walker and N.P. James (eds.). Geological Association of Canada, p.323-347.

Jones, B. and Desrochers, A. 1992. Shallow platform carbonates. *In:* Facies Models: Response to Sea-Level Change. R.G. Walker and N.P. James (eds.). Geological Association of Canada, p.277-301.

Lavoie, D. 1995. A Late Ordovician high-energy temperate-water carbonate ramp, southern Quebec, Canada: implications for Late Ordovician oceanography. Sedimentology, v.42, p.95-116.

Lees, A. 1975. Possible influence of salinity and temperature on modern shelf carbonate sedimentation. Marine Geology, v.19, p.159-198.

Lees, A. and Buller, A.T. 1972. Modern temperate-water and warm-water shelf carbonate sediments contrasted. Marine Geology, v.13, p.M67-M73.

McLaren, D.J. 1963. Goose Fiord to Bjorne Peninsula. *In*: Geology of North-central Part of the Arctic Archipelago, Northwest Territories (Operation Franklin). Y.O. Fortier et al. (eds.). Geological Survey of Canada, Memoir 320, p.310-337.

Minato, M. 1960. Eine Permische Koralle von Konig Oscarland im Nordwestlichen Ellesmereland. Stockholm University, Stockholm Contribution to Geology, v.6, p.25-36.

Morin, J. 1992. Facies analysis of Lower Permian cyclic carbonates, west-central Ellesmere Island, Canadian Arctic. Unpublished M.Sc. thesis, University of Ottawa, 164p.

Nassichuk, W.W., Furnish, W.M., and Glenister, B.F. 1965. The Permian ammonoids on Ellesmere Island. Geological Survey of Canada, Paper 75-1C, p.267-277.

Nassichuk, W.W. and Wilde, G.L. 1977. Permian fusulinaceans and stratigraphy at Blind Fiord, southwestern Ellesmere Island. Geological Survey of Canada, Bulletin 268, 59p.

Nelson, C.S. 1978. Temperate shelf carbonate sediments in the Cenozoic of New Zealand. Sedimentology, v.25, p.737-771.

Nelson, C.S. 1988. An introductory perspective on non-tropical shelf carbonates. Sedimentary Geology, v.60, p.3-12.

Nelson, C.S., Keane, S.L. and Head, P.S. 1988. Non-tropical carbonate deposits on the modern New Zealand shelf. Sedimentary Geology, v.60, p.71-94.

Osleger, D. 1991. Subtidal carbonate cycles: implications for allocyclic vs. autocyclic controls. Geology, v. 19, p.917-920.

Posamentier, H.W., Jervey, M.T. and Vail, P.R. 1988. Eustatic controls on clastic deposition I-conceptual framework. In: Sea Level Changes: An Integrated Approach. C.W. Wilgus et al. (eds.). SEPM Special Paper 42, p.109-124.

Rao, C.P. 1981. Criteria for recognition of cold-water carbonate sedimentation: Berriedale Limestone (Lower Permian), Tasmania, Australia. Journal of Sedimentary Petrology, v.51, p.491-506.

Rao, C.P. 1988. Paleoclimate of some Permo-Triassic carbonates of Malaysia. Sedimentary Geology, v.60, p.163-171.

Reidiger, C.L. and Harrison, J.C. 1993. Stratigraphy and sedimentology of the Canyon Fiord Formation, Melville Island. *In*: The Geology of Melville Island, Arctic Canada. R.L. Christie and N.J. McMillan (eds.). Geologic Survey of Canada, Bulletin 450, p.121-138.

Schei, P. 1901. Summary of geological results (The Second Norwegian North Polar Expedition in the "Fram", 1898-1902). Geographical Journal, v.22, p.56-65.

Schlager, W. 1981. The paradox of drowned reefs and carbonate platforms. Geological Society of America Bulletin, v.92, p.197-211.

Scott, E. 1992. The stratigraphy and sedimentology of Artinskian (Lower Permian) strata, west-central Ellesmere Island, Canadian Arctic Archipelago. Unpublished M.Sc. thesis, University of Calgary, 226p.

Scott, E., Henderson, C.M., and Beauchamp, B. 1991. Field investigations of Artinskian (Lower Permian) strata, west-central Ellesmere Island. *In*: Current Research, Part B, Geological Survey of Canada, Paper 91-1B, p. 81-92.

Stemmerik, L. and Worsley, D. 1989. Late Palaeozoic sequence correlations, North Greenland, Svalbard and the Barents Shelf. *In*: Correlation in Hydrocarbon Exploration. J.D. Collinson (ed.). London, Norwegian Petroleum Society (Graham and Trotman), p.99-111.

Tait, R.V. 1981. Elements of Marine Ecology. Butterworths, London, 356p.

Thériault, P. 1991. Synrift sedimentation in the Upper Carboniferous Canyon Fiord Formation, SW Ellesmere Island, Canadian Arctic. Unpublished M.Sc. thesis, University of Ottawa, 210p.

Thériault, P. and Beauchamp, B. 1991. Preliminary interpretation of the depositional history and tectonic significance of the Carboniferous Canyon Fiord Formation, west-central Ellesmere Island, Arctic Archipelago. Geological Survey of Canada Paper, 90-1B, p.93-103.

Thériault, P., Beauchamp, B., Harrison, J.C., Mayr, U. and Steel, R.1995. Serpukhovian and Bashkirian (Carboniferous) stratigraphy (Borup Fiord and Otto Fiord formations; Unit C1), Hvitland Peninsula and adjacent areas, northwestern Ellesmere Island, Arctic Canada. *In*: Current Research 1995-B, Geological Survey of Canada, p.29-36.

Thorsteinsson, R. 1974. Carboniferous and Permian stratigraphy of Axel Heiberg Island and western Ellesmere Island, Canadian Arctic Archipelago. Geological Survey of Canada, Bulletin 224, 115p.

Tozer, E.T. 1963. Blind Fiord. *In*: Geology of North-central Part of the Arctic Archipelago, Northwest Territories (Operation Franklin). Y.O. Fortier et al. (eds.). Geological Survey of Canada, Memoir 320, p.380-385.

Trettin, H.P. 1989. The Arctic Islands. *In*: The Geology of North America, v. A: an Overview. A.W. Bally and A.R. Palmer (eds.). Geological Society of America, Boulder, Colorado, p.349-370.

Troelson, J.C. 1950. Contributions to the geology of northwest Greenland, Ellesmere and Axel Heiberg Islands. Medd. om Grønland, v.147, No.7, p.1-86.

Tschernyshew, T. and Stepanov, P. 1916. Obercarbon fauna von Konig Oscars und Heibergsland: Report of the second Norwegian Expedition in the Fram, 1893-1902. Vidensky-Selsk. I Kristiana, v.4, No.34, p.1-67.

Ustritsky, V.I. 1973. Permian climate. *In*: The Permian and Triassic systems and their mutual boundaries. A. Logan and L.V. Hills (eds.). Canadian Society of Petroleum Geologists, Memoir 2, p.733-744.

Van Wagoner, J.C., Mitchum, R.M., Campion, K.M. and Rashmanian, V.D. 1990. Siliciclastic sequence stratigraphy in well logs, cores and outcrops: concepts for high resolution correlation of time and facies. American Association of Petroleum Geology, Methods in Exploration Series No.7, 55p.

Van Wagoner, N.A., Mudie, P.J., Cole, F.E. and Daborn, G. 1989. Siliceous sponge communities, biological zonation, and Recent sea-level change on the Arctic margin: Ice Island results. Canadian Journal of Earth Sciences, v.26, p. 2341-2355.

Wahlman, G.P. 1985. Lower Permian (Wolfcampian) *Archaeolithoporella-Tubiphytes*-sponge boundstones from the subsurface of west Texas. *In*: Paleoalgology: Contemporary Research and Applications. D.F. Toomey and M.H. Nitecki (eds.). New York, Springer-Verlag, p.208-215.

Walker, R.G. 1992. Turbidites and submarine fans. *In:* Facies Models: Response to Sea-Level Change. R.G. Walker and N.P. James (eds.). Geological Association of Canada, p.239-264.

Wright, V.P. 1986. Facies sequences on a carbonate ramp: the Carboniferous Limestone of South Wales. Sedimentology, v.33, p.221-241.

Wright, V.P. and Faulkner, T.J. 1990. Sediment dynamics of Early Carboniferous ramps: a proposal. Geological Journal, v.25, p.139-144.

Zeigler, P.A. 1988. Evolution of the Arctic-North Atlantic and the Western Tethys. American Association of Petroleum Geologists, Memoir 43, 198p.

**PLATES**

## PLATE 1

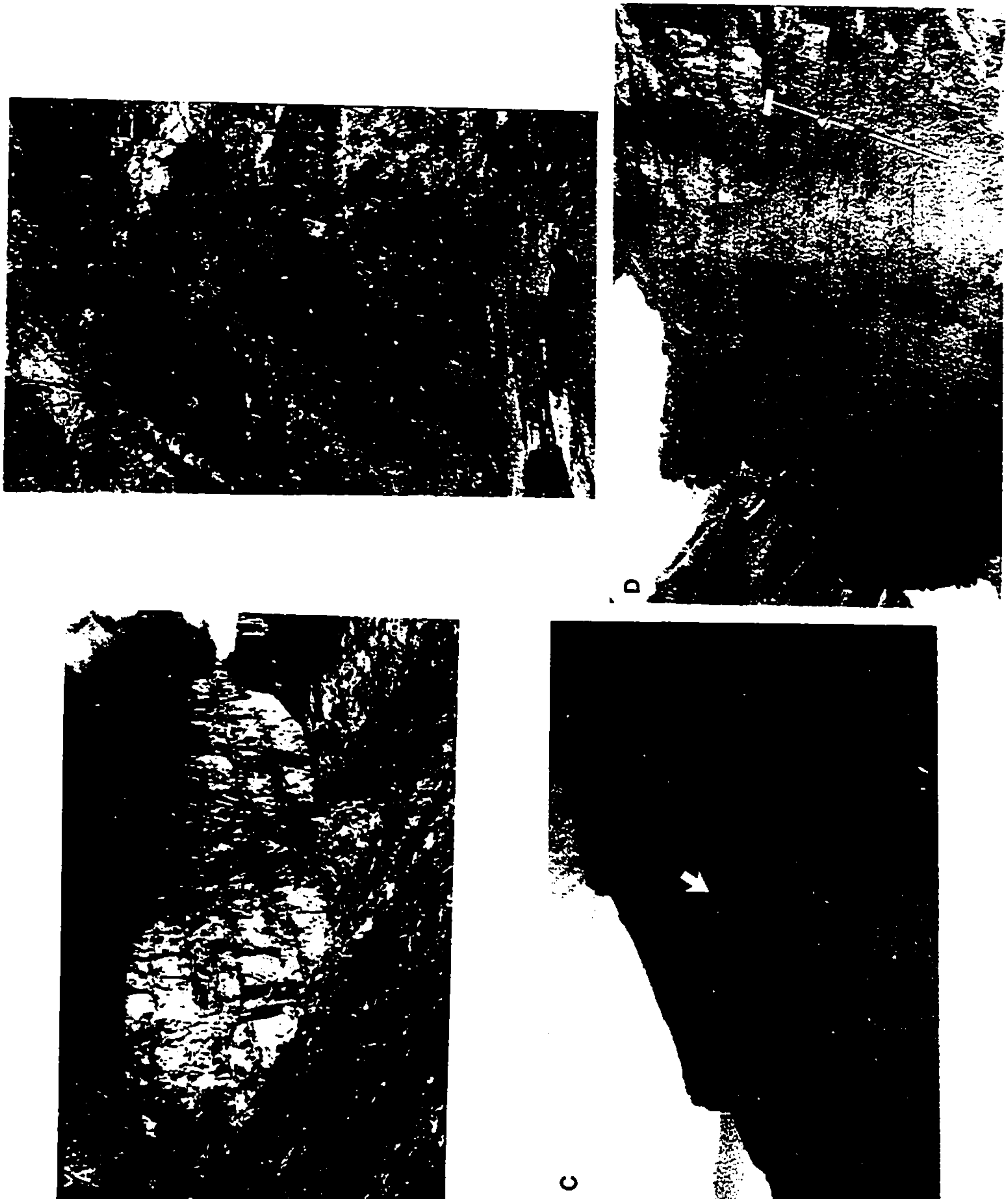
### Great Bear Cape and Raanes formations

**A**. Outcrop photograph of the Great Bear Cape Formation at Section 3. This formation is yellowish-weathering, cliff forming, medium- to very thickly-bedded packstone to grainstone with abundant echinoderms, bryozoans, brachiopods. The outcrop is 4.6 m high.

**B**. Very thickly bedded, yellowish-weathering Great Bear Cape Formation close-up (section 3). Note hammer for scale (arrow).

**C**. Outcrop photograph of the Raanes Formation at Section 13. This formation is dominantly greenish-weathering, dominantly recessive, locally resistant, thinly to medium bedded, silty to shaly and variably cherty wackestone to packstone, containing bryozoans, brachiopods, crinoids and sponge spicules. Note decametre-scale cyclicity (discussed in Chapter 3). Person for scale (arrow).

**D**. Thinly- to medium-bedded, greenish-weathering Raanes Formation (section 7). Note the differences in bedding colour and thickness from the Great Bear Cape Formation. Pogo (1.5 m) for scale.



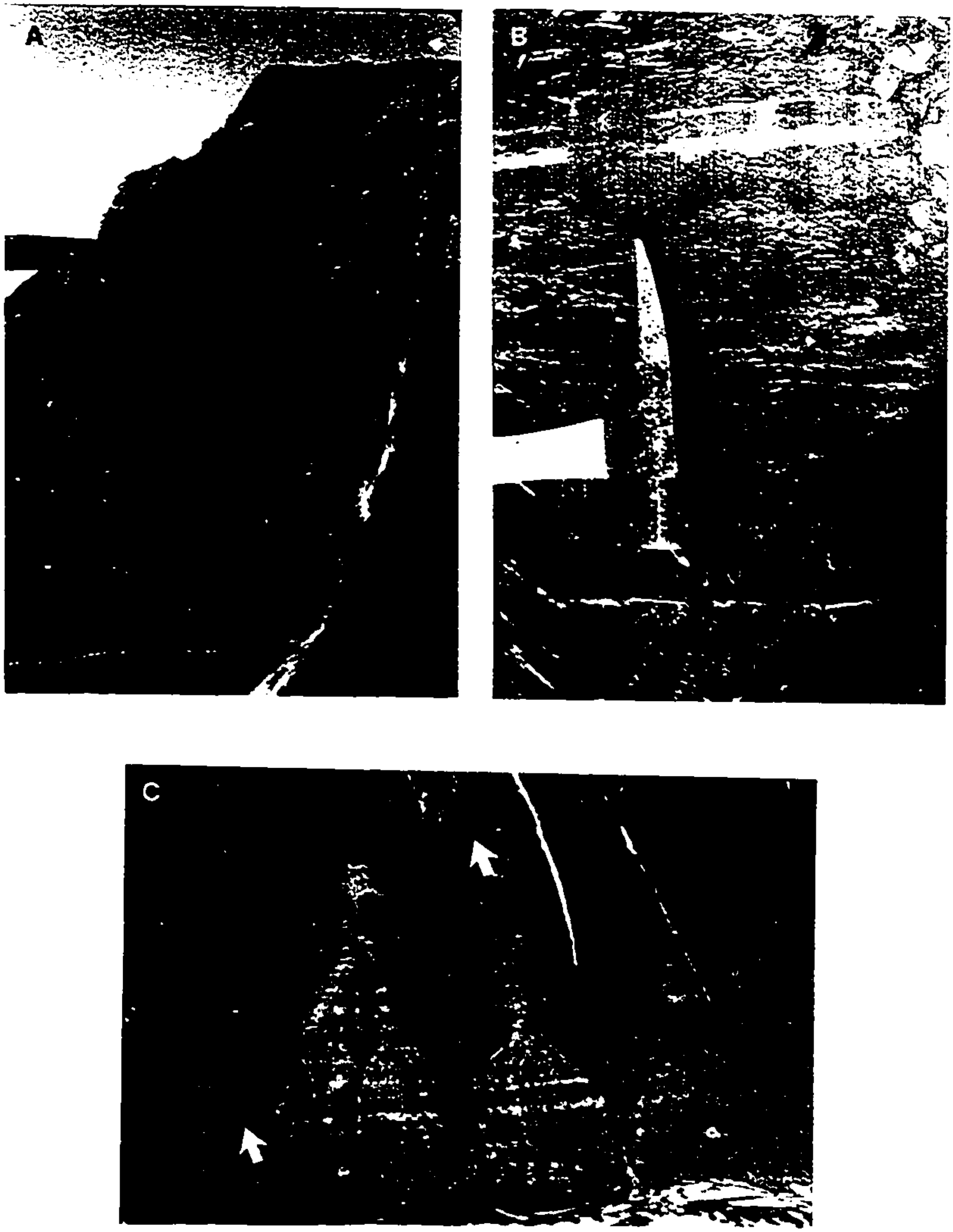
## PLATE 2

### Trappers Cove Formation

**A.** Outcrop photograph of the Trappers Cove Formation (section 3). This formation is composed of medium- to thickly bedded black to dark gray spiculitic shale and chert. The shale:chert ratio decreases upsection and forward the basin margin. At this location, the Trappers Cove Formation is 1000 m thick. Photograph shows 100 m of the outcrop.

**B.** Close-up photograph of black spiculitic shale and chert (section 3). Note microturbidite (arrow). Hammer for scale.

**C.** Cliff photograph of the Trappers Cove Formation near the mouth of Otto Fiord. The cliff is approximately 500 m high and illustrates the truncation surfaces common throughout the Trappers Cove Formation (arrows).


A
B
C

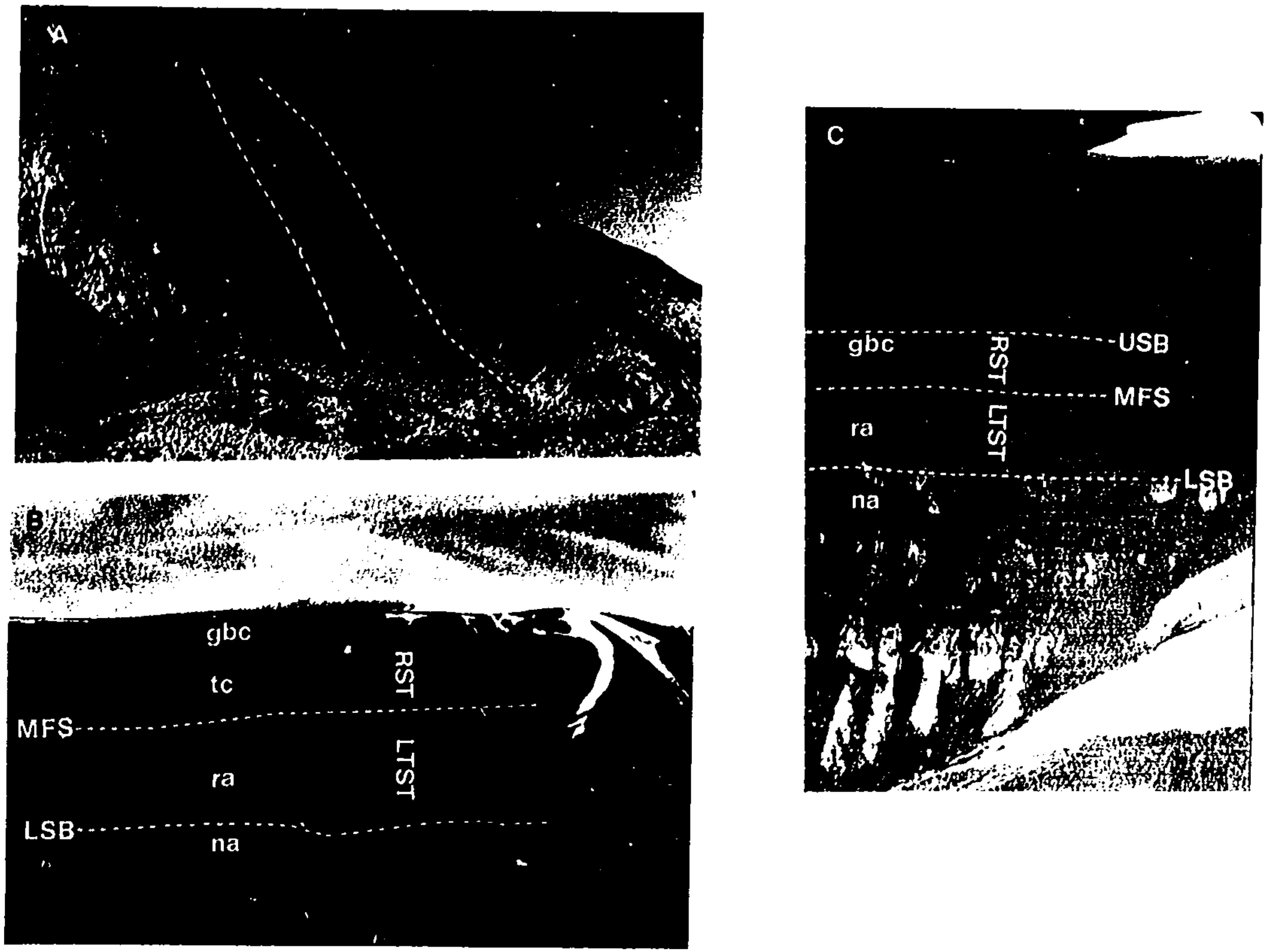
## PLATE 3

### Artinskian to Kungurian Sequence

**A**. Outcrop photograph at section 6. This section is interpreted to be in a paleohigh as the Artinskian to Kungurian Sequence is relatively thin (70 m) at this location. The MFS was removed by a period of erosion within the sequence. Abbreviations: LSB = Lower Sequence Boundary; USB = Upper Sequence Boundary; MFS = Maximum Flooding Surface; FS = Flooding Surface; LTST = Late Transgressive Systems Tract; ETST = Early Trangressive Systems Tract; RST = Regressive Systems Tract; na = Nansen Formation; ra = Raanes Formation; gbc = Great Bear Cape Formation; and tc = Trappers Cove Formation.

**B** Outcrop photograph at section 7. This section is interpreted to a be block faulted area that subsided area adjacent to the paleohigh (section 6). The Artinskian to Kungurian Sequence is relatively thicker (400 m) at this location. Shown are the LSB within the Nansen Formation, the MFS at the contact of the Raanes and Trappers Cove formations. The USB is not present in this exposure. Abbreviations are explained above.

**C**. Cliff photograph of the Artinskian to Kungurian Sequence at section 11. This section represents the sequence in the inner-mid shelf region (87 m). The LSB is within the Nansen Formation, the MFS is present at the Raanes - Great Bear Cape Formation lithostratigraphic contact, and the USB lies within the Great Bear Cape Formation. The Artinskian to Kungurian Sequence in this area is overlain by the Ufimian - Kazanian Sequence (see Figure 2). Abbreviations are explained above.


A
B
gbc
tc
RST
MFS
ra
LTST
LSB
na
C
gbc
RST
USB
MFS
ra
LTST
LSB
na

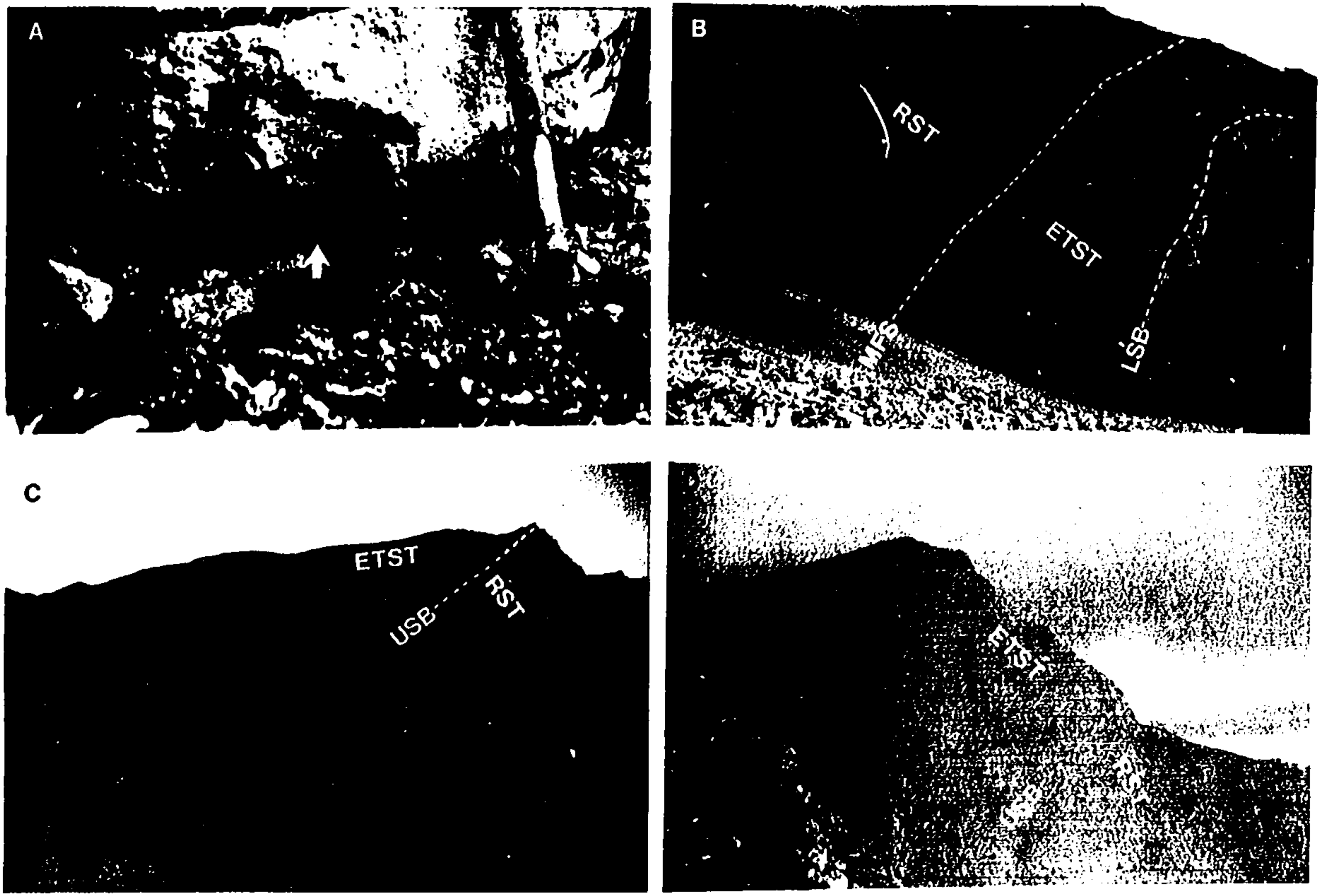
## PLATE 4
## Artinskian to Kungurian Sequence

**A**. Close-up photograph of the LSB on the shelf (section 11), in the Nansen Formation, denoted by a thin zone of red limestone (arrow), interpreted to be terra rosa material incorporated into the rock. The depositional texture below the red zone is a grainstone and above the red zone is a packstone, defining the sequence boundary and indicating the onset of a transgression.

**B** Outcrop photograph indicating the position of the LSB within the Hare Fiord Formation in the basin (section 9). At this section the shallowest water facies in the basin (LSB) is present at the top of a debris flow. The ETST (130 m) is represented by the Hare Fiord Formation, the MFS by the lithostratigraphic contact of the Hare Fiord and Trappers Cove formations, and the RST by the Trappers Cove Formation. Abbreviations: LSB = Lower Sequence Boundary; RST = Regressive Systems Tract; ETST = Early Transgressive Systems Tract; MFS = Maximum Flooding Surface.

**C** Cliff photograph indicating the position of the USB in an outer shelf section (section 3). The USB occurs at the break in slope and reflects increased mud content of the sediment, with rise of relative sea-level. Also shown are the RST of the Artinskian to Kungurian Sequence and the ETST of the overlying sequence. Photograph shows 120m of outcrop. Abbreviations: USB = Upper Sequence Boundary; RST = Regressive Systems Tract; and ETST = Early Transgressive Systems Tract.

**D** Cliff photograph of an outer shelf section (section 10). The USB occurs at the break in slope. Above the USB, decametre-scale transgressive-regressive cyclicity is present in the ETST of the overlying sequence. Photograph shows 80m of outcrop. Abbreviations: USB = Upper Sequence Boundary; RST = Regressive Systems Tract; and ETST = Early Transgressive Systems Tract.


A
B
RST
ETST
MFS
LSB
C
ETST
RST
USB
ETST

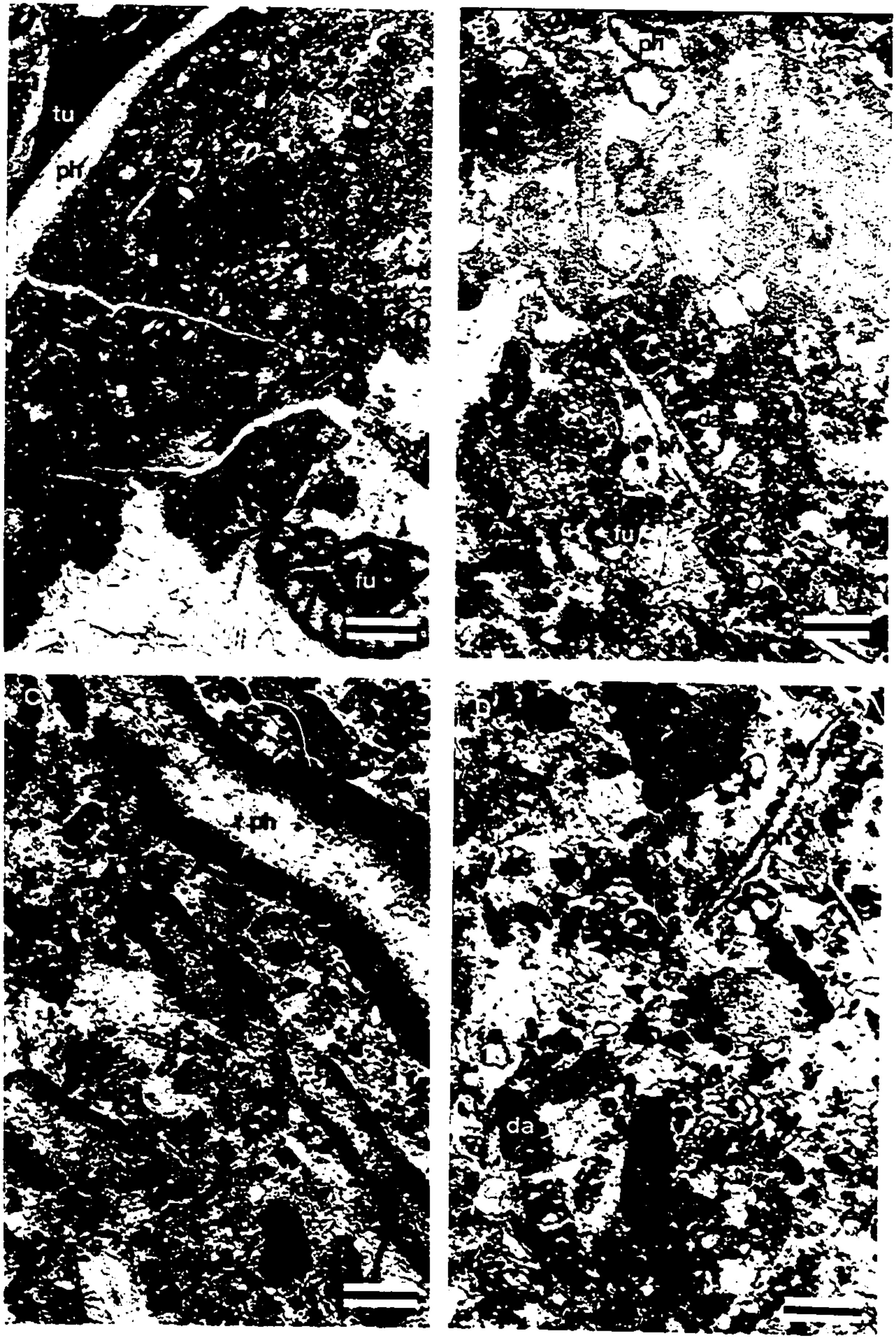
## PLATE 5

### Chloroforam Facies Association

**A** Photomicrograph of Chloroforam Wackestone to Packstone (section 13, c-310846). Main components constituting this facies and present in the photo include phylloid algae (ph), *Tubiphytes* (tu), small benthic foraminifers (fo) and fusulinids (fu). Scale bar is 0.5 mm.

**B** Photomicrograph of Chloroforam Wackestone to Packstone (section 8, c-311960). This sample was collected from a sediment gravity flow deposit at the base of a basinal section thus reflecting shelf sedimentation early in the Artinskian to Kungurian Sequence. Main components constituting this facies and present in the photo include phylloid algae (ph), dasycladacean algae (da) and fusulinids (fu). Scale bar is 0.25 mm.

**C, D** Photomicrographs of Chloroforam Grainstone (sections 11, c-310867 and section 13, c-310874, respectively). Main components constituting this facies include phylloid algae (ph), dasycladacean algae (da), small benthic foraminifers (fo), fusulinids and *Tubiphytes* (not present in photograph). Minor components present include echinoderms (ec). Scale bar is 0.5 mm.



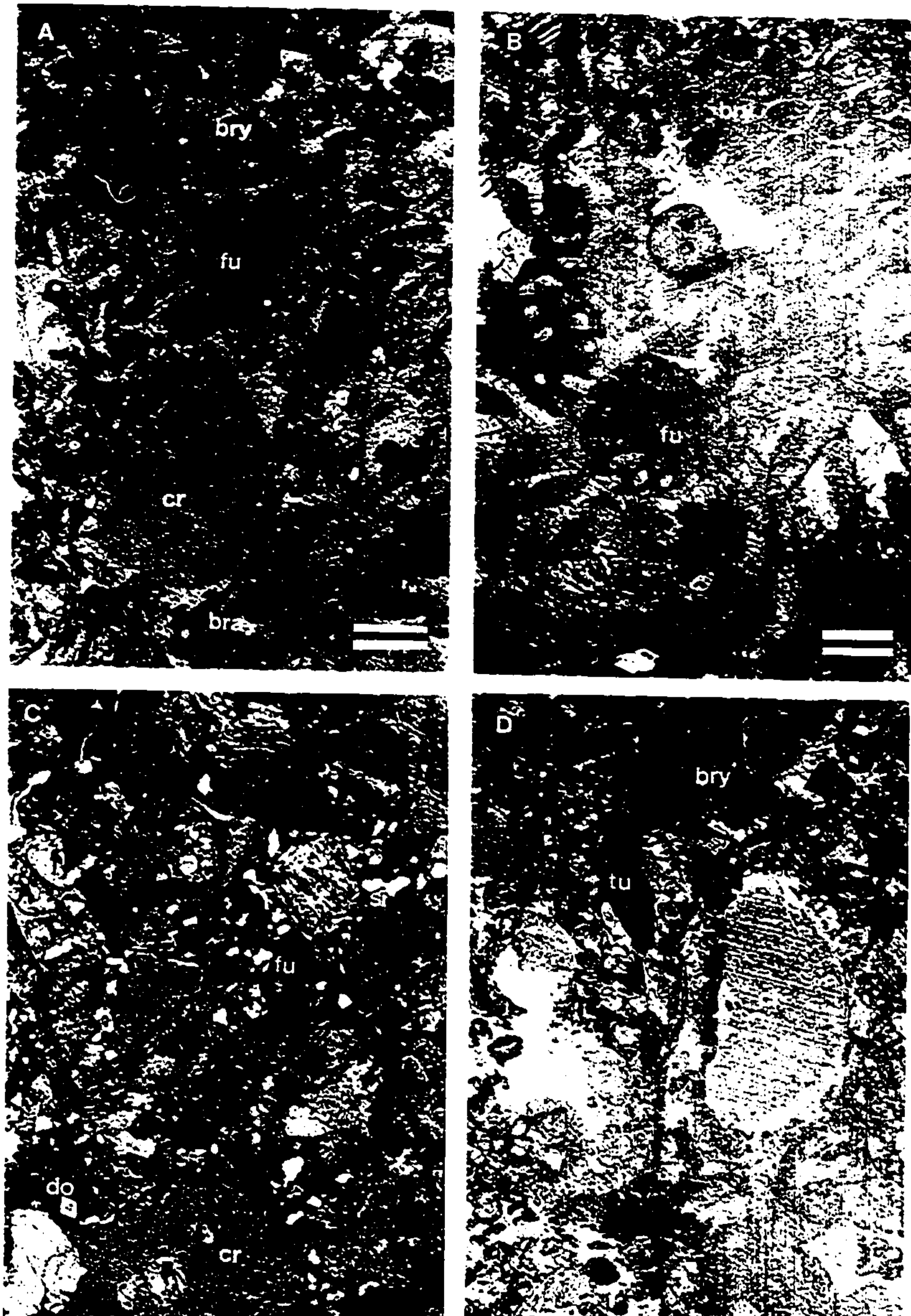
tu
ph
fu
ph
fu
ph
da

## PLATE 6

### Bryonoderm-Extended Facies Association

**A, B** Photomicrographs of Bryonoderm-Extended Grainstone (section 5, c-311176). Main components constituting this facies include echinoderms (ec), bryozoans (bry), brachiopods (bra), fusulinids (fu) and *Tubiphytes* (not shown). Scale bar is 0.5 mm.

**C, D** Photomicrographs of Bryonoderm-Extended Packstone (sections 11 and 12, c-311775 and c-311722). Main components include echinoderms (ec), bryozoans (bry), fusulinids (fu) and *Tubiphytes* (tu). Abiotic components include silt-sized quartz grains (si) and non-ferroan dolomite rhombs (do). Note that *Tubiphytes* is fragmented indicating post-burial mechanical compaction. Scale bar is 0.25 mm.

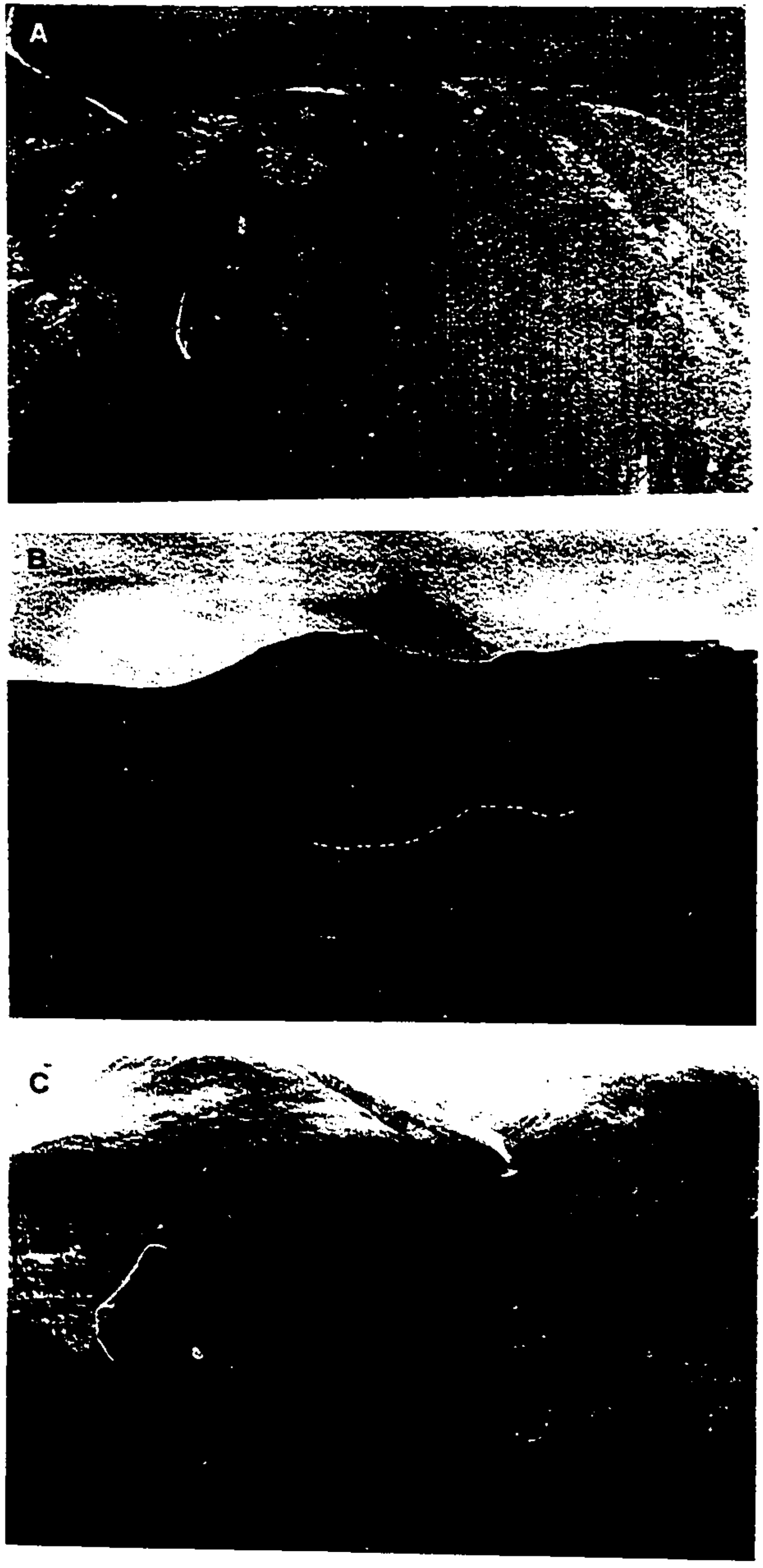

A
bry
fu
cr
bra
B
fu
C
fu
do
cr
D
bry
tu

## PLATE 7

### Bryonoderm-Extended Facies Association: Reefal Limestone

**A, B** Outcrop photographs of massive reefal limestone present within the Raanes Formation at the head of Otto Fiord close to section 13. Reef in photograph A is approximately 100 m high and that in photograph B approximately 10 m to 15 m high (base of reef is outlined).

**C** Outcrop photograph of massive reefal limestone present within the Raanes Formation at the mouth of Otto Fiord at section 14. This mound is approximately 366 m thick..

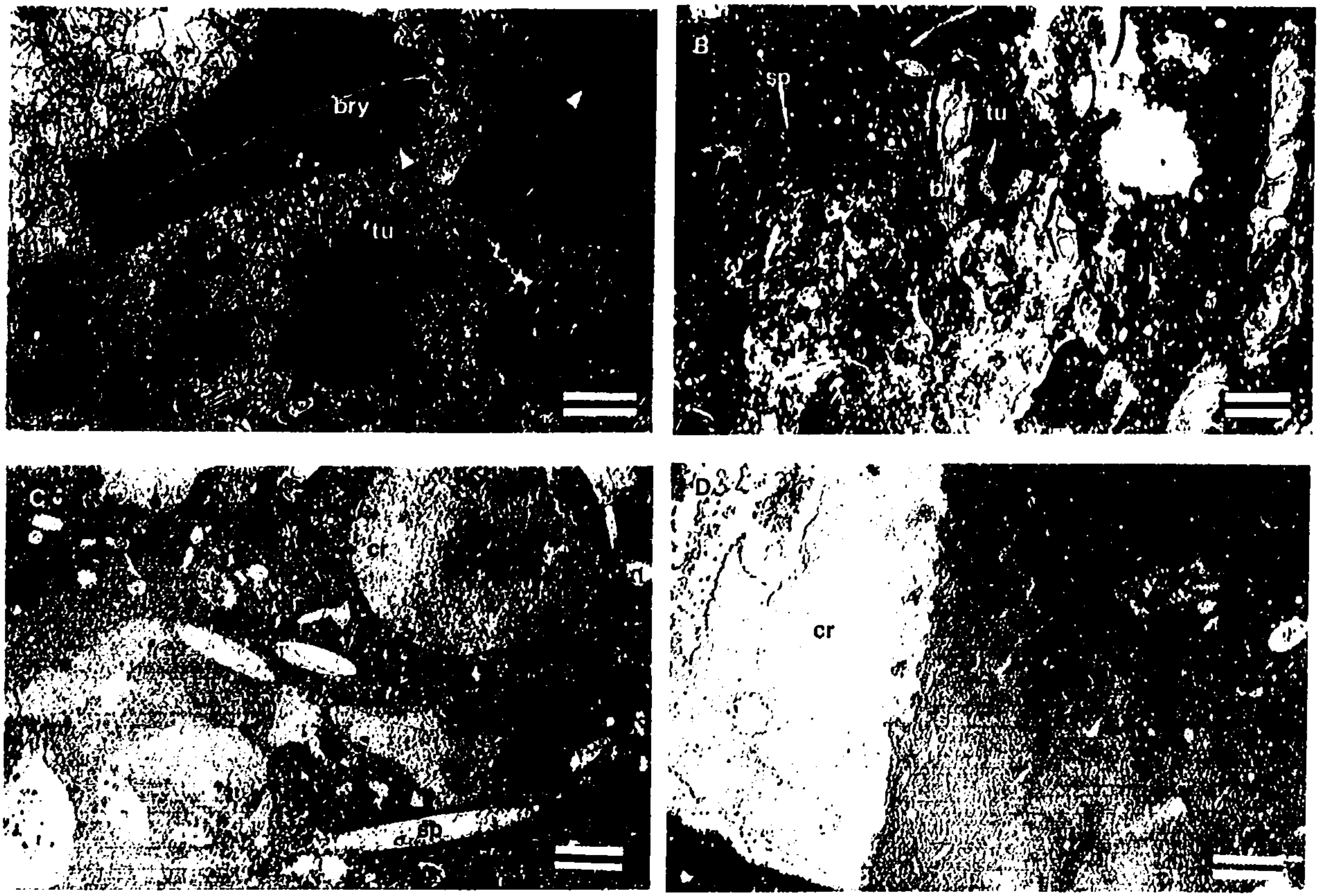

A
B
C

# PLATE 8

## Bryonoderm-Extended Facies Association: Reefal Limestone

**A, B** Photomicrographs of Bryonoderm-Extended Reefal Limestone Core Facies (section 7, c-311890). This boundstone-bafflestone is composed mainly of abundant micrite, fenestellid and ramose bryozoans (bry) in life position with encrusting *Tubiphytes* (tu), and rare sponge spicules (sp). Early marine cement (arrow) is present rimming pore spaces and non-ferroan equant spar occludes the remaining porosity. Scale bar is 0.5 mm.

**C, D** Photomicrographs of the Bryonoderm-Extended Reefal Limestone Flank Facies (section 14, c-311852 and c-311854). This facies is a wackestone that is dominantly composed of abundant micrite, echinoderms (ec) and large and small sponge spicules (sp). Scale bar is 0.5 mm.



bry
tu
B
sp
tu
C
cr
cr
sp
D
cr

## PLATE 9

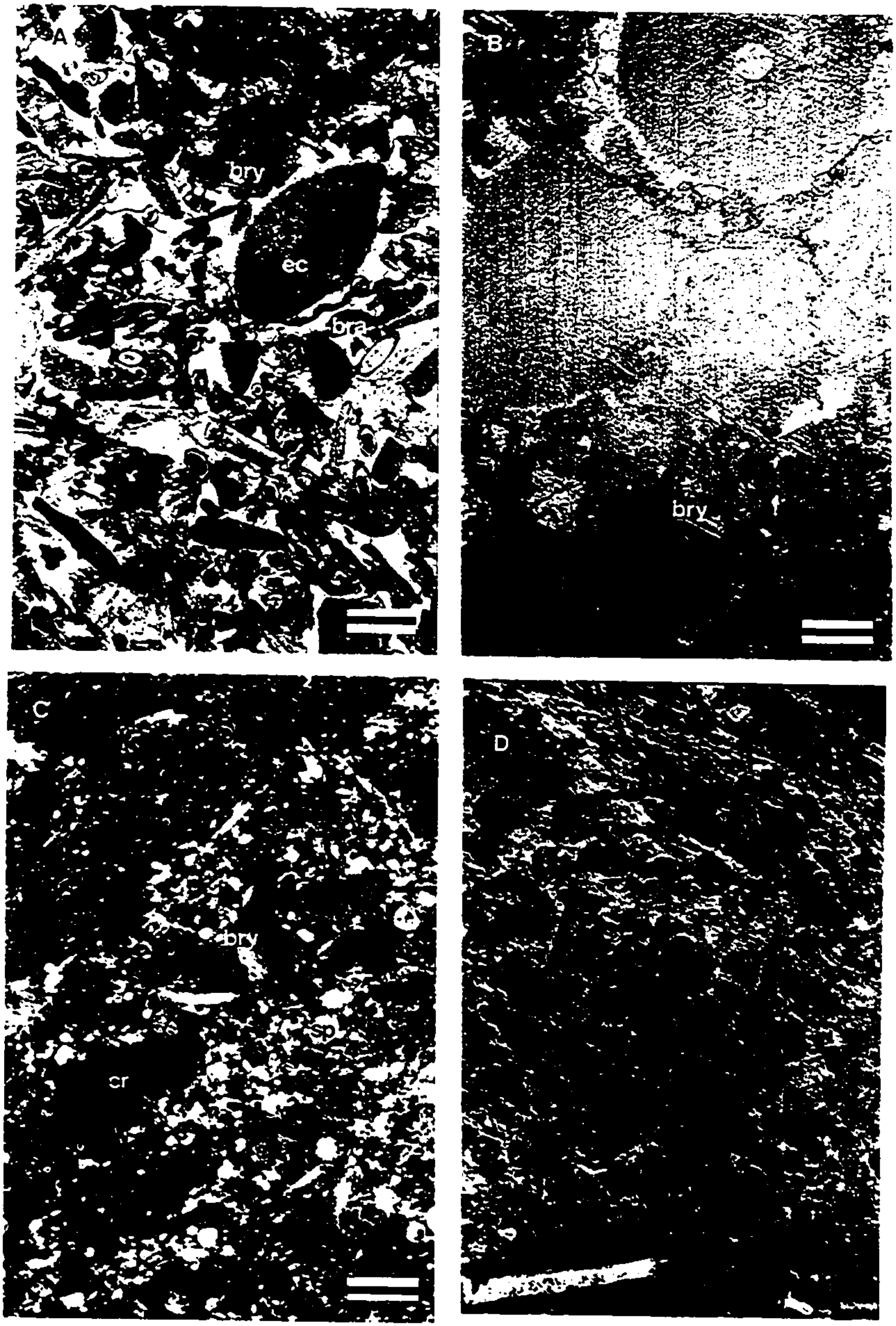
### Bryonoderm Facies Association

**A** Photomicrograph of Bryonoderm Grainstone (section 7, c-311904). This facies is composed mainly of abundant echinoderms (ec), bryozoans (bry), brachiopods (bra) and rare sponge spicules (sp). Scale bar is 0.5 mm.

**B** Photomicrograph of Bryonoderm Grainstone (section 5, c-311207) including echinoderms (ec) and bryozoans (bry). Note the dissolution of the bryozoan (arrow) against the more resistant echinoderm. Scale bar is 0.25 mm.

**C** Photomicrograph of Bryonoderm Wackestone to Packstone (section 4, c-311780). This facies is composed of echinoderms (ec), bryozoans (br) and abundant large and small sponge spicules (sp). The matrix is mainly composed of a mixture of micrite and green clay. Scale bar is 0.25 mm.

**D** Bedding plane view of preferentially silicified *Thalassinoides* burrows within Bryonoderm Wackestone to Packstone (section 5). Hammer for scale.


A
bry
ec
bra
B
bry
C
bry
sp
cr
D

## PLATE 10

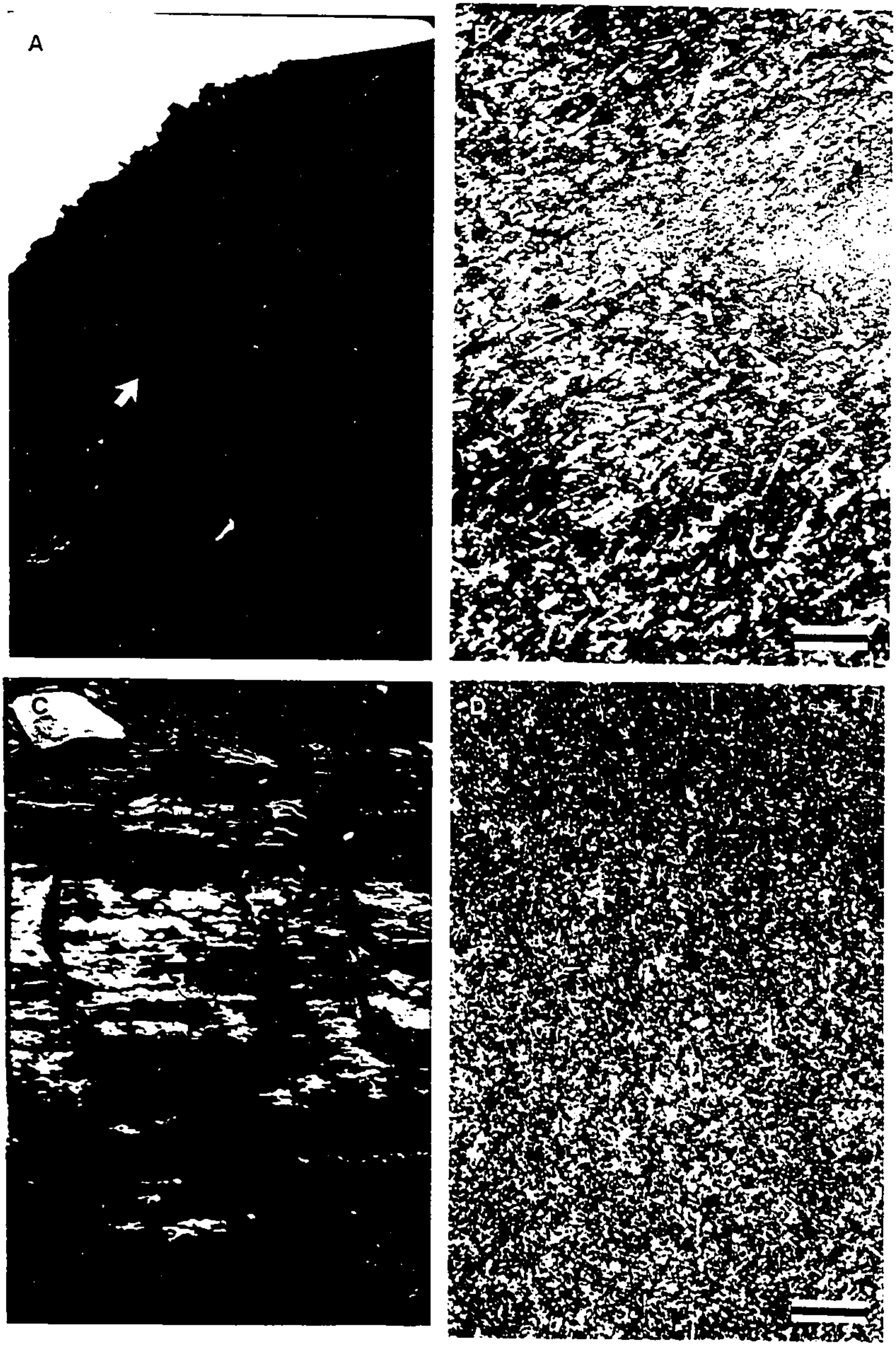
### Hyalosponge Facies Association

**A** Outcrop photo of Hyalosponge Mudrock (at arrow; section 9). This facies dominates in the upper portion of the RST and is interbedded with the Siliceous/Spiculitic Shale Facies. Hammer for scale.

**B** Photomicrograph of Hyalosponge Mudrock (section 15, c-311274). Sponge spicules (sp) dominate and bioclastic debris is rare. Scale bar is 0.5 mm.

**C** Outcrop photo of the Siliceous/Spiculitic Shale Facies (section 9). This facies dominates at the top of the TST and the base of the RST in basin sections and is interbedded with the Hyalosponge Mudrock. Hammer for scale.

**D** Photomicrograph of Siliceous/Spiculitic Shale (section 3, c-310801). Shale and small sponge spicules (sp) dominate. Scale bar is 0.5 mm.


A
B
C
D

## PLATE 11

### Mixed Facies Association

**A** Photomicrograph of Bryonoderm Spiculite (section 11, c-311934). Rare biotic components include bryozoans (bry), brachiopod (bra) fragments, large sponge spicules (sp) and abundant small spicules. Scale bar is 0.25 mm.

bra
bry
sp

## PLATE 12

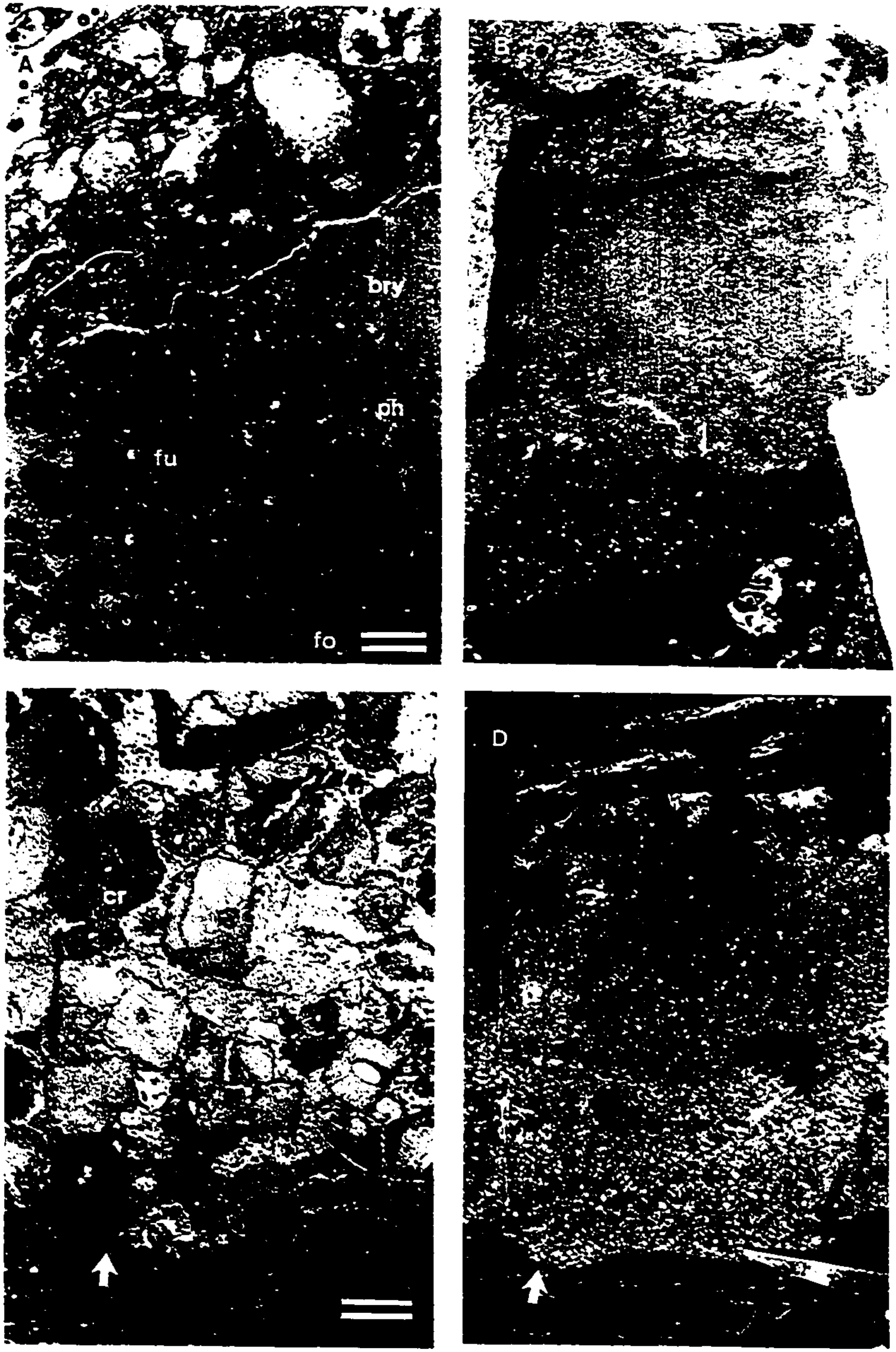
### Mixed Facies Association

**A** Photomicrograph of a debrite (section 8, c-311969). Note the clasts of the Chloroforam Wackestone containing phylloid algae (ph), fusulinids (fu) and benthic foraminifers (fo). Bryozoans (bry) are also present in a siliceous/spiculitic shale matrix. Scale bar is 0.5 mm.

**B** Outcrop photo of a debrite (section 8). This facies dominates in the lower portion of the TST and is interbedded with the Hyalosponge Facies Association. Hammer for scale.

**C** Photomicrograph of a crinoidal (cr) turbidite. Note the sharp scoured base (arrow; section 9, c-311835). Scale bar is 1.0 mm.

**D** Outcrop photo of a crinoidal turbidite (section 9). This facies dominates at the base of the RST in basinal sections and is interbedded with the Hyalosponge Facies Association. Note the scoured base (arrow) and the normally graded bedding. Hammer for scale.



A
bry
ph
fu
fo
B
cr
D

# APPENDICES

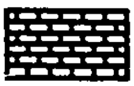
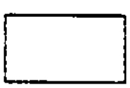
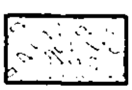
## APPENDIX 1: SECTION LOCATIONS

Locations of measured sections in the Otto Fiord area, northwest Ellesmere Island. Refer to Figure 1 in the body of the text for map of locations. The Field Location numbers are used in original sample numbers (Appendix 3).

| Section | Field Location | Latitude | Longitude |
|---|---|---|---|
| 1 | 12 | 80° 59' N | 88° 01' W |
| 2 | 6 | 81° 04' N | 87° 56' W |
| 3 | 1 | 81° 04' N | 86° 50' W |
| 4 | 3 | 81° 17' N | 85° 49' W |
| 5 | 5 | 81° 18' N | 85° 29' W |
| 6 | 14 | 81° 21' N | 84° 56' W |
| 7 | 15 | 81° 26' N | 84° 34' W |
| 8 | 11 | 81° 03' N | 85° 30' W |
| 9 | 8 | 81° 07' N | 84° 54' W |
| 10 | 9 | 81° 09' N | 84° 20' W |
| 11 | 10 | 81° 13' N | 84° 17' W |
| 12 | 2 | 81° 13' N | 82° 05' W |
| 13 | 4 | 81° 20' N | 84° 48' W |
| 14 | 13 | 81° 01' N | 89° 17' W |
| 15 | 7 | 81° 08' N | 86° 57' W |

# APPENDIX 2: STRATIGRAPHIC SECTIONS

# APPENDIX 2 -LEGEND

| LITHOLOGY | | ASSOCIATED LITHOFACIES | |
|---|---|---|---|
| *MID- TO OUTER SHELF* | | | |
|  | Limestone | Chloroforam Grainstone | C1 |
| | | Chloroforam Wackestone to Packstone | C2 |
| | | Bryonoderm-ExtendedGrainstone | BE1 |
| | | Bryonoderm-Extended Packstone | BE2 |
| | | Bryonoderm Grainstone | B1 |
| *REEF* | | | |
|  | Reefal Limestone | Bryonoderm-Extended Reefal Limestone | BE3 |
| *SHELF MARGIN* | | | |
|  | Cherty Argillaceous Limestone | Bryonoderm Wackestone to Packstone | B2 |
|  | Calcareous Chert | Bryonoderm Spiculite | B3 |
| *SLOPE/BASIN* | | | |
|  | Bedded Chert | Hyalosponge Mudrock | H |
|  | Fissile Shale | Siliceous/Spiculitic Shale | SS |
|  | Debrite/Turbidite | Debrite/Turbidite | DT |

*TEXTURES*

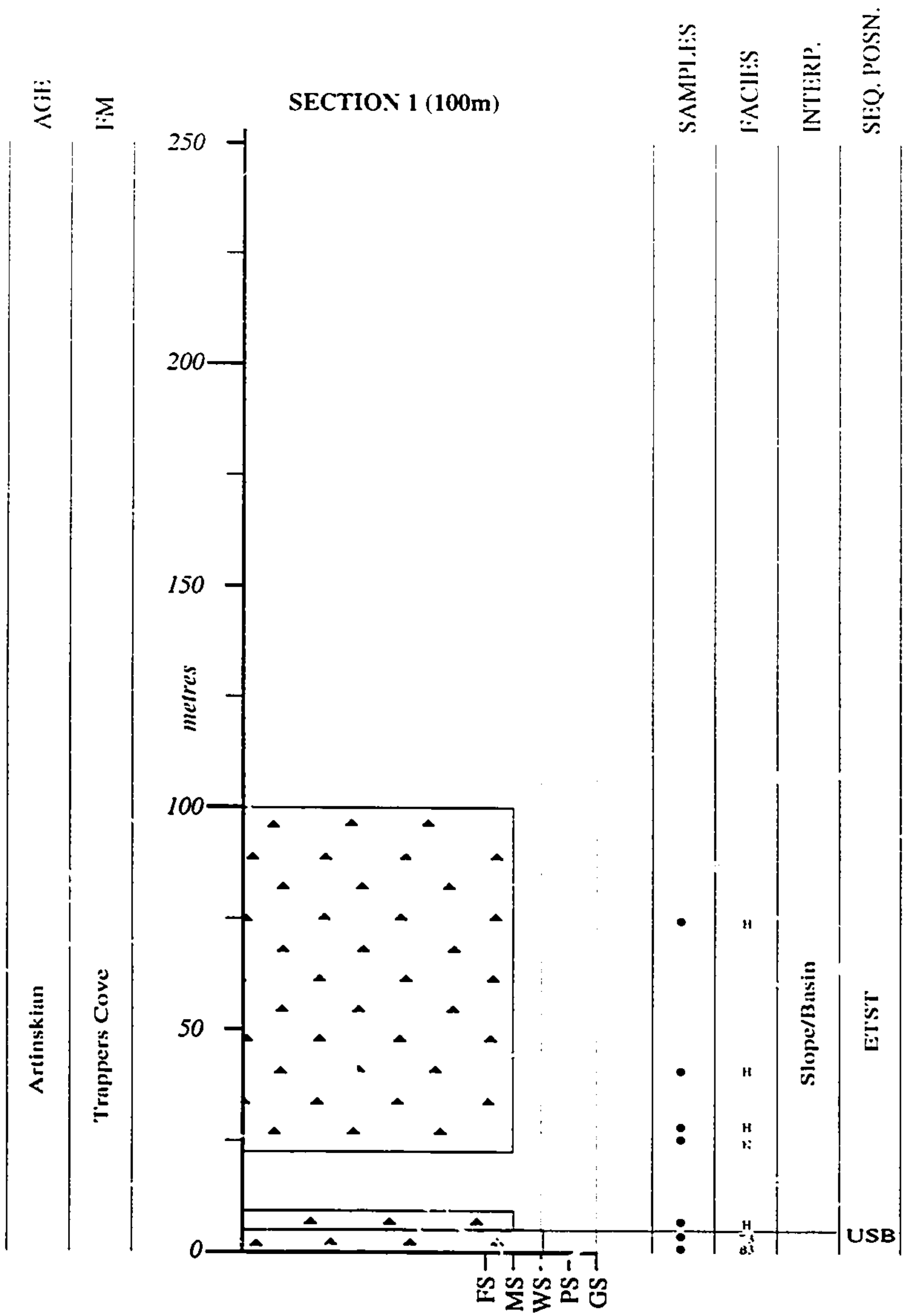
FS = Fissile Shale

MS = Mudstone

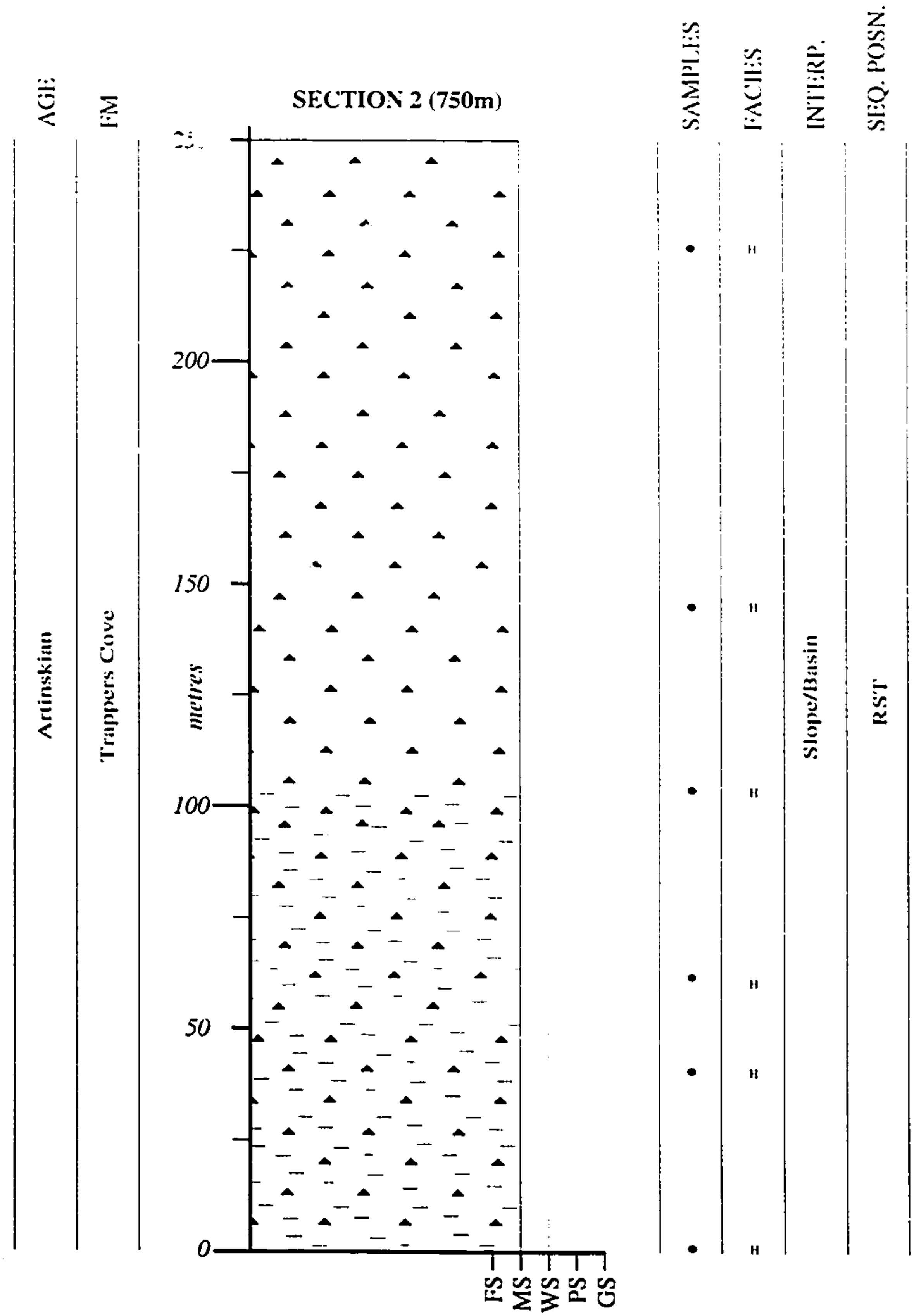
WS = Wackestone

PS = Packstone

GS = Grainstone



AGE
FM
SECTION 1 (100m)
SAMPLES
FACIES
INTERP.
SEQ. POSN.
250
200
150
metres
100
50
0
Artinskian
Trappers Cove
Slope/Basin
ETST
USB
H
FS
MS
WS
PS
GS



AGE
FM
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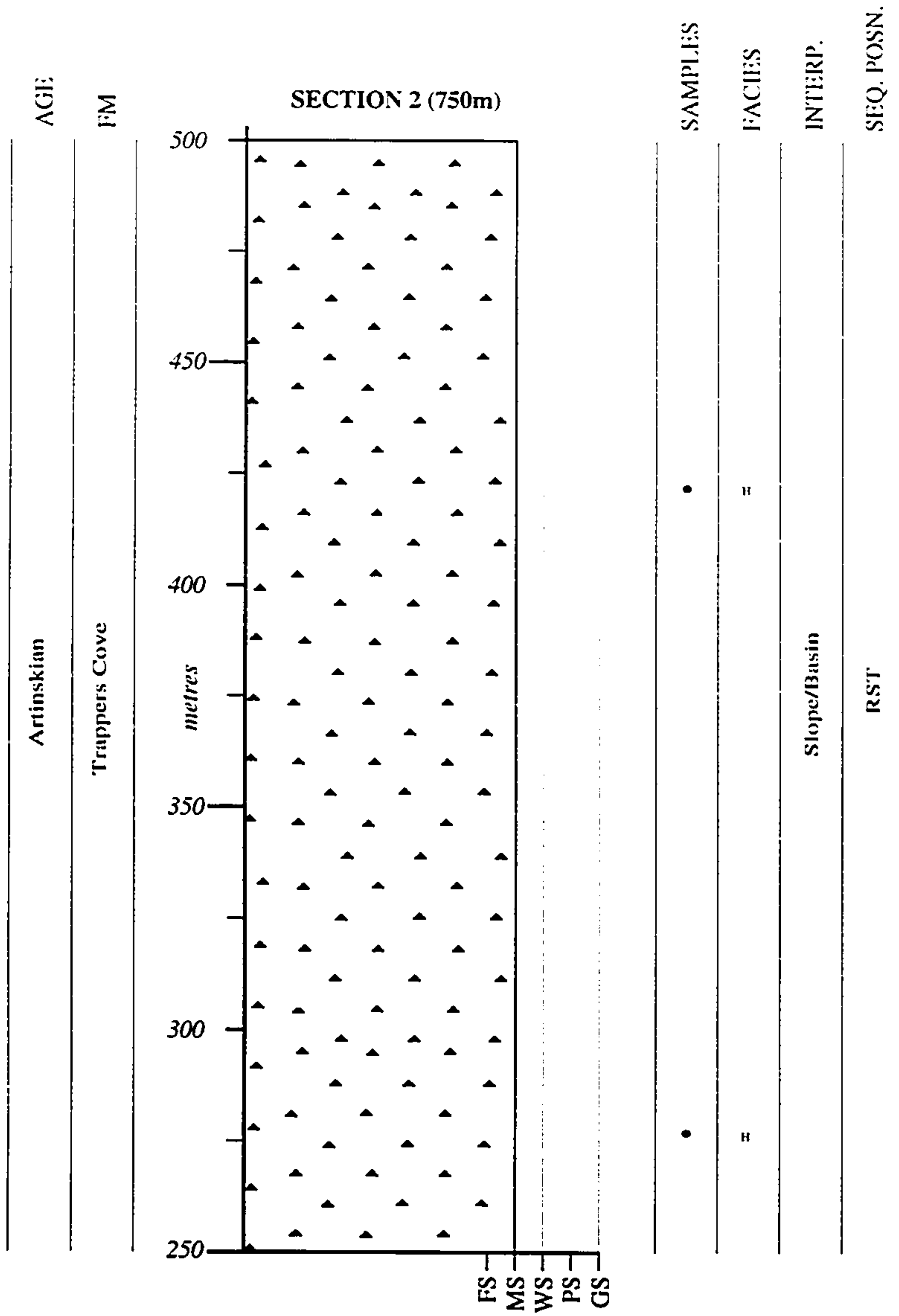
SAMPLES
FACIES
INTERP.
SEQ. POSN.
Artinskian
Trappers Cove
metres
200
150
100
50
0
Slope/Basin
RST
FS
MS
WS
PS
GS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FM
SECTION 2 (750m)
SAMPLES
FACIES
INTERP.
SEQ. POSN.
500
450
400
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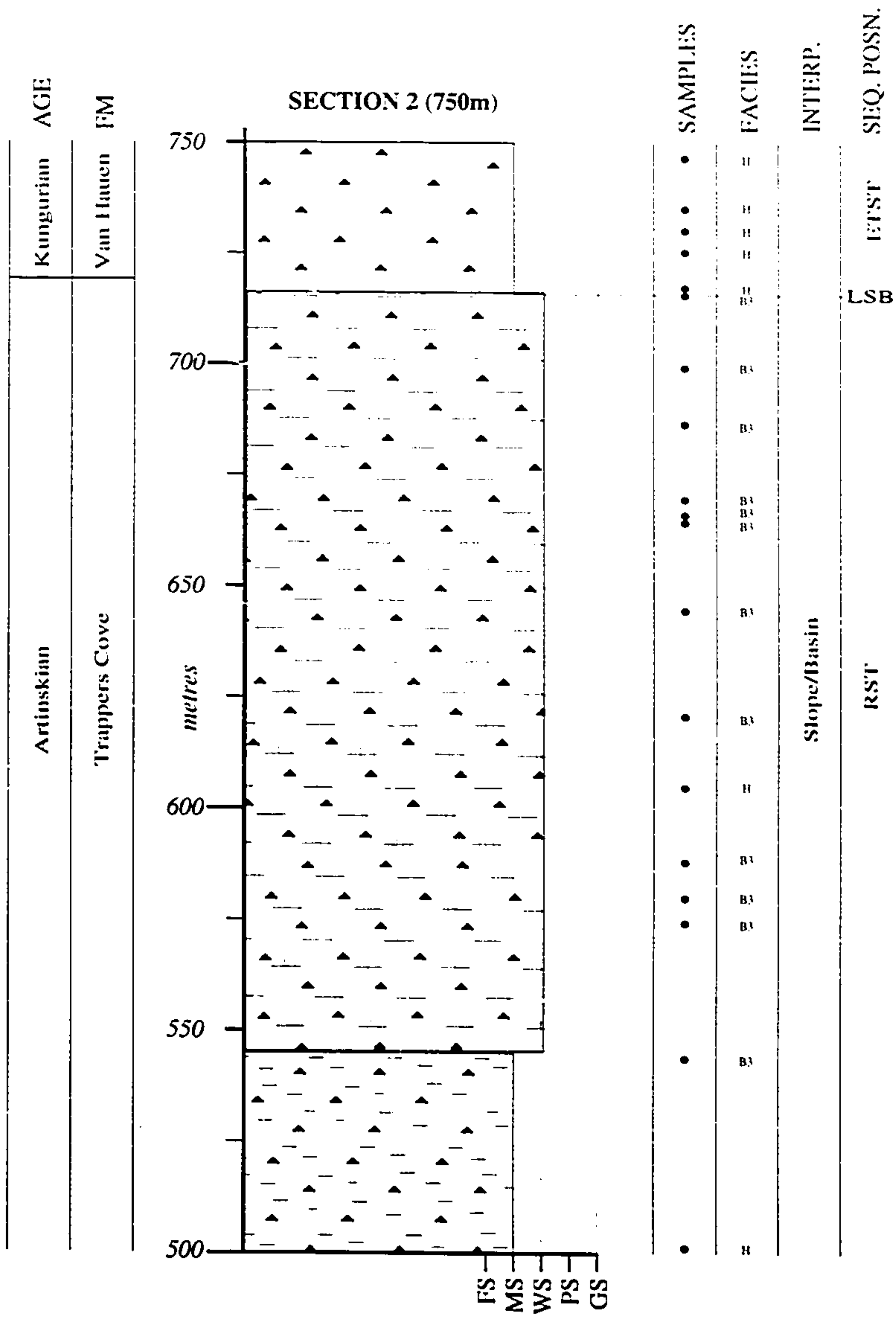
300
250
metres
Artinskian
Trappers Cove
Slope/Basin
RST
FS
MS
WS
PS
GS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FM
Kungurian
Van Hauen
Artinskian
Trappers Cove
metres
750
700
650
600
550
500
FS
MS
WS
PS
GS
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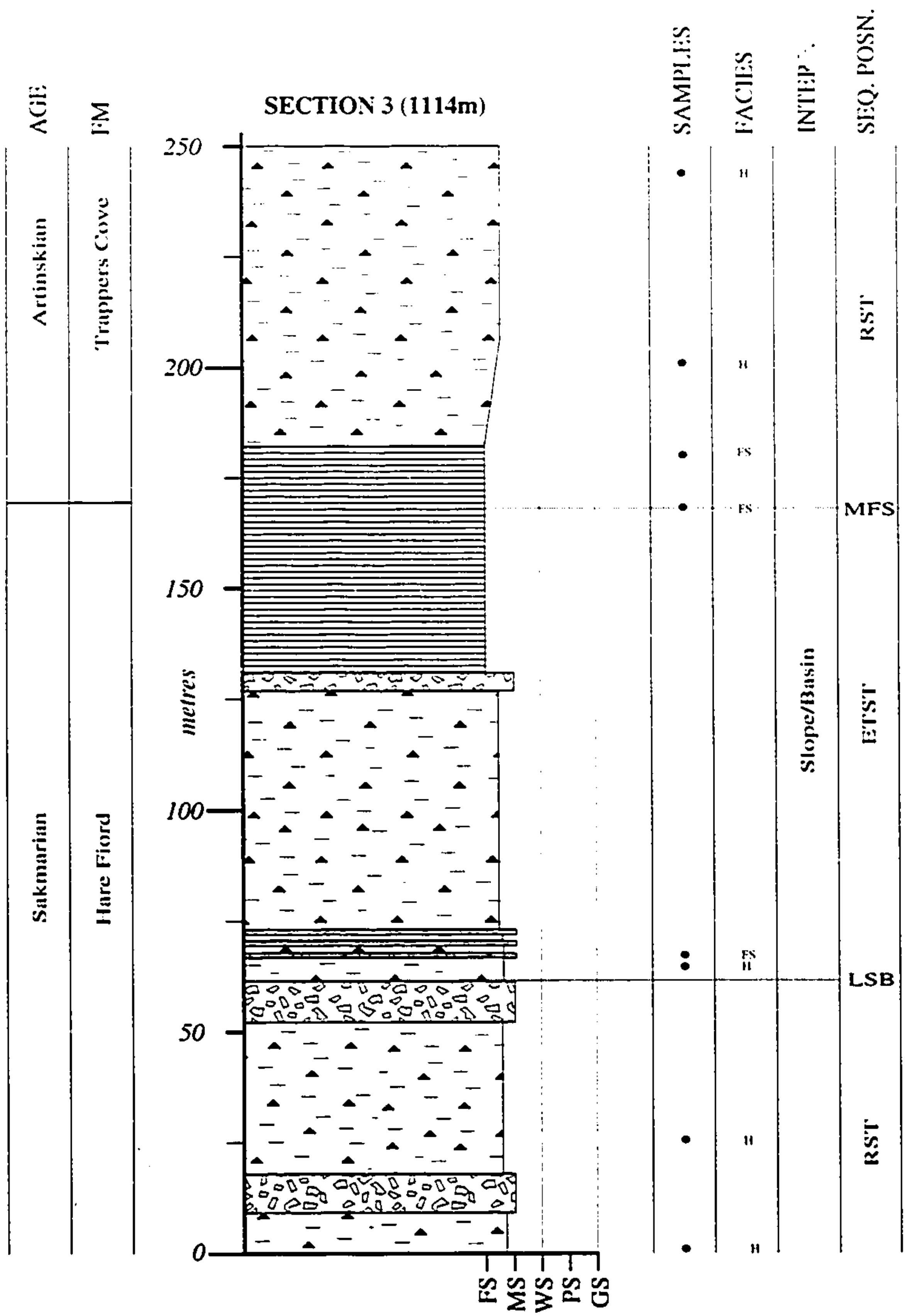
FACIES
INTERP.
SEQ. POSN.
H
B3
Slope/Basin
ETST
LSB
RST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INTEP
SEQ. POSN.
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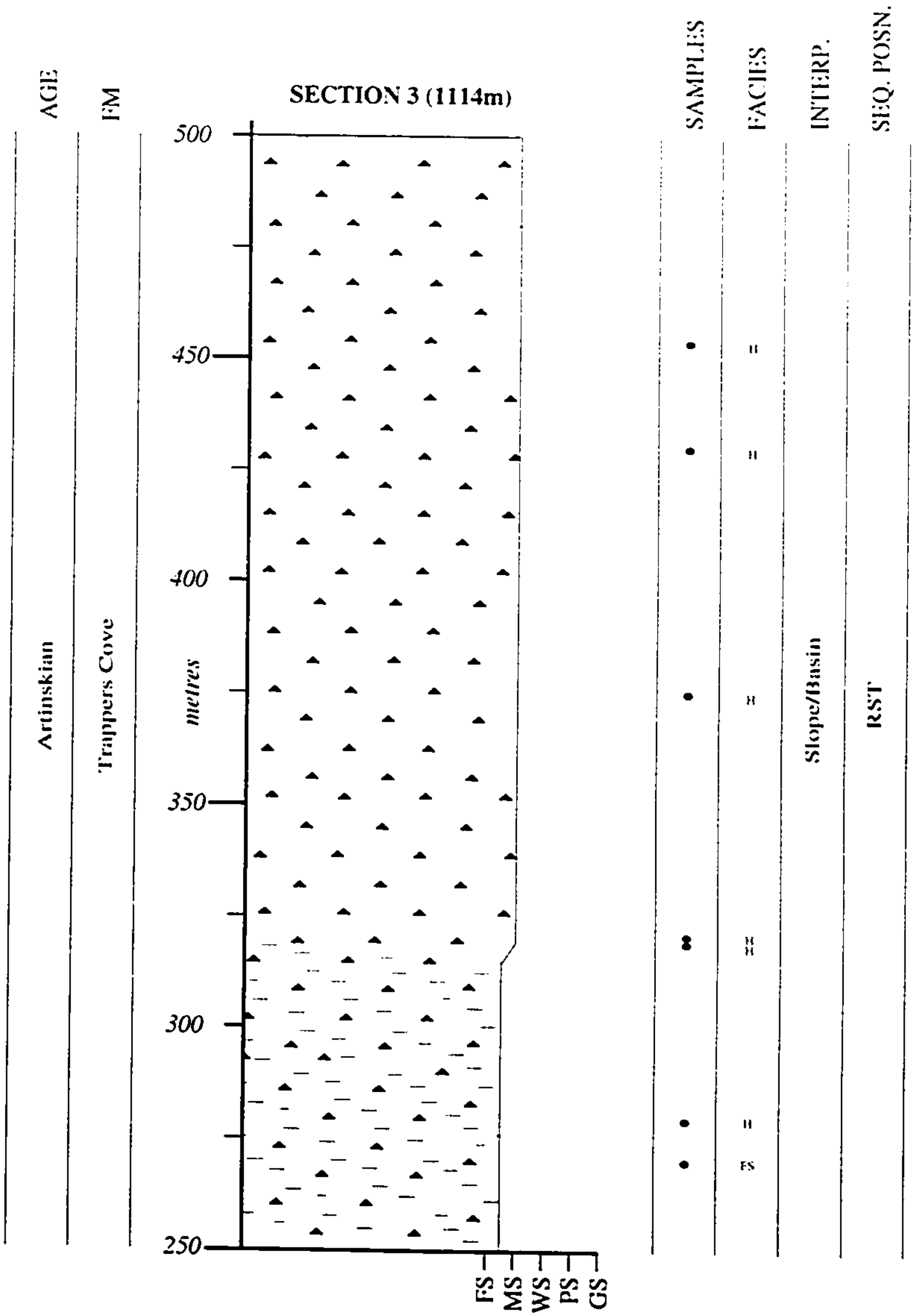
Trappers Cove
Sakmarian
Hare Fiord
250
200
150
100
50
0
metres
H
FS
MFS
Slope/Basin
ETST
RST
LSB
FS
MS
WS
PS
GS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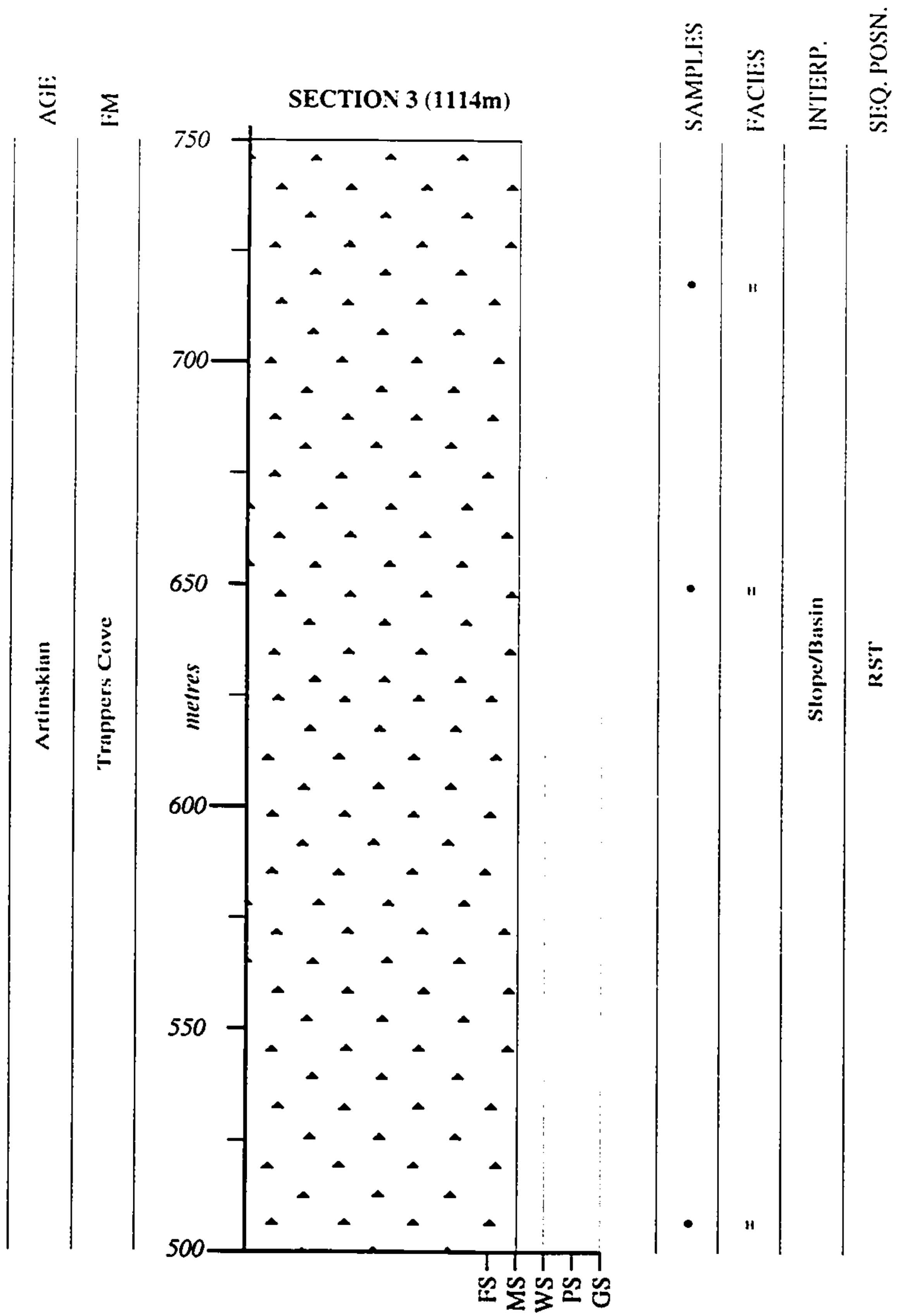
AGE
FM
SAMPLES
FACIES
INTERP.
SEQ. POSN.
Artinskian
Trappers Cove
metres
500
450
400
350
300
250
H
H
H
H
H
H
FS
Slope/Basin
RST
FS
MS
WS
PS
GS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FM
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FACIES
INTERP.
SEQ. POSN.
Artinskian
Trappers Cove
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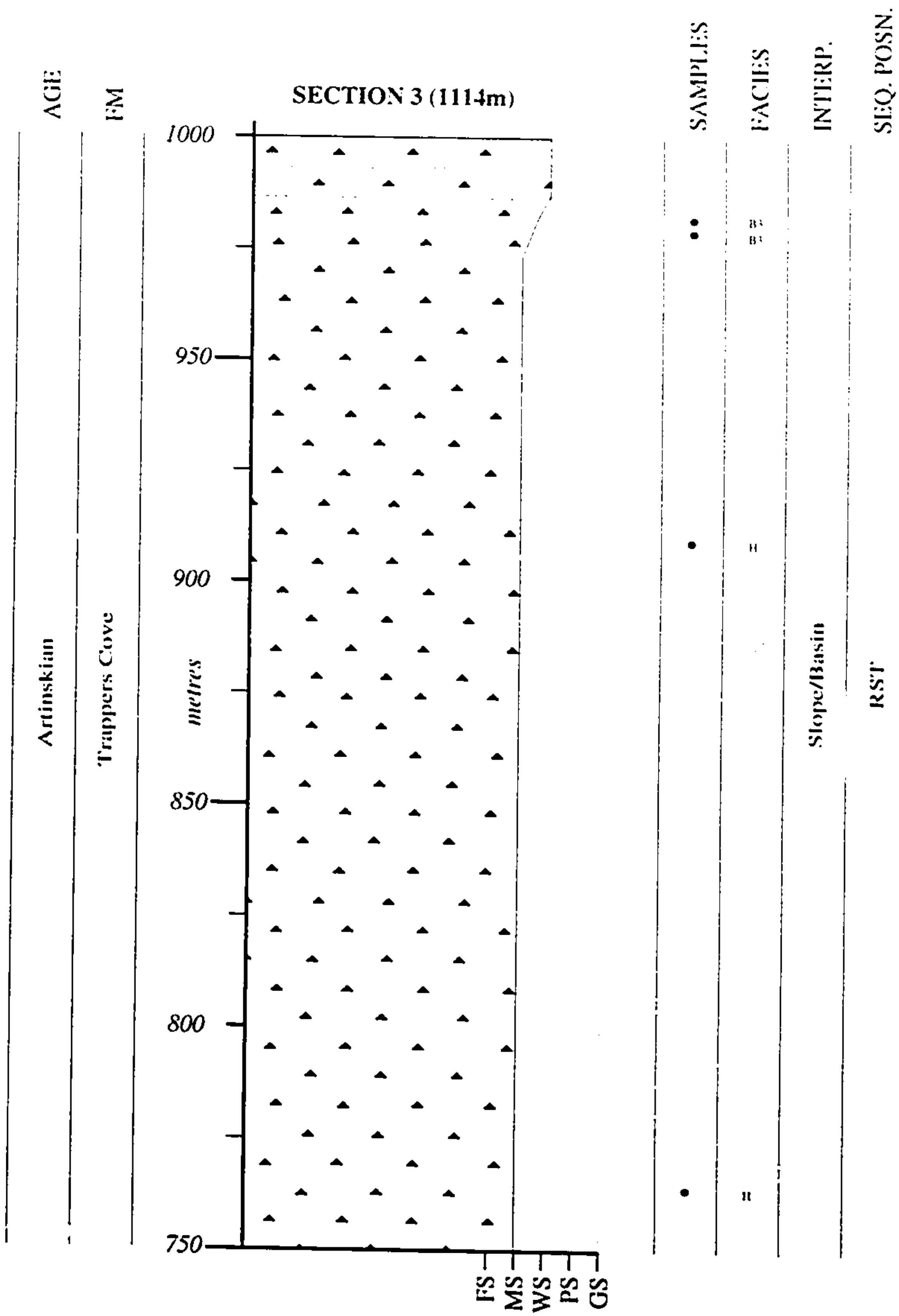
700
650
600
550
500
Slope/Basin
RST
FS
MS
WS
PS
GS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INTERP.
SEQ. POSN.
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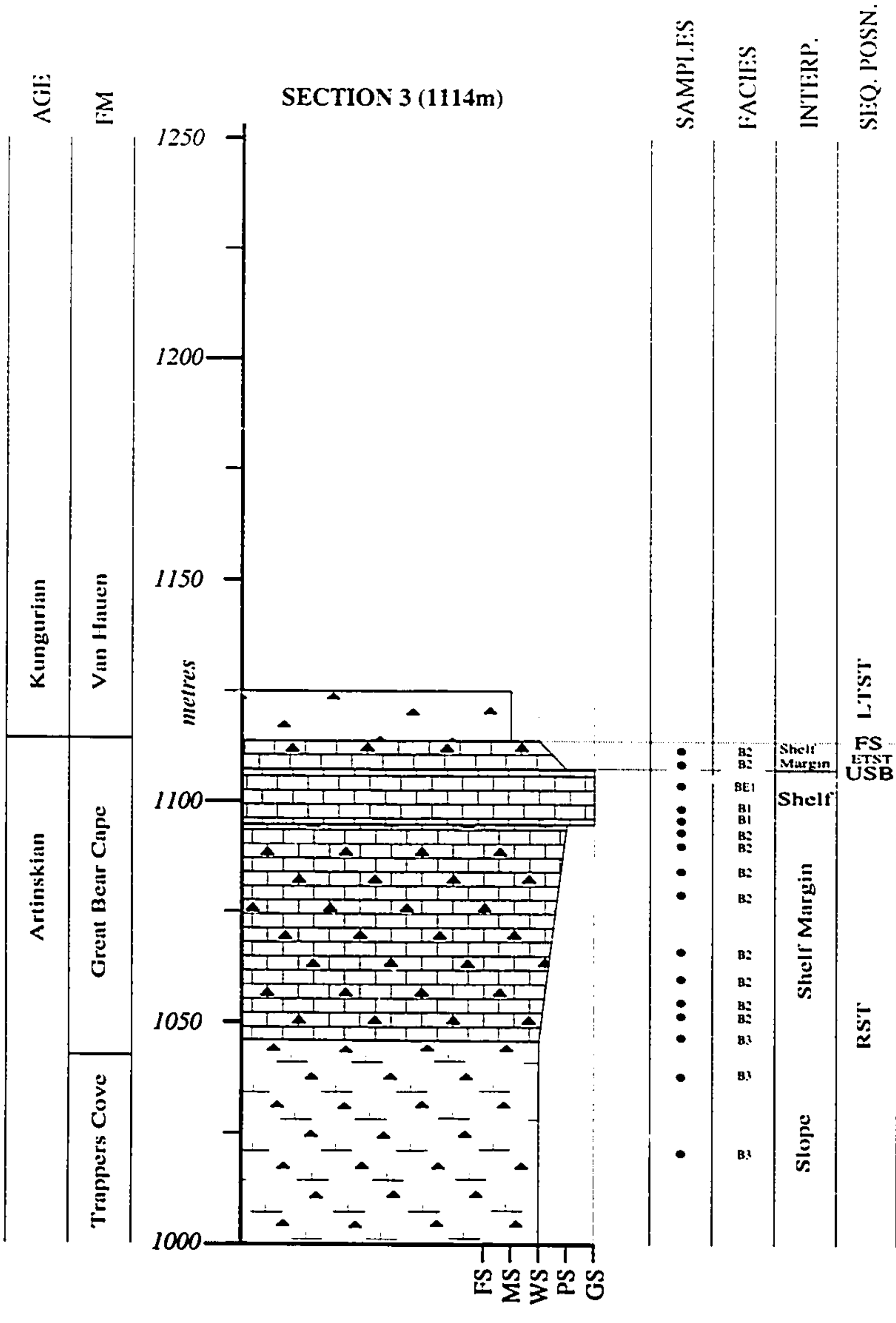
metres
Artinskian
Trappers Cove
Slope/Basin
RST
FS
MS
WS
PS
GS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INTERP.
SEQ. POSN.
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1200
1150
1100
1050
1000
metres
Kungurian
Artinskian
Van Hauen
Great Bear Cape
Trappers Cove
B2
B2
BE1
B1
B1
B2
B2
B2
B2
B2
B2
B2
B2
B3
B3
B3
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Shelf
Shelf Margin
Slope
LTST
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ETST
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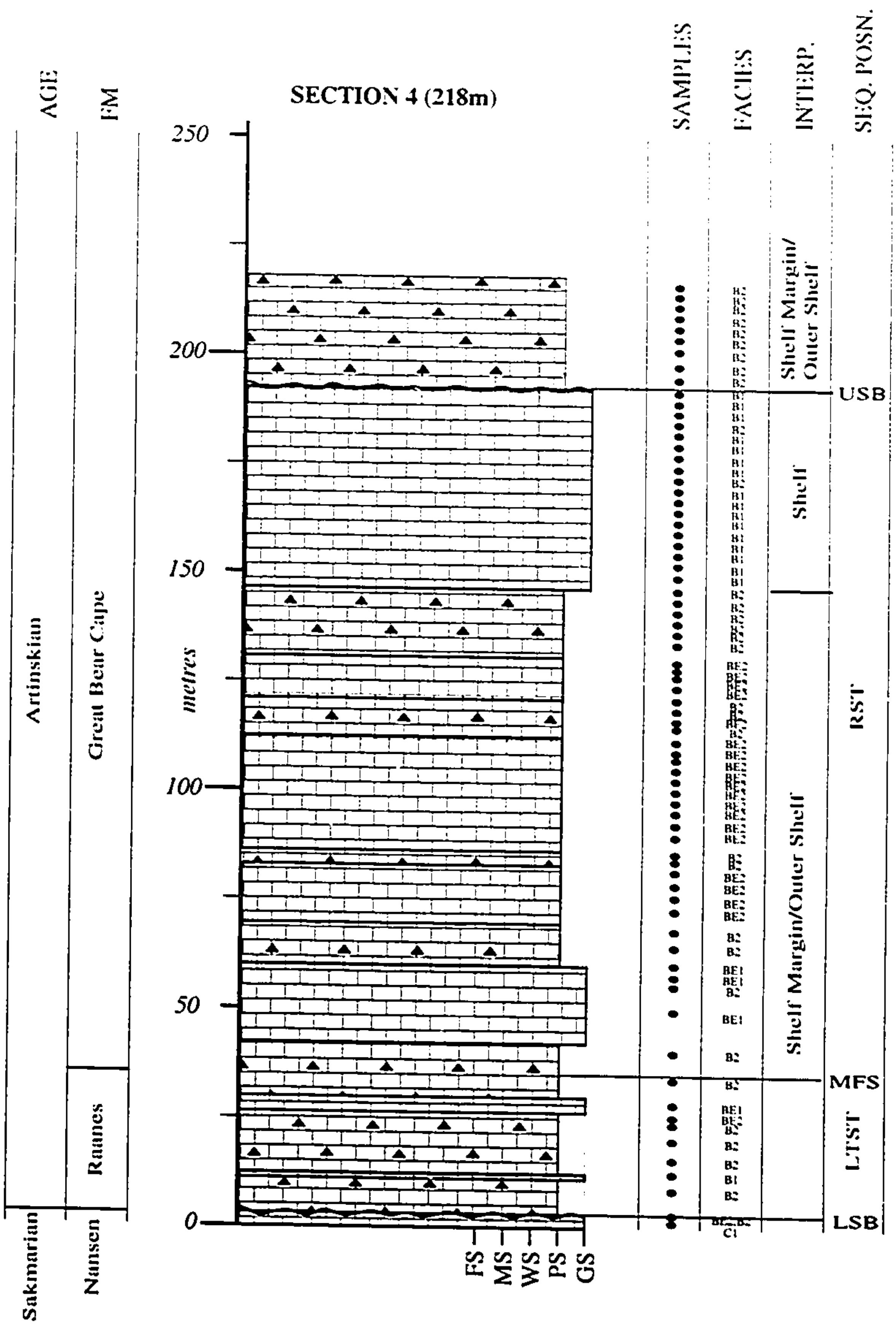
PS
GS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SAMPLES
FACIES
INTERP.
SEQ. POSN.
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200
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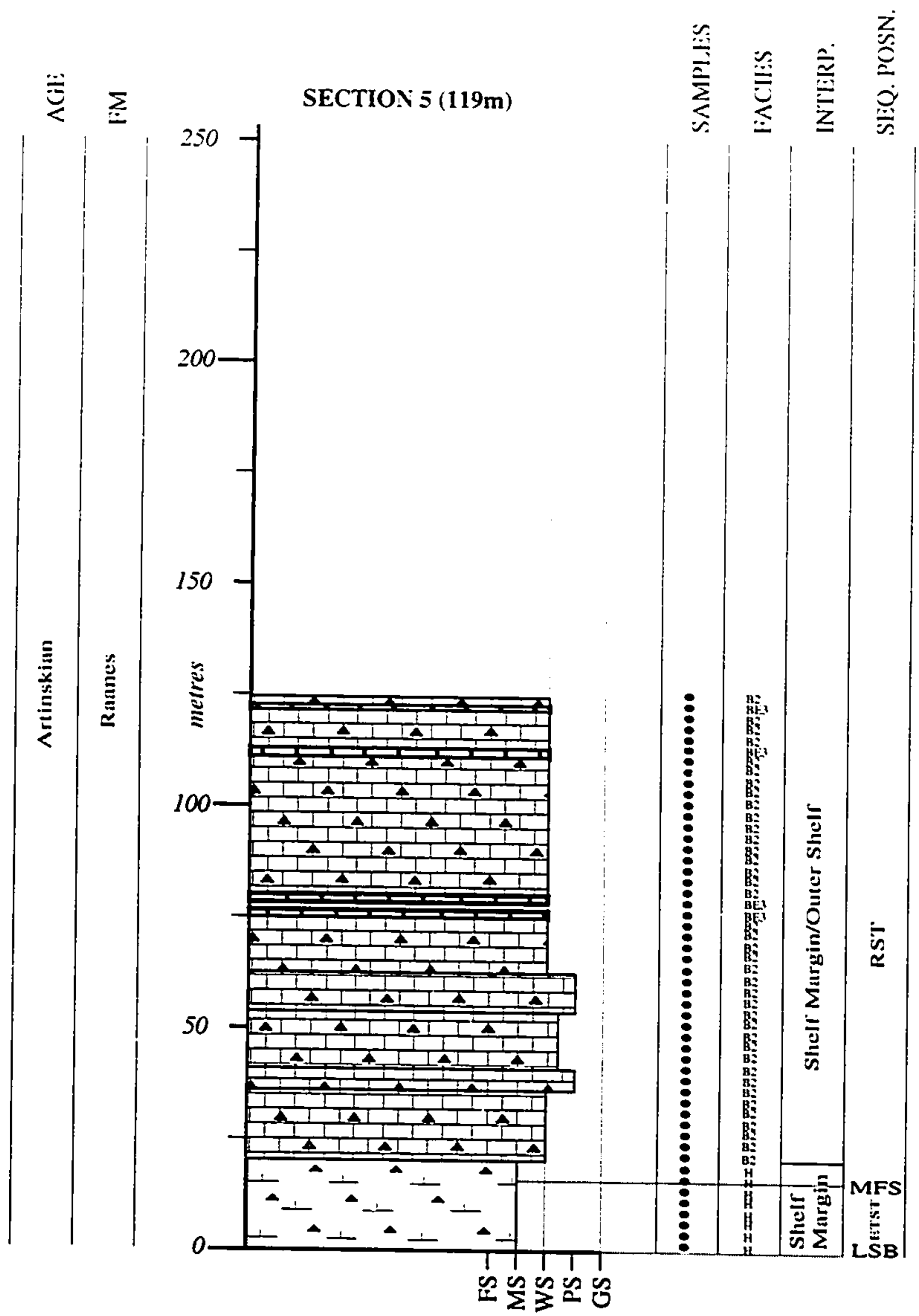
100
50
0
metres
Artinskian
Sakmarian
Great Bear Cape
Raanes
Nansen
FS
MS
WS
PS
GS
Shelf Margin/ Outer Shelf
Shelf
Shelf Margin/Outer Shelf
USB
RST
MFS
LTST
LSB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SAMPLES
FACIES
INTERP.
SEQ. POSN.
Artinskian
Raanes
metres
250
200
150
100
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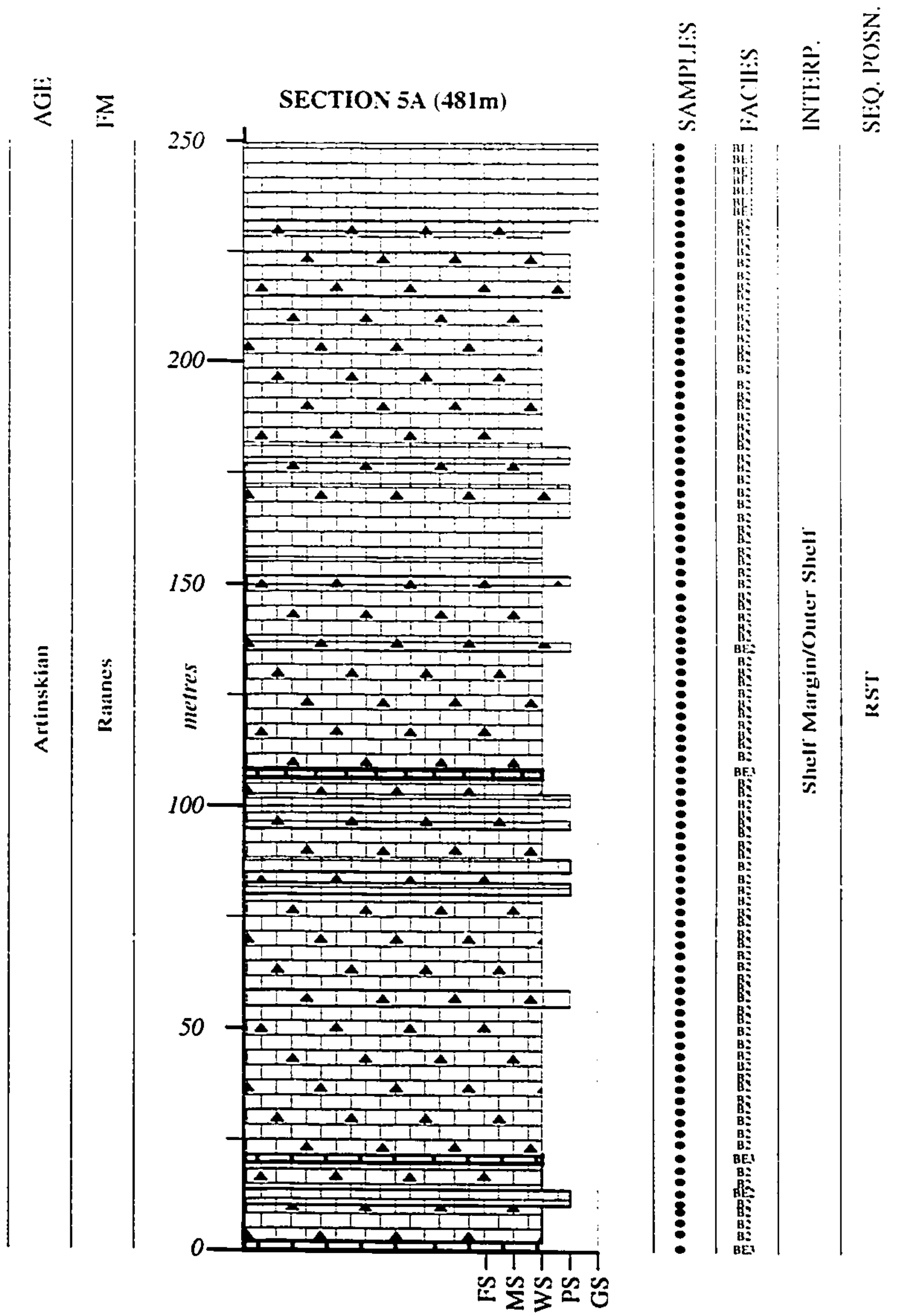
0
FS
MS
WS
PS
GS
Shelf Margin/Outer Shelf
Shelf Margin
RST
MFS
HST
LSB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SAMPLES
FACIES
INTERP.
SEQ. POSN.
Artinskian
Raanes
metres
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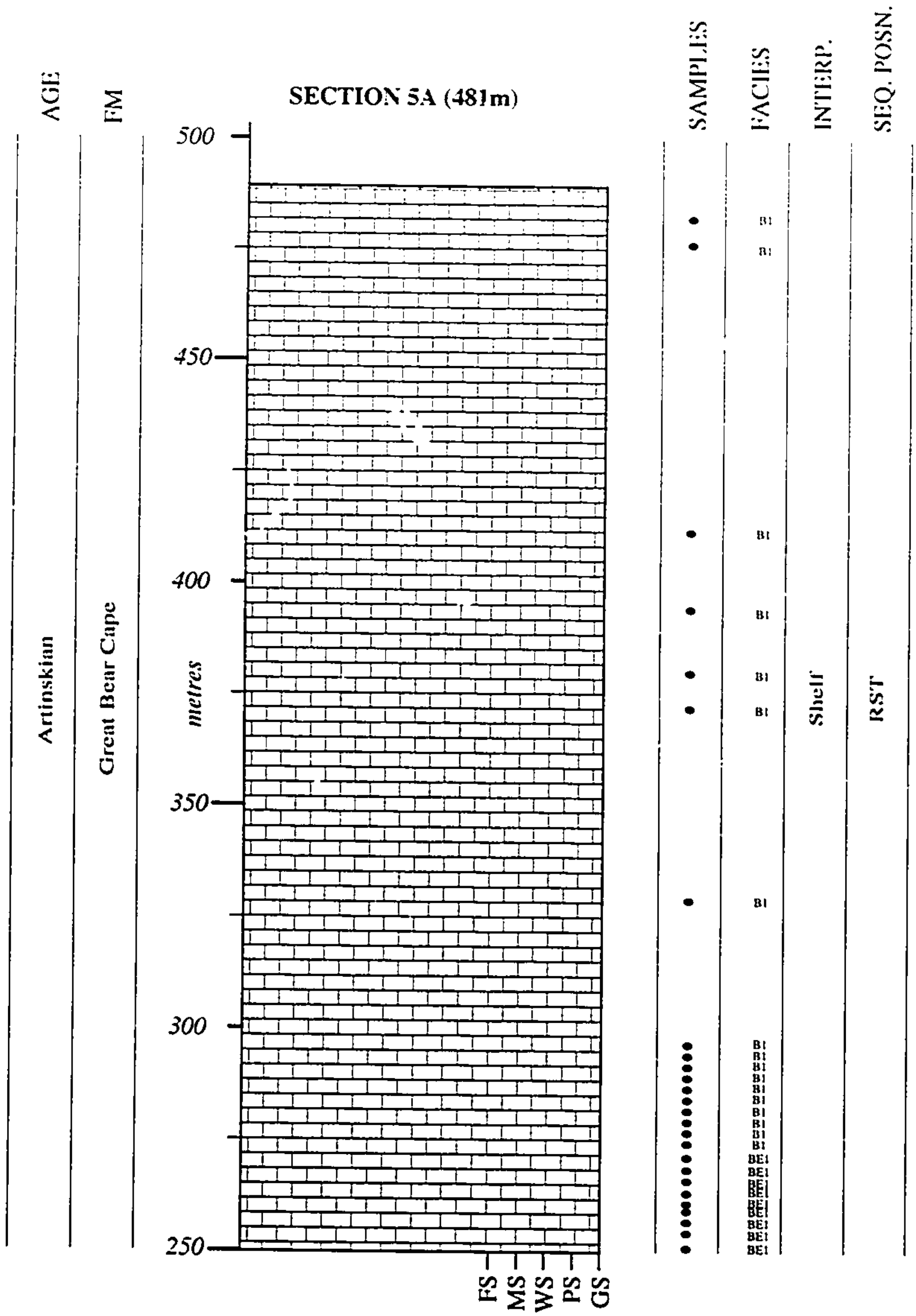
200
150
100
50
0
Shelf Margin/Outer Shelf
RST
FS
MS
WS
PS
GS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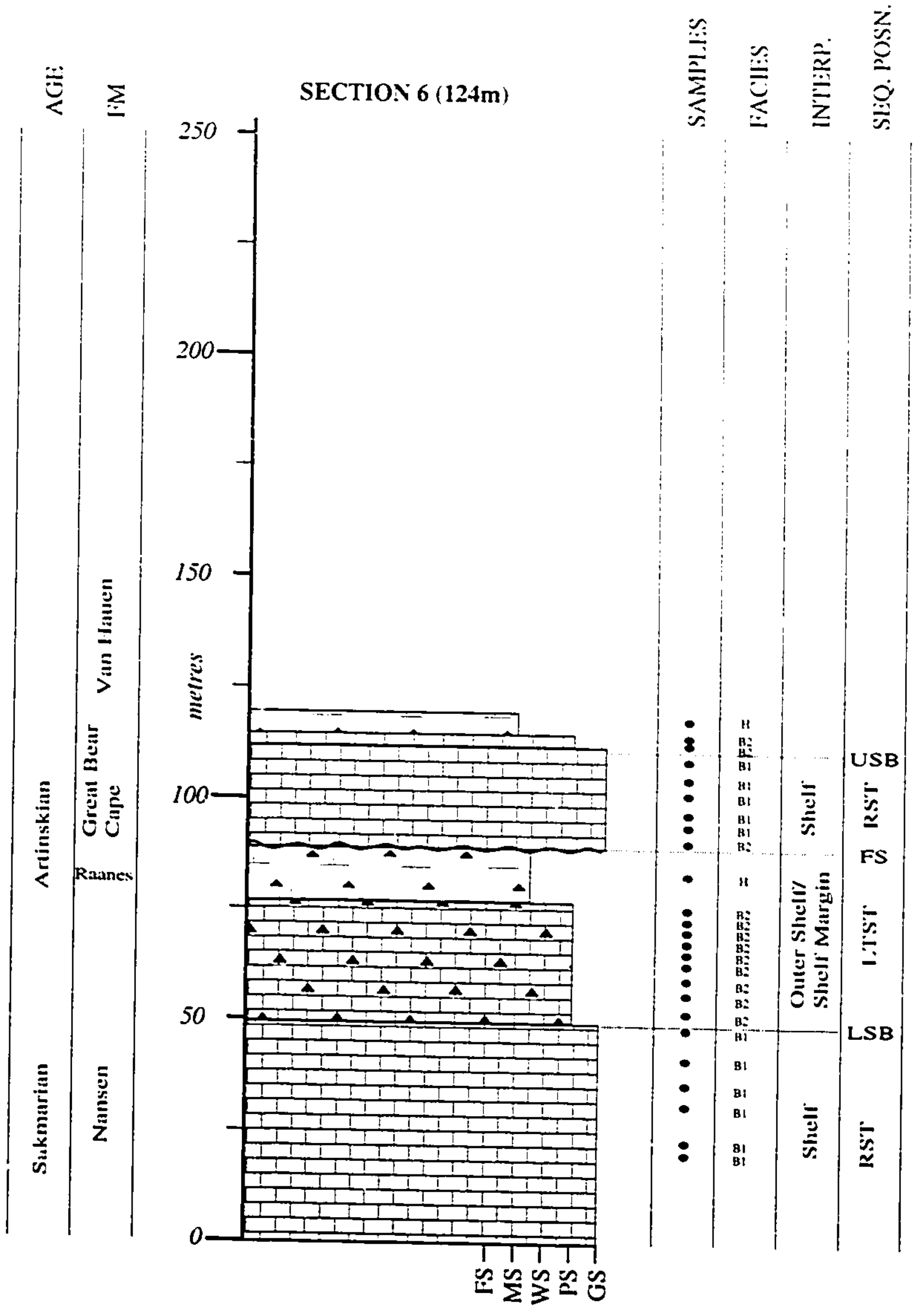
AGE
FM
SAMPLES
FACIES
INTERP.
SEQ. POSN.
500
450
400
350
300
250
metres
Artinskian
Great Bear Cape
Shelf
RST
B1
BE1
FS
MS
WS
PS
GS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SAMPLES
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150
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50
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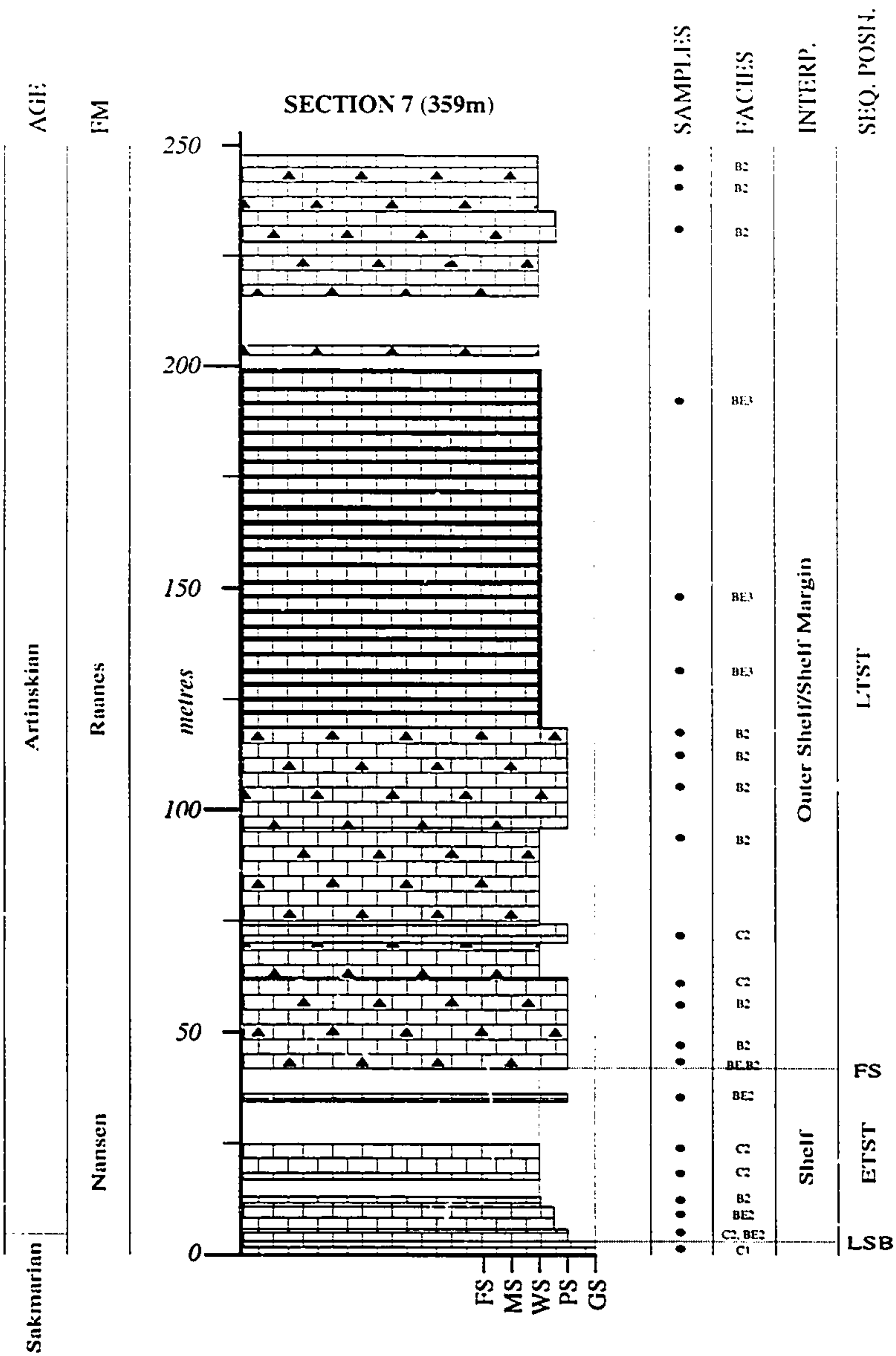
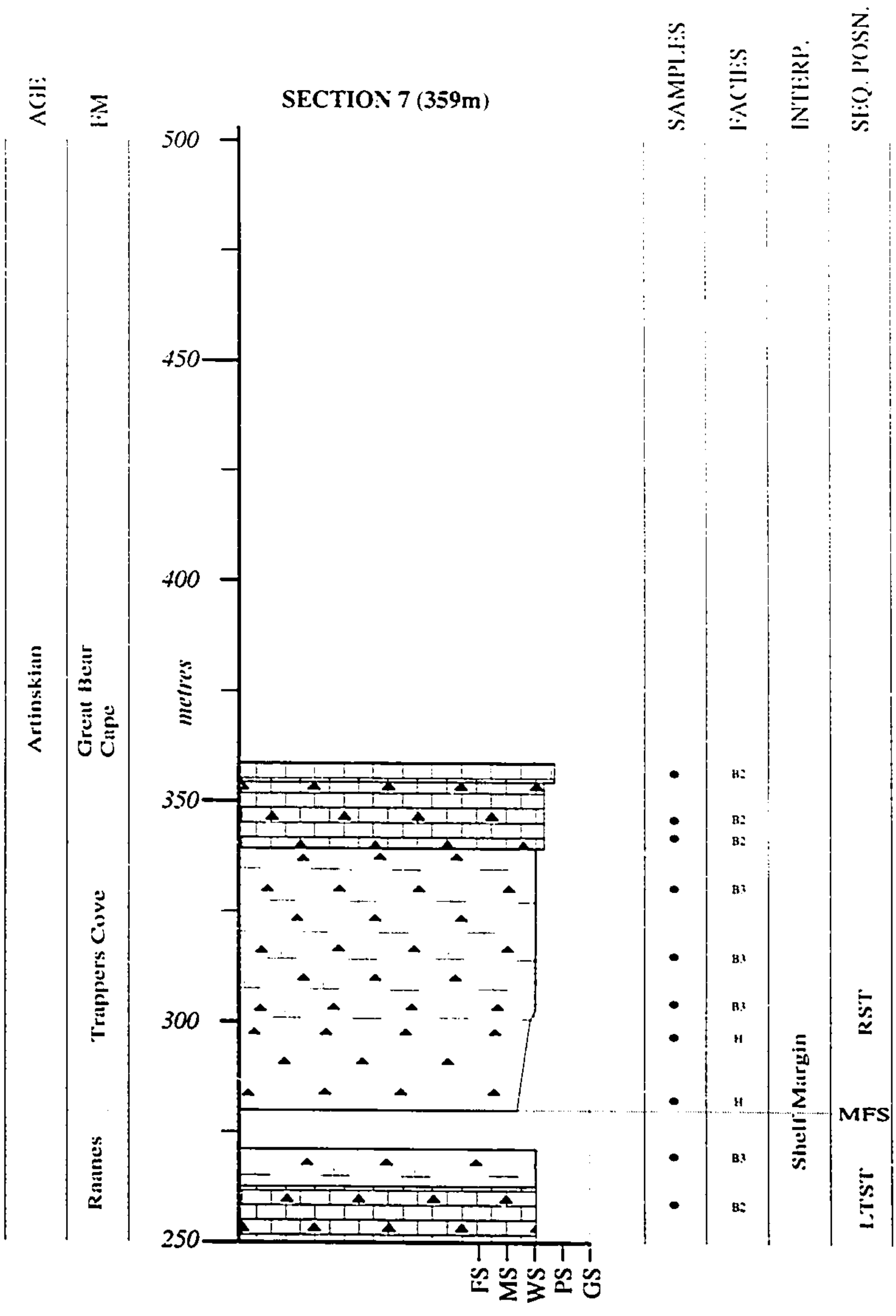
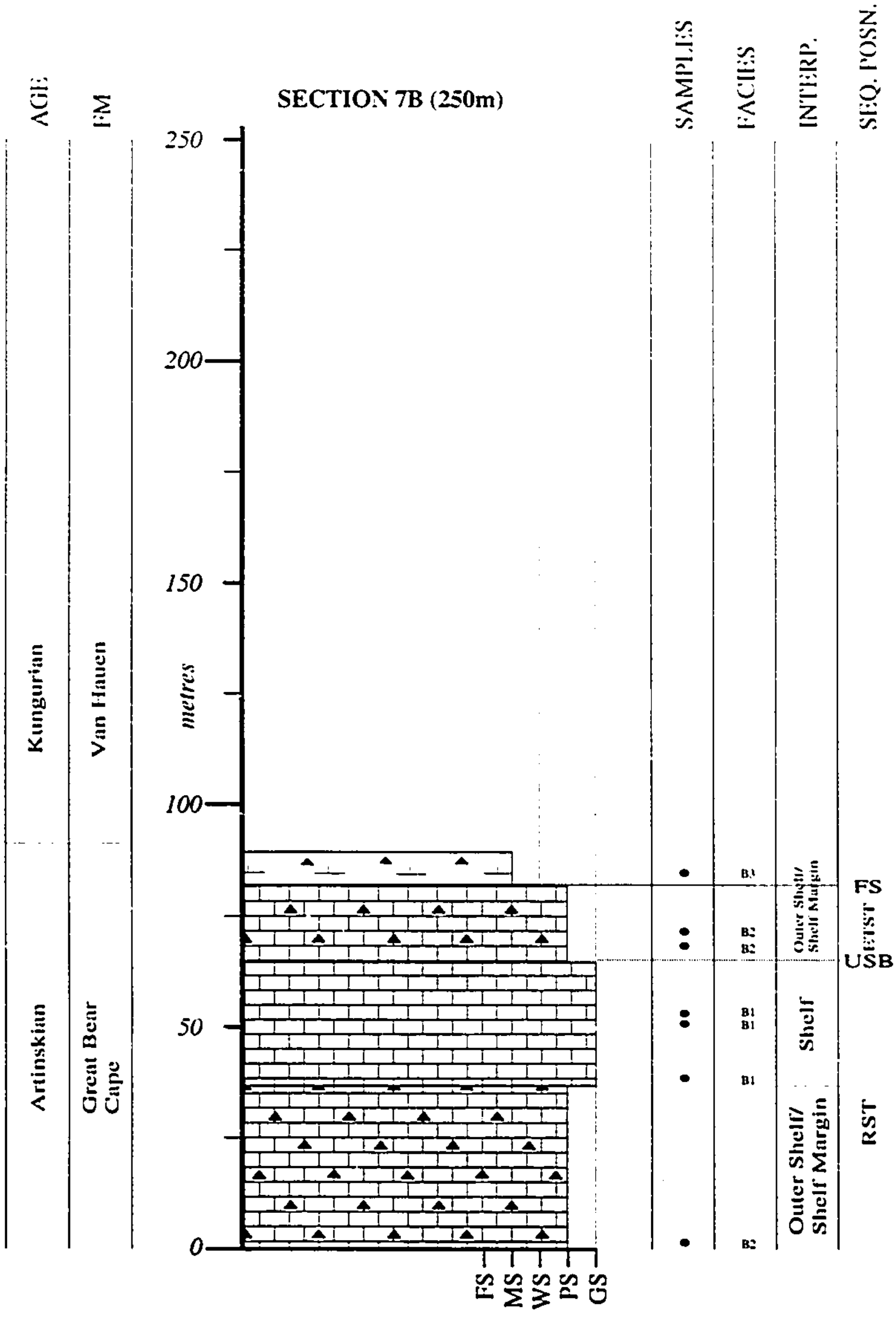
metres
Artinskian
Sakmarian
Van Hauen
Great Bear Cape
Raanes
Nansen
FS
MS
WS
PS
GS
USB
RST
FS
LTST
LSB
RST
Shelf
Outer Shelf/ Shelf Margin
Shelf

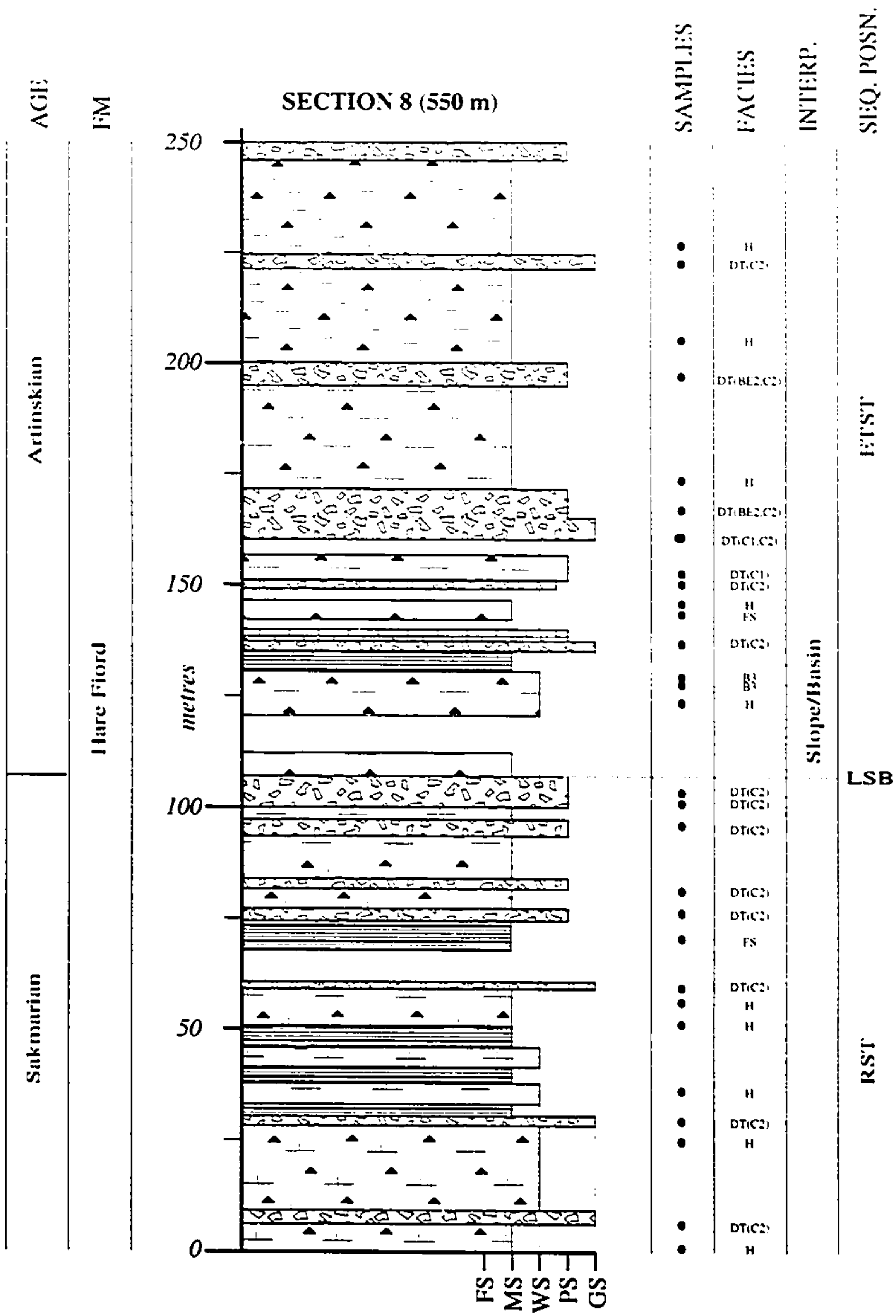


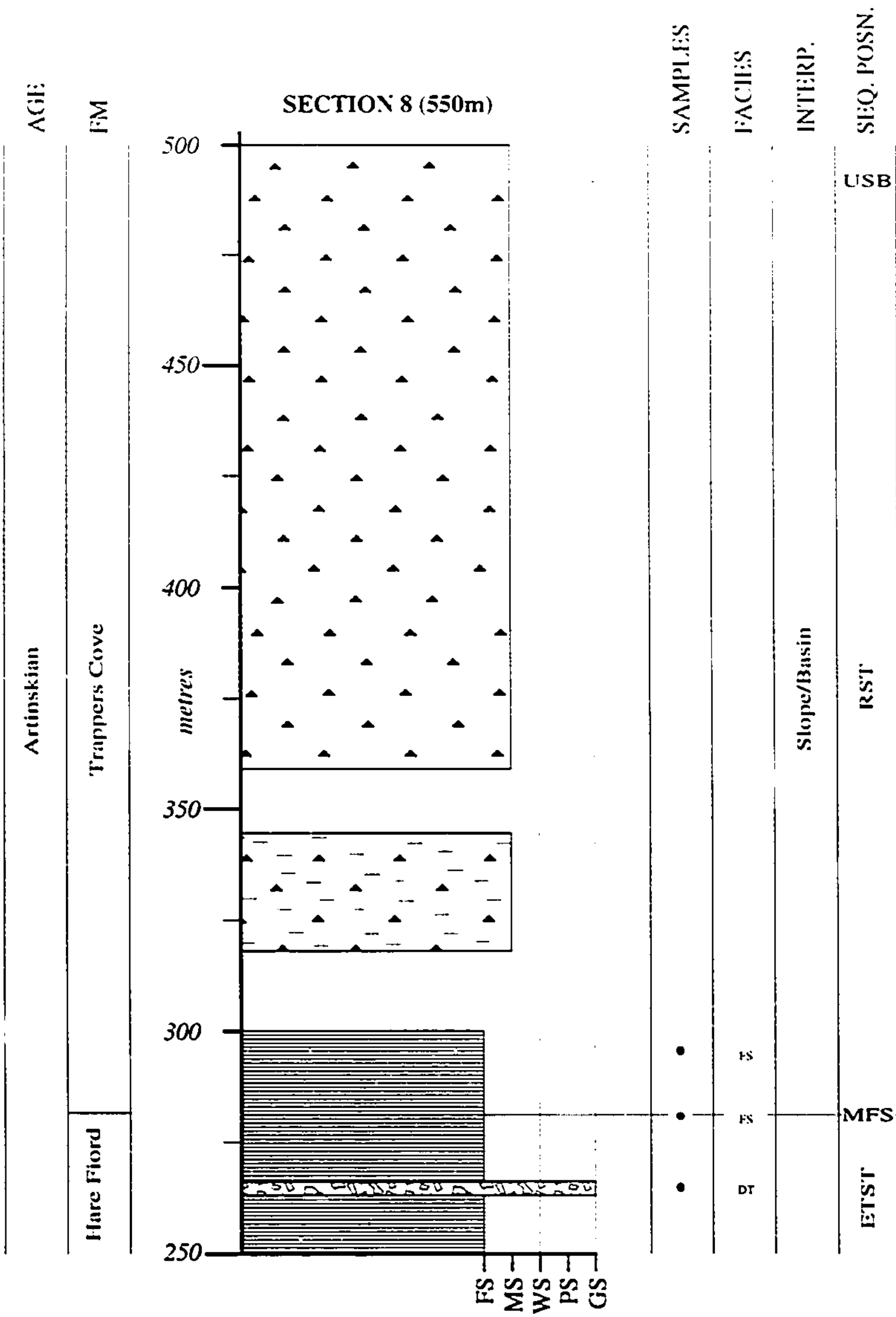
SECTION 7 (359m)
AGE
FM
SAMPLES
FACIES
INTERP.
SEQ. POSN.
Artinskian
Sakmarian
Raanes
Nansen
metres
250
200
150
100
50
0
FS
MS
WS
PS
GS
B2
BE3
C2
BE2
BE,B2
C2, BE2
C1
Outer Shelf/Shelf Margin
Shelf
LTST
FS
ETST
LSB

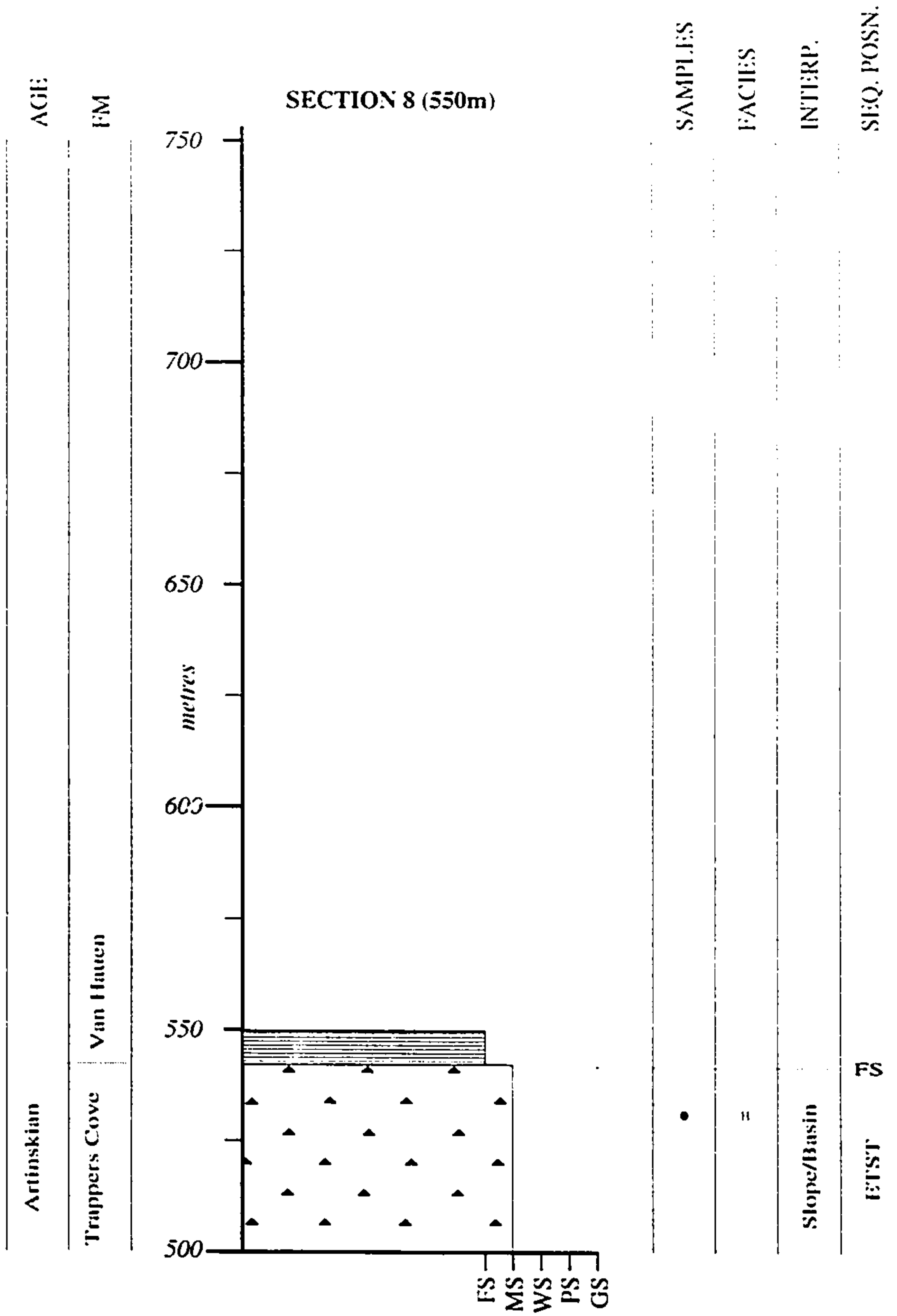


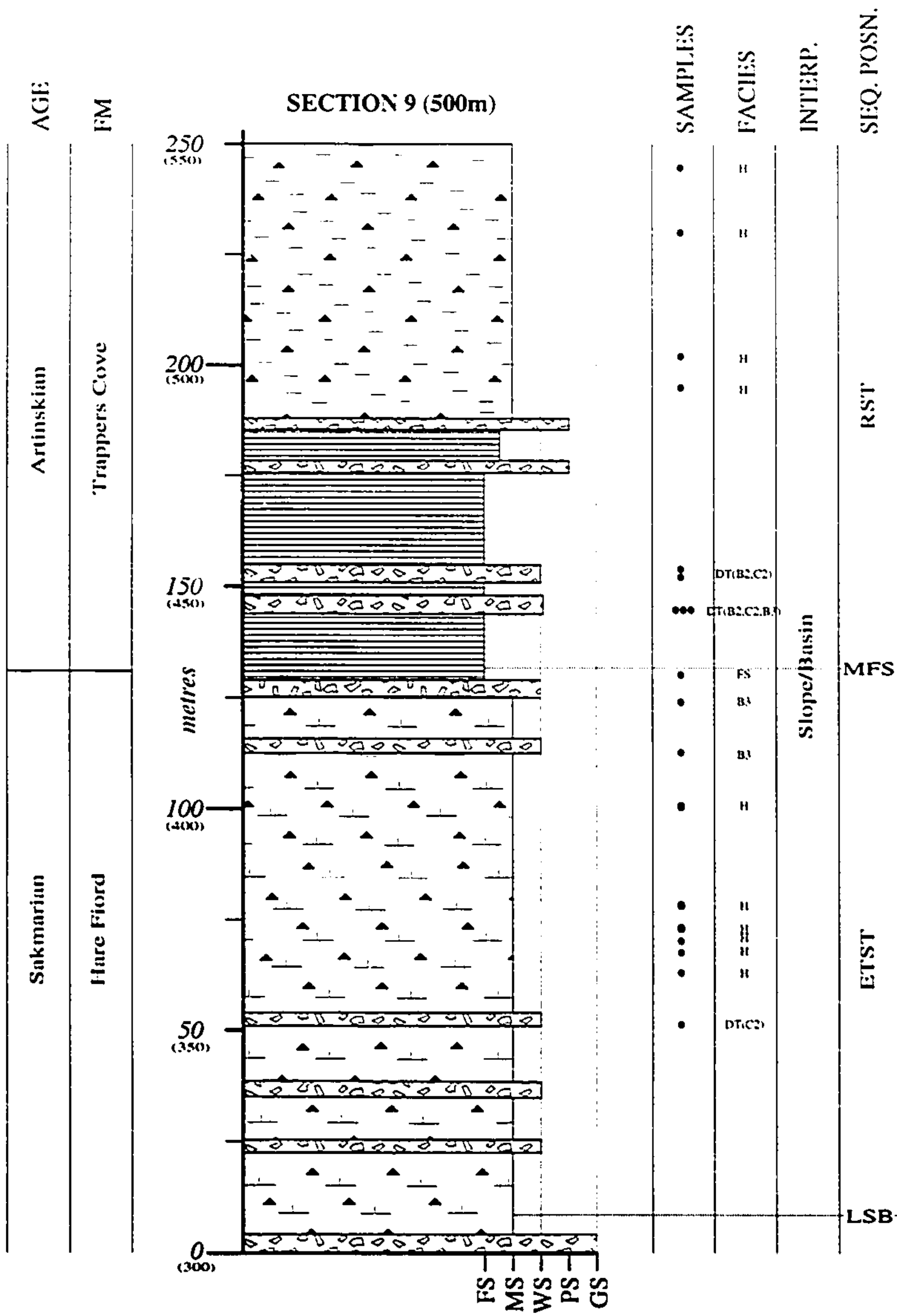
SECTION 7 (359m)
AGE
FM
SAMPLES
FACIES
INTERP.
SEQ. POSN.
500
450
400
350
300
250
metres
Artinskian
Great Bear Cape
Trappers Cove
Raanes
B2
B2
B2
B3
B3
B3
H
H
B3
B2
Shelf Margin
RST
MFS
LTST
FS
MS
WS
PS
GS


SECTION 7B (250m)
AGE
FM
SAMPLES
FACIES
INTERP.
SEQ. POSN.
Kungurian
Artinskian
Van Hauen
Great Bear Cape
metres
250
200
150
100
50
0
FS
MS
WS
PS
GS
B3
B2
B2
B1
B1
B1
B2
Outer Shelf/ Shelf Margin
Shelf
Outer Shelf/ Shelf Margin
FS
TST
USB
RST

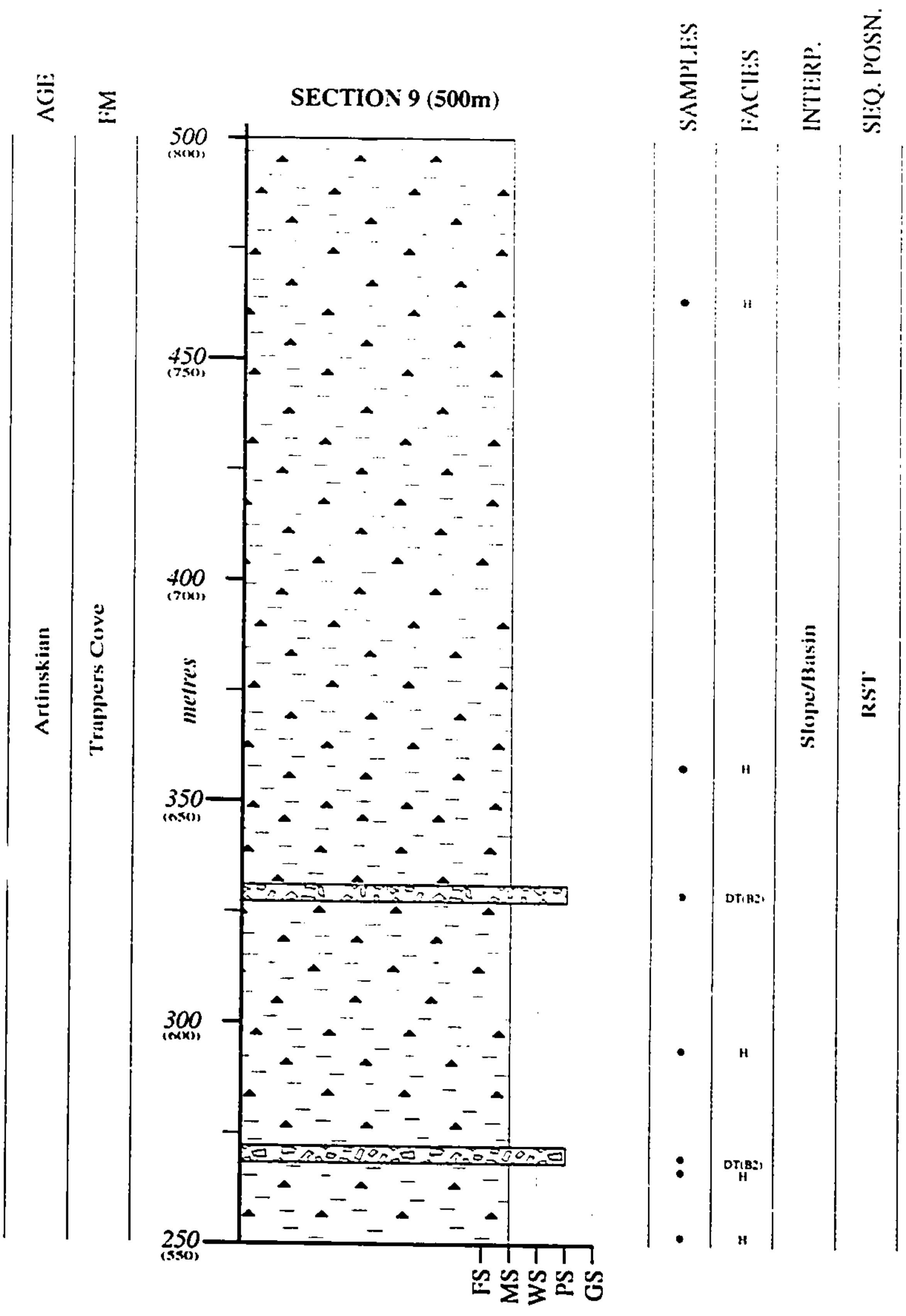

SECTION 8 (550 m)
AGE
FM
SAMPLES
FACIES
INTERP.
SEQ. POSN.
Artinskian
Sakmarian
Hare Fiord
metres
250
200
150
100
50
0
Slope/Basin
ETST
LSB
RST
FS
MS
WS
PS
GS
H
DT(C2)
DT(BE2,C2)
DT(C1,C2)
DT(C1)
FS
B3
H

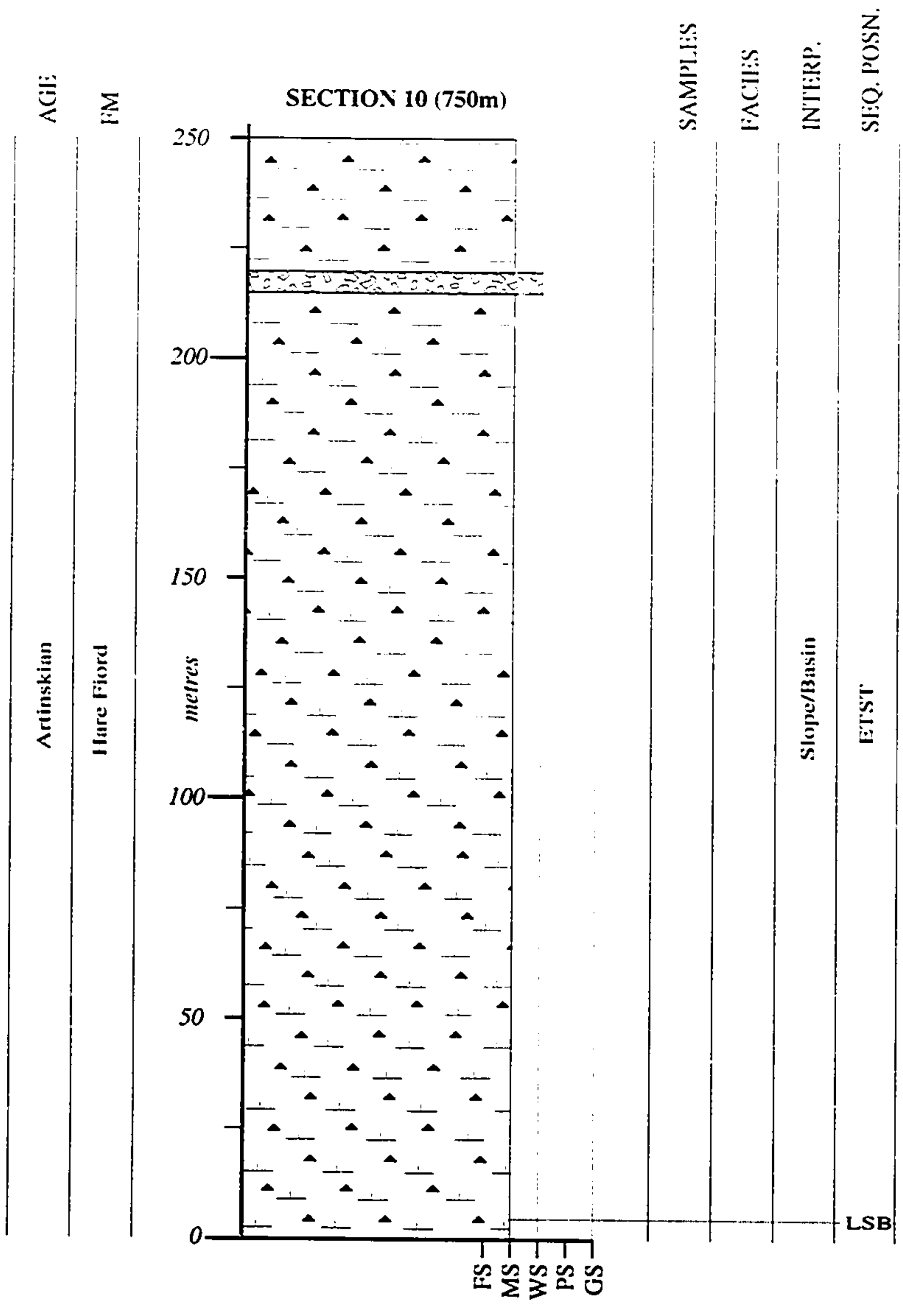

AGE
FM
SECTION 8 (550m)
SAMPLES
FACIES
INTERP.
SEQ. POSN.
500
450
400
350
300
250
metres
Artinskian
Trappers Cove
Hare Fiord
Slope/Basin
USB
RST
MFS
ETST
FS
FS
DT
FS
MS
WS
PS
GS

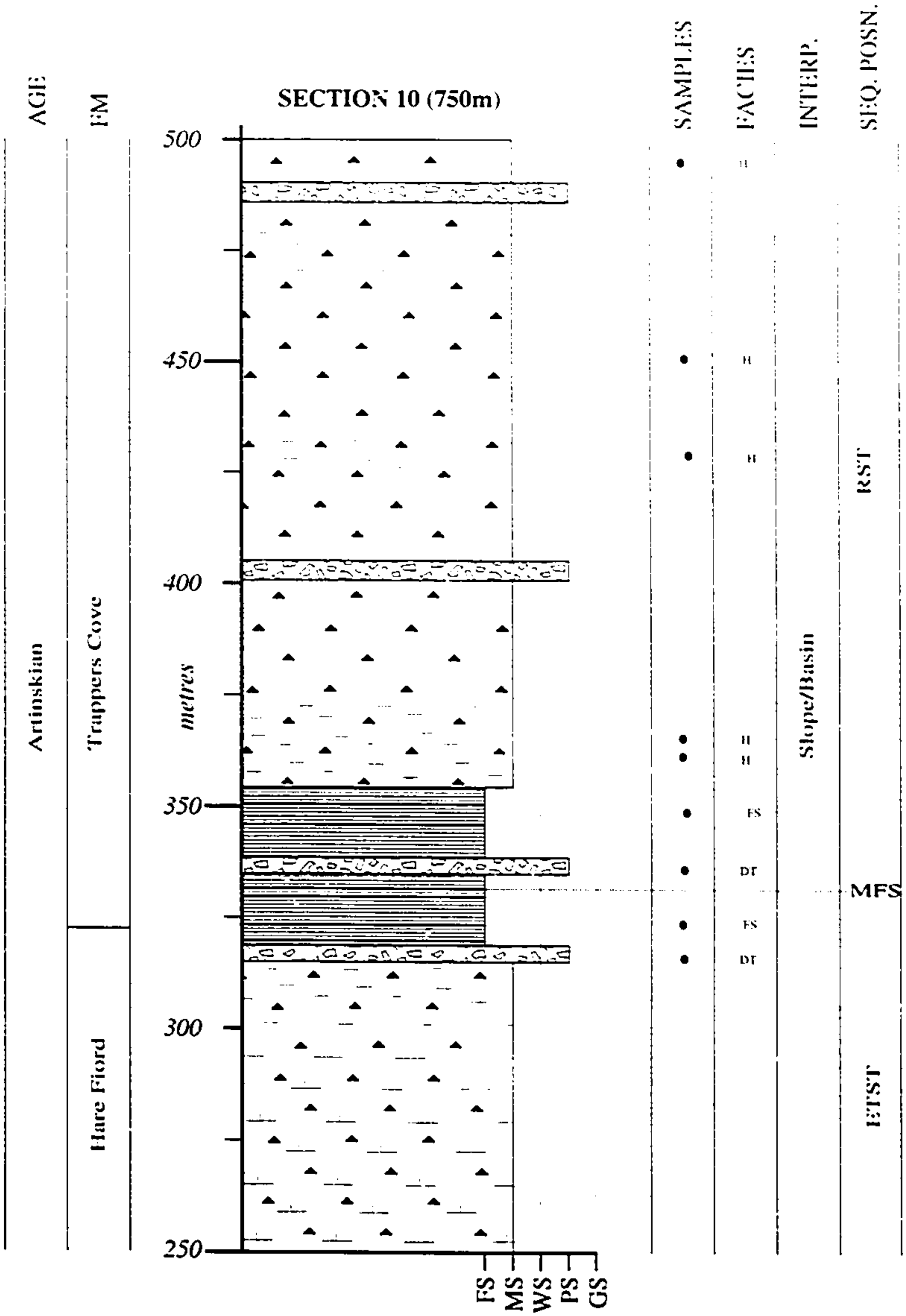

SECTION 8 (550m)
AGE
FM
SAMPLES
FACIES
INTERP.
SEQ. POSN.
750
700
650
600
550
500
metres
Artinskian
Trappers Cove
Van Hauen
Slope/Basin
FS
ETST
FS
MS
WS
PS
GS



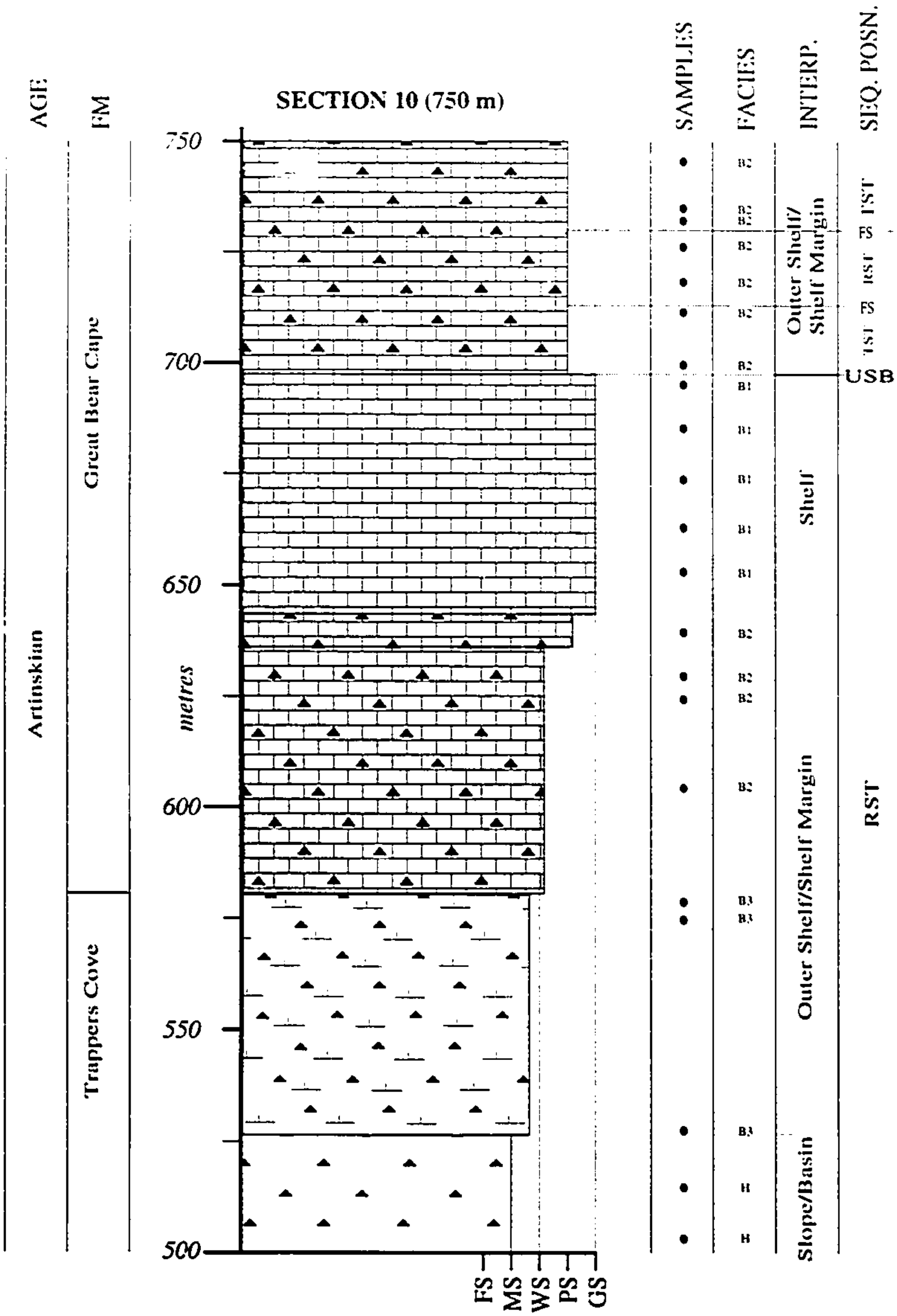
SECTION 9 (500m)
AGE
FM
SAMPLES
FACIES
INTERP.
SEQ. POSN.
Artinskian
Sakmarian
Trappers Cove
Hare Fiord
metres
250 (550)
200 (500)
150 (450)
100 (400)
50 (350)
0 (300)
FS
MS
WS
PS
GS
H
DT(B2,C2)
DT(B2,C2,B3)
FS
B3
DT(C2)
Slope/Basin
RST
MFS
ETST
LSB

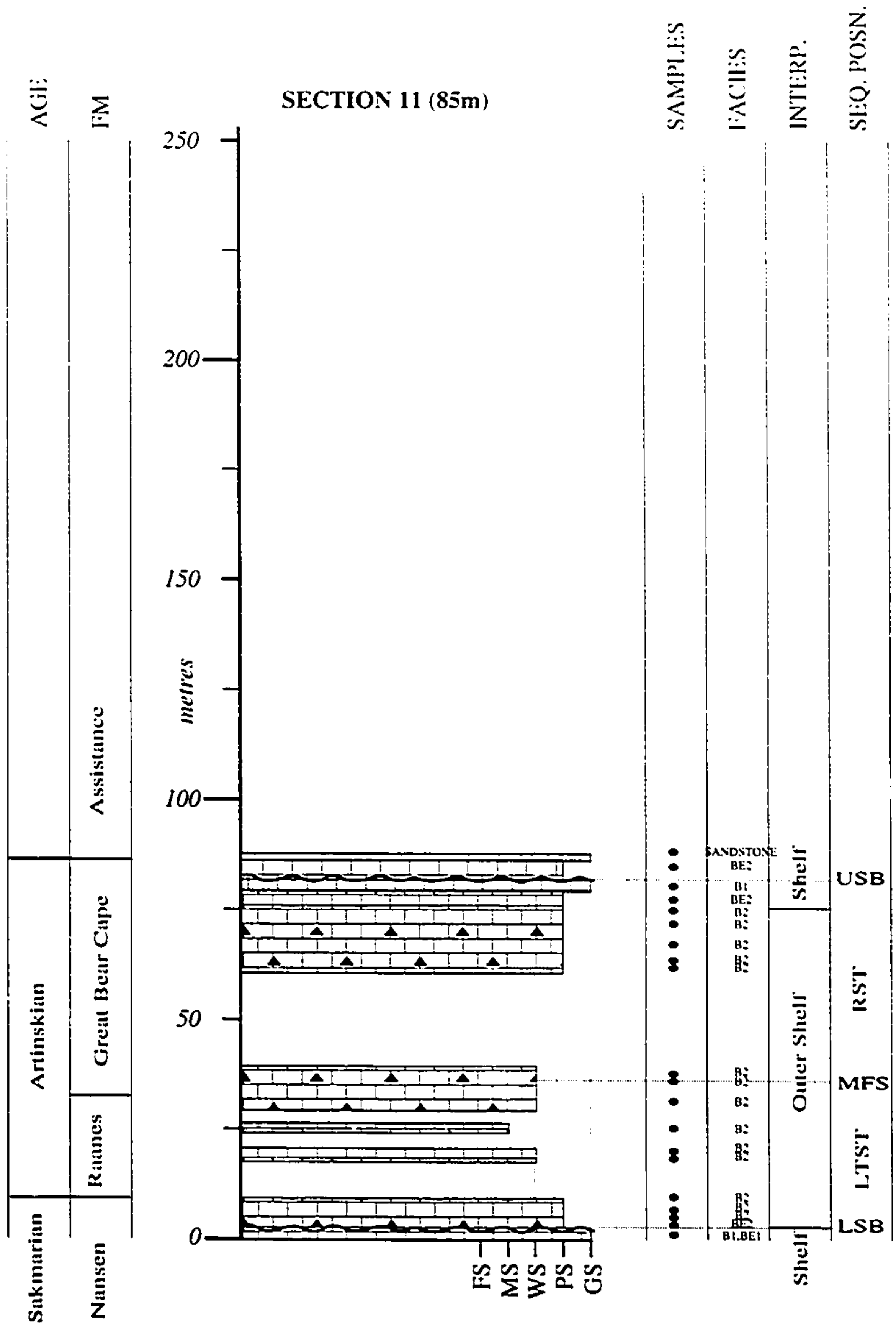

AGE
FM
SECTION 9 (500m)
SAMPLES
FACIES
INTERP.
SEQ. POSN.
500 (800)
450 (750)
400 (700)
350 (650)
300 (600)
250 (550)
metres
Artinskian
Trappers Cove
Slope/Basin
RST
H
H
DT(B2)
H
DT(B2)
H
H
FS
MS
WS
PS
GS


SECTION 10 (750m)
AGE
FM
SAMPLES
FACIES
INTERP.
SEQ. POSN.
250
200
150
100
50
0
metres
Artinskian
Hare Fiord
Slope/Basin
ETST
LSB
FS
MS
WS
PS
GS

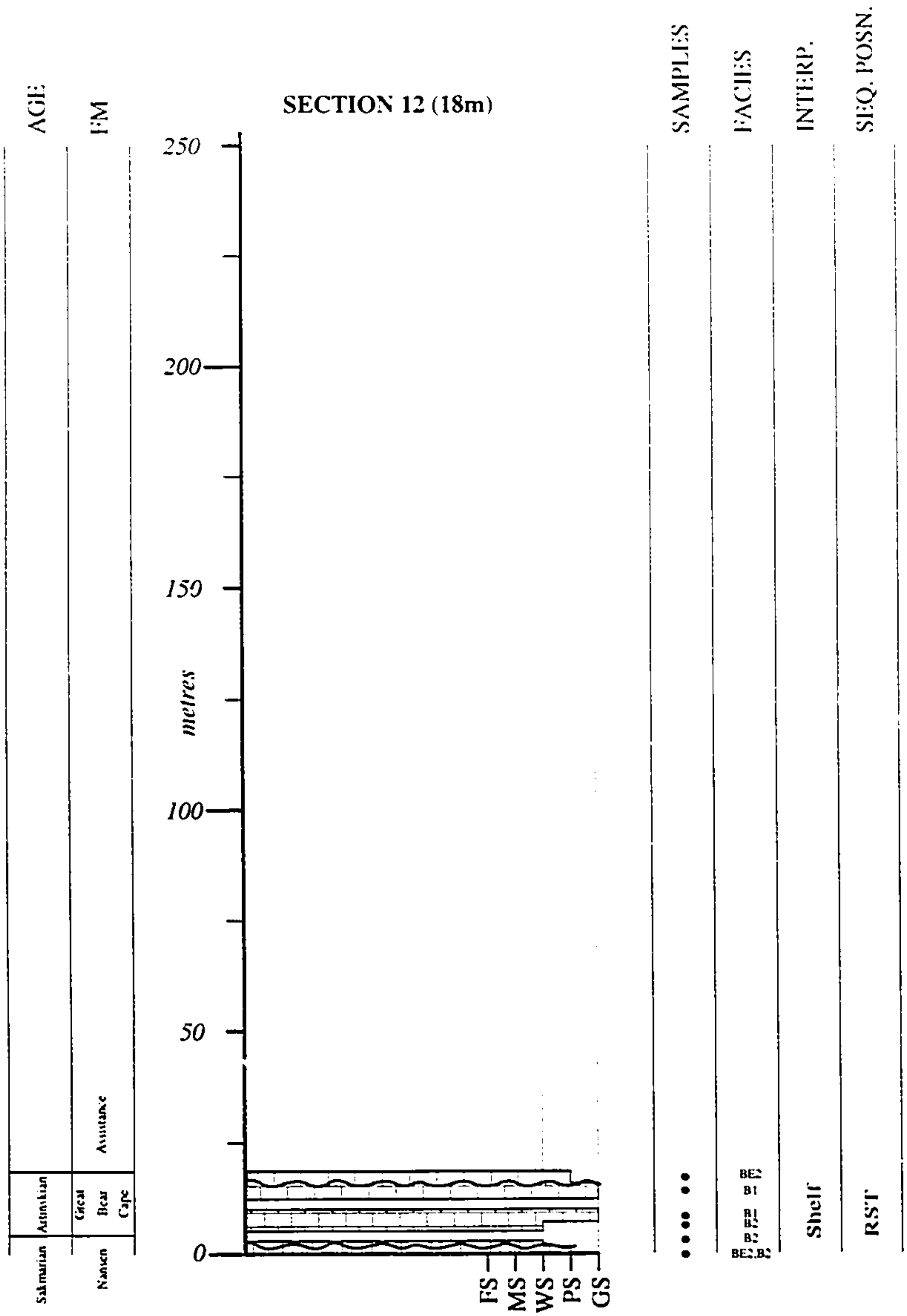


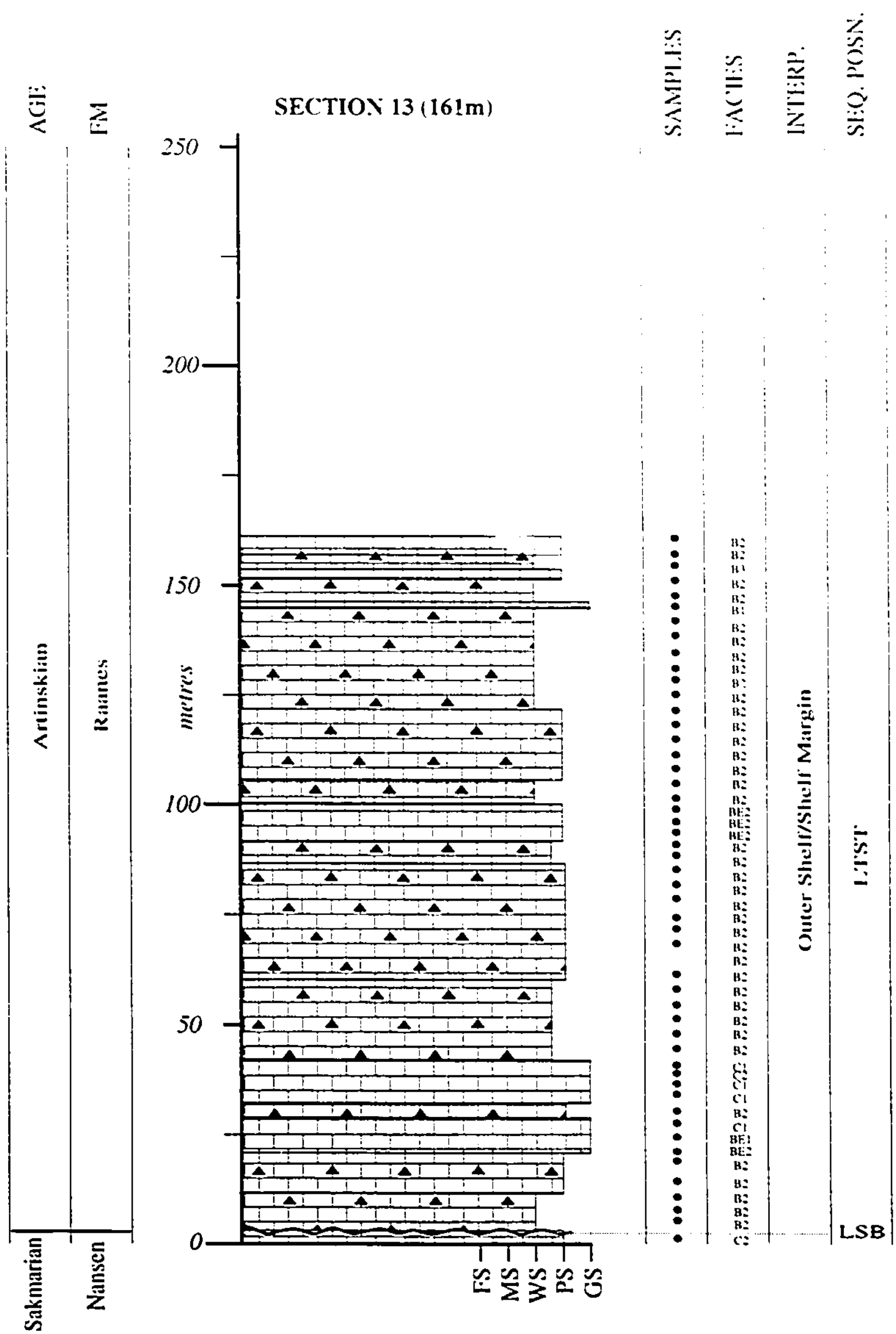
SECTION 10 (750m)
AGE
FM
SAMPLES
FACIES
INTERP.
SEQ. POSN.
Artinskian
Trappers Cove
Hare Fiord
metres
500
450
400
350
300
250
Slope/Basin
RST
MFS
ETST
FS
DT
FS
MS
WS
PS
GS

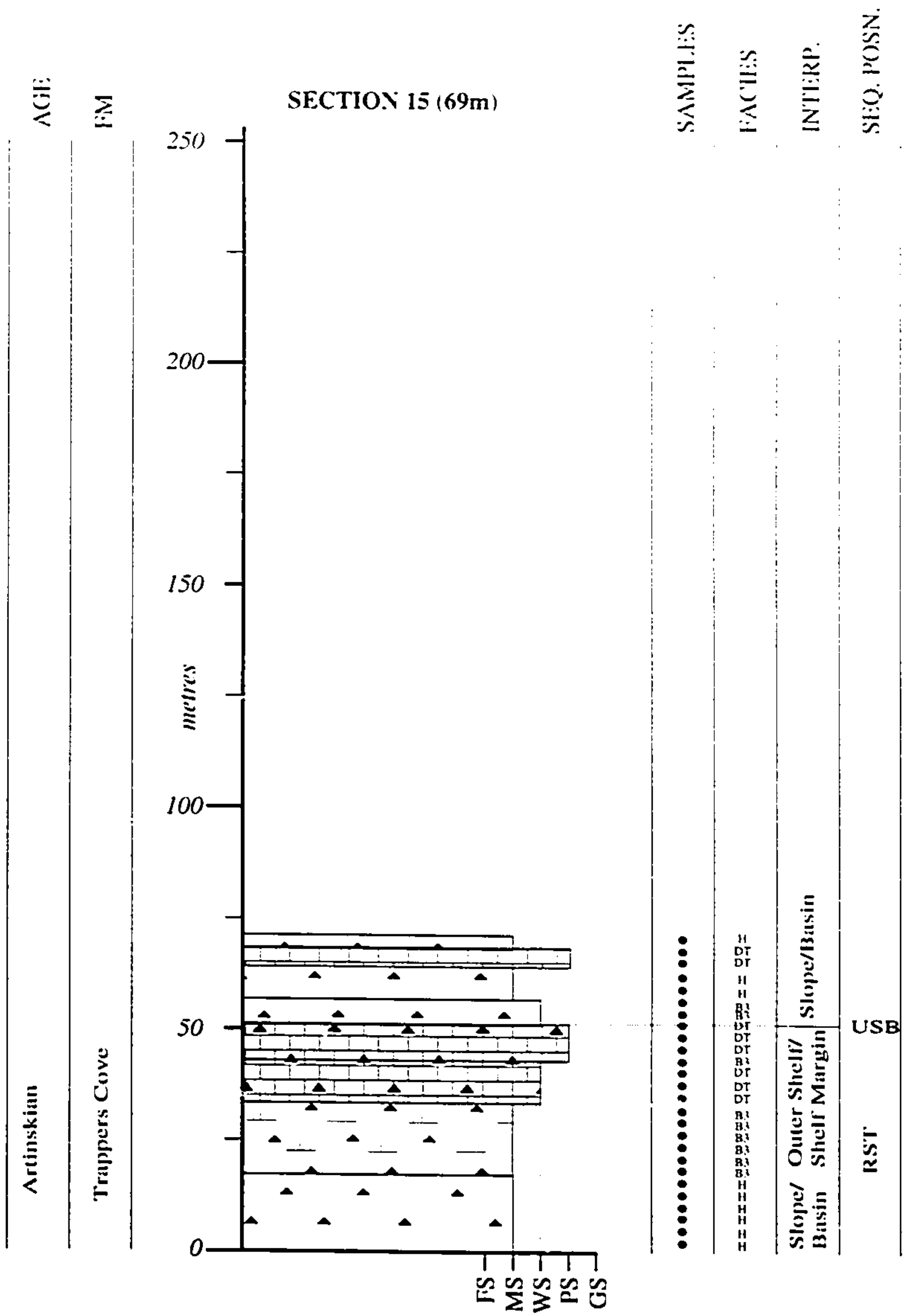

SECTION 10 (750 m)
AGE
FM
SAMPLES
FACIES
INTERP.
SEQ. POSN.
750
700
650
600
550
500
metres
Artinskian
Great Bear Cape
Trappers Cove
Outer Shelf/ Shelf Margin
Shelf
Outer Shelf/Shelf Margin
Slope/Basin
TST
FS
RST
FS
TST
USB
RST
FS
MS
WS
PS
GS



SECTION 11 (85m)
AGE
FM
SAMPLES
FACIES
INTERP.
SEQ. POSN.
Sakmarian
Artinskian
Nansen
Raanes
Great Bear Cape
Assistance
metres
250
200
150
100
50
0
FS
MS
WS
PS
GS
SANDSTONE
BE2
B1.BE1
Shelf
Outer Shelf
Shelf
USB
RST
MFS
LTST
LSB


SECTION 12 (18m)
AGE
FM
SAMPLES
FACIES
INTERP.
SEQ. POSN.
metres
250
200
150
100
50
0
Sakmarian
Asselian
Artinskian
Nansen
Great Bear Cape
Assistance
FS
MS
WS
PS
GS
BE2
B1
B1
B2
B2
BE2,B2
Shelf
RST


AGE
FM
SECTION 13 (161m)
SAMPLES
FACIES
INTERP.
SEQ. POSN.
250
200
150
100
50
0
metres
Artinskian
Raanes
Sakmarian
Nansen
FS
MS
WS
PS
GS
Outer Shelf/Shelf Margin
LTST
LSB


AGE
FM
SECTION 15 (69m)
SAMPLES
FACIES
INTERP.
SEQ. POSN.
Artinskian
Trappers Cove
250
200
150
metres
100
50
0
FS
MS
WS
PS
GS
H
DT
B3
Slope/Basin
Slope/ Basin
Outer Shelf/ Shelf Margin
USB
RST

# APPENDIX 3: LITHOLOGIC SAMPLES

ABBREVIATIONS:

| | | | |
|---|---|---|---|
| *LITHOLOGY*: | FS | = | Fissile Shale |
| | MS | = | Mudstone |
| | WS | = | Wackestone |
| | PS | = | Packstone |
| | GS | = | Grainstone |
| | | = | |
| *FACIES*: | C1 | = | Chloroforam Grainstone |
| | C2 | = | Chloroforam Wackestone to Packstone |
| | BE1 | = | Bryonoderm-Extended Grainstone |
| | BE2 | = | Bryonoderm-Extended Packstone |
| | BE3 | = | Bryonoderm-Extended Reefal Limestone |
| | B1 | = | Bryonoderm Grainstone |
| | B2 | = | Bryonoderm Wackestone to Packstone |
| | B3 | = | Bryonoderm Spiculite |
| | H | = | Hyalosponge Mudrock |
| | SS | = | Siliceous/Spiculitic Shale |
| | DT | = | Debrite/Turbidite |
| | | | |
| | HS | = | Hand Specimen |
| | TS | = | Thin Section |

**FIELD LOCATION 1 - SECTION 3**

| SAMPLE# | GSC# | LEVEL (m) | LITH | FACIES | HS | TS |
|---|---|---|---|---|---|---|
| 01-01 | 310801 | 168 | MS | FS | X | X |
| 01-02 | 311999 | 181.5 | MS | FS | X | |
| 01-03 | 310802 | 203.2 | MS | H | X | X |
| 01-04 | 310803 | 244.5 | WS | H | X | X |
| 01-05 | 310804 | 271.5 | MS | FS | X | |
| 01-06 | 310805 | 279 | MS | H | X | X |
| 01-07 | 310806 | 320 | MS | H | X | |
| 01-08 | 310807 | 319.5 | MS | H | X | X |
| 01-09 | 310808 | 376.5 | MS | H | X | |
| 01-10 | 310809 | 429 | MS | H | X | |
| 01-11 | 310810 | 454.5 | MS | H | X | |
| 01-12 | 310811 | 508.5 | MS | H | X | |
| 01-13 | 310812 | 649.5 | MS | H | X | X |
| 01-14 | 310813 | 718.5 | MS | H | X | |
| 01-15 | 310804 | 763.5 | MS | H | X | |
| 01-16 | 310815 | 0 | MS | H | X | |
| 01-17 | 310816 | 25.5 | MS | H | X | |
| 01-18 | 312000 | 64.5 | MS | H | X | |
| 01-19 | 310817 | 66 | MS | FS | X | |
| 01-20 | 310818 | 908 | MS | H | X | X |
| 01-21 | 310819 | 978 | WS | B3 | X | X |
| 01-22 | 310820 | 982 | WS | B3 | X | |
| 01-23 | 310821 | 1020 | WS | B3 | X | |
| 01-25 | 310822 | 1038 | WS | B3 | X | X |
| 01-26 | 312002 | 1044 | WS | B3 | X | |
| 01-27 | 310823 | 1053 | WS | B2 | X | |
| 01-28 | 310824 | 1054.5 | WS | B2 | X | X |
| 01-29 | 310825 | 1059 | WS | B2 | X | |
| 01-30 | 310826 | 1066.5 | WS-PS | B2 | X | X |
| 01-31 | 310827 | 1078.5 | WS | B2 | X | |
| 01-32 | 310828 | 1083 | WS | B2 | X | |
| 01-33 | 310829 | 1083 | WS | B2 | X | |
| 01-34 | 310830 | 1086 | PS | B2 | X | |
| 01-35 | 310831 | 1086 | PS | B2 | X | |
| 01-36 | 310832 | 1089 | PS | B2 | X | |
| 01-37 | 310833 | 1090.1 | GS | B1 | X | |
| 01-38 | 310834 | 1093.5 | GS | B1 | X | |
| 01-39 | 310835 | 1101 | GS | B1 | X | |
| 01-40 | 310836 | 987 | SPONGE | | X | |
| 01-41 | 310837 | 987 | SPONGE | | X | |
| 01-42 | 310838 | 1114 | PS | B2 | X | |
| 01-43 | 310839 | 1113.5 | PS | B2 | X | |
| 01-44 | 310840 | 1113 | PS | B2 | X | |
| 01-45 | 310841 | 1112 | PS | B2 | X | |
| 01-46 | 310842 | 1111 | PS | B2 | X | |
| 01-47 | 310843 | 1110 | PS | B2 | X | |
| 01-48 | 310844 | 1109 | PS | B2 | X | |

| | | | | | | |
|---|---|---|---|---|---|---|
| 01-49 | 310845 | 1108 | PS | B2 | X | |
| 01-612 | 311754 | 1086 | PS | B2 | X | X |
| 01-614 | 311755 | 1089 | PS | B2 | X | X |
| 01-616 | 311756 | 1092 | GS | B1 | X | X |
| 01-618 | 311757 | 1095 | GS | B1 | X | X |
| 01-620 | 311758 | 1098 | GS | B1 | X | X |
| 01-622 | 311759 | 1101 | GS | B1 | X | X |
| 01-624 | 311760 | 1104 | GS | BE1 | X | X |
| 01-626 | 311761 | 1107 | PS | B2 | X | X |
| 01-627 | 311762 | 1108.5 | PS | B2 | X | X |
| 01-628 | 311763 | 1110 | PS | B2 | X | X |
| 01-630 | 311764 | 1113 | PS | B2 | X | X |

**FIELD LOCATION 2 - SECTION 12**

| SAMPLE# | GSC# | LEVEL (m) | LITH | FACIES | HS | TS |
|---|---|---|---|---|---|---|
| 02-01 | 311765 | 0.5 | PS | BE2 | X | X |
| 02-02 | 311766 | 0 | PS | B2 | X | X |
| 02-03 | 311767 | 2.5 | WS | B2 | X | X |
| 02-04 | 311768 | 5.5 | WS | B2 | X | X |
| 02-BL | 311771 | 16.5 | GS | B1 | X | X |
| 02-BK | 311772 | 12.7 | GS | B1 | X | X |
| 02-BO | 311775 | 18 | PS-WS | BE2 | X | X |

**FIELD LOCATION 3 - SECTION 4**

| SAMPLE# | GSC# | LEVEL (m) | LITH | FACIES | HS | TS |
|---|---|---|---|---|---|---|
| 03-01 | 311776 | 1 | GS | C1 | X | X |
| 03-02 | 311777 | 3.5 | PS | BE2 | X | X |
| 03-03 | 311778 | 3.6 | PS | B2 | X | X |
| 03-04 | 312003 | 5.1 | PS | B2 | X | |
| 03-05 | 312004 | 6.6 | PS | B2 | X | |
| 03-06 | 311779 | 8.1 | PS | B2 | X | X |
| 03-07 | 312005 | 9.6 | PS | B2 | X | |
| 03-08 | 312006 | 11.1 | PS | B2 | X | |
| 03-09 | 312007 | 12.6 | GS | B1 | X | |
| 03-10 | 312008 | 14.1 | PS | B2 | X | |
| 03-11 | 311780 | 15.6 | PS | B2 | X | X |
| 03-12 | 312009 | 17.1 | PS | B2 | X | |
| 03-13 | 312010 | 18.6 | PS | B2 | X | |
| 03-14 | 311781 | 20.1 | PS | B2 | X | X |
| 03-15 | 312011 | 21.6 | PS | B2 | X | |
| 03-16 | 311782 | 23.1 | PS | B2 | X | X |
| 03-17 | 311783 | 24.6 | PS | B2 | X | X |
| 03-18 | 311784 | 26.1 | PS | BE2 | X | X |
| 03-19 | 311785 | 27.6 | GS | BE1 | X | X |
| 03-20 | 312012 | 29.1 | GS | BE1 | X | |
| 03-21 | 312013 | 30.6 | PS | B2 | X | |
| 03-22 | 311786 | 32.1 | PS | B2 | X | X |

| | | | | | | |
|---|---|---|---|---|---|---|
| 03-23 | 312014 | 33.6 | PS | B2 | X | |
| 03-24 | 312015 | 35.1 | PS | B2 | X | |
| 03-25 | 312016 | 36.6 | PS | B2 | X | |
| 03-26 | 311787 | 38.1 | PS | B2 | X | X |
| 03-27 | 312017 | 39.6 | PS | B2 | X | |
| 03-28 | 312018 | 41.1 | PS | B2 | X | |
| 03-29 | 311789 | 58.1 | GS | BE1 | X | X |
| 03-30 | 311790 | 62.6 | PS | B2 | X | X |
| 03-31 | 312019 | 64.1 | GS | BE1 | X | |
| 03-32 | 311791 | 65.6 | GS | BE1 | X | X |
| 03-33 | 311792 | 68.6 | PS | B2 | X | X |
| 03-34 | 312020 | 70.1 | PS | B2 | X | |
| 03-35 | 312021 | 71.6 | PS | B2 | X | |
| 03-36 | 312022 | 73.1 | PS | B2 | X | |
| 03-37 | 311793 | 74.6 | PS | BE2 | X | X |
| 03-38 | 312023 | 76.1 | PS | BE2 | X | |
| 03-39 | 312024 | 77.6 | PS | BE2 | X | |
| 03-40 | 311794 | 79.1 | PS | BE2 | X | X |
| 03-41 | 311795 | 94.1 | PS | B2 | X | X |
| 03-42 | 312025 | 95.6 | PS | B2 | X | |
| 03-43 | 311796 | 97.1 | PS | BE2 | X | X |
| 03-44 | 312026 | 98.6 | PS | BE2 | X | |
| 03-45 | 311797 | 100.1 | PS | BE2 | X | X |
| 03-46 | 311798 | 101.6 | PS | BE2 | X | X |
| 03-47 | 312027 | 103.1 | PS | BE2 | X | |
| 03-48 | 312028 | 104.6 | PS | BE2 | X | |
| 03-49 | 312029 | 106.1 | PS | BE2 | X | |
| 03-50 | 311799 | 107.6 | PS | BE2 | X | X |
| 03-51 | 312030 | 109.1 | PS | BE2 | X | |
| 03-52 | 311800 | 110.6 | PS | BE2 | X | X |
| 03-53 | 312031 | 112.1 | PS | BE2 | X | |
| 03-54 | 312032 | 113.6 | PS | B2 | X | |
| 03-55 | 312033 | 115.1 | PS | BE2 | X | |
| 03-56 | 311801 | 116.6 | PS | B2 | X | X |
| 03-57 | 312034 | 118.1 | PS | B2 | X | |
| 03-58 | 311802 | 119.6 | PS | B2 | X | X |
| 03-59 | 312035 | 121.1 | PS | B2 | X | |
| 03-60 | 311803 | 122.6 | PS | BE2 | X | X |
| 03-61 | 312036 | 124.1 | PS | BE2 | X | |
| 03-62 | 312037 | 125.6 | PS | BE2 | X | |
| 03-63 | 311803A | 127.1 | PS | BE2 | X | X |
| 03-64 | 312038 | 128.6 | PS | BE2 | X | |
| 03-65 | 312039 | 132.1 | PS | B2 | X | |
| 03-66 | 311803B | 132.6 | PS | B2 | X | X |
| 03-67 | 311804 | 134.1 | PS | B2 | X | X |
| 03-68 | 312040 | 135.6 | PS | B2 | X | |
| 03-69 | 312041 | 137.1 | PS | B2 | X | |
| 03-70 | 312042 | 138.6 | PS | B2 | X | |
| 03-71 | 312043 | 140.1 | PS | B2 | X | |
| 03-72 | 311805 | 141.6 | PS | B2 | X | X |
| 03-73 | 312044 | 143.1 | PS | B2 | X | |
| 03-74 | 311806 | 144.6 | PS | B2 | X | X |
| 03-75 | 312045 | 146.1 | PS | B2 | X | |

| | | | | | | |
|---|---|---|---|---|---|---|
| 03-76 | 311807 | 147.6 | GS | B1 | X | X |
| 03-77 | 312046 | 149.1 | PS | B2 | X | |
| 03-78 | 312047 | 150.6 | PS | B2 | X | |
| 03-79 | 311808 | 152.1 | GS | B1 | X | X |
| 03-80 | 312048 | 153.6 | GS | B1 | X | |
| 03-81 | 312049 | 155.1 | GS | B1 | X | |
| 03-82 | 312050 | 156.6 | GS | B1 | X | |
| 03-83 | 312051 | 158.1 | GS | B1 | X | |
| 03-84 | 311809 | 159.6 | GS | B1 | X | X |
| 03-85 | 312052 | 161.1 | GS | B1 | X | |
| 03-86 | 312053 | 162.6 | GS | B1 | X | |
| 03-87 | 312054 | 164.1 | GS | B1 | X | |
| 03-88 | 312055 | 165.6 | GS | B1 | X | |
| 03-89 | 311810 | 167 | GS | B1 | X | X |
| 03-90 | 312056 | 168.6 | GS | B1 | X | |
| 03-91 | 311811 | 170 | PS | B2 | X | X |
| 03-92 | 312057 | 171.6 | GS | B1 | X | |
| 03-93 | 312058 | 173.1 | GS | B1 | X | |
| 03-94 | 312059 | 174.6 | GS | B1 | X | |
| 03-95 | 311812 | 176 | GS | B1 | X | X |
| 03-96 | 311813 | 177.5 | GS | B1 | X | X |
| 03-97 | 312060 | 179.1 | GS | B1 | X | |
| 03-98 | 312061 | 180.6 | PS | B2 | X | |
| 03-99 | 311814 | 182 | GS | B1 | X | X |
| 03-100 | 312062 | 183.6 | GS | B1 | X | |
| 03-101 | 312063 | 185.1 | GS | B1 | X | |
| 03-102 | 311815 | 186.5 | GS | B1 | X | X |
| 03-103 | 311816 | 188 | PS | B2 | X | X |
| 03-104 | 311817 | 189.5 | PS | B2 | X | X |
| 03-105 | 311818 | 194 | PS-GS | B2 | X | X |
| 03-106 | 311819 | 195.5 | PS | B2 | X | X |
| 03-107 | 311820 | 197 | PS | B2 | X | X |
| 03-108 | 311820A | 195.6 | PS | B2 | X | |
| 03-109 | 311821 | 213.5 | PS | B2 | X | X |
| 03-110 | 311822 | 215.5 | PS | B2 | X | X |
| 03-111 | 311823 | 217.5 | PS | B2 | X | X |

**FIELD LOCATION 4 - SECTION 13**

| SAMPLE# | GSC# | LEVEL (m) | LITH | FACIES | HS | TS |
|---|---|---|---|---|---|---|
| 04-01 | 310846 | 0 | WS | C2 | X | X |
| 04-02 | 310847 | 1.5 | WS | C2 | X | X |
| 04-03 | 310848 | 3 | WS | C2 | X | X |
| 04-04 | 310849 | 3 | WS | C2 | X | X |
| 04-05 | 310850 | 3.75 | PS | C2 | X | X |
| 04-06 | 310851 | 6 | PS | B2 | X | |
| 04-07 | 310852 | 7.5 | PS | B2 | X | |
| 04-08 | 310853 | 9 | PS | B2 | X | X |
| 04-09 | 310854 | 10.5 | PS | B2 | X | |
| 04-10 | 310855 | 12 | PS | B2 | X | |

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|---|---|---|---|---|---|---|
| 04-11 | 310856 | 13.5 | PS | B2 | X | X |
| 04-12 | 310857 | 15 | PS | B2 | X | |
| 04-13 | 310858 | 16.5 | PS | B2 | X | |
| 04-14 | 310859 | 18 | PS | B2 | X | X |
| 04-15 | 310860 | 18.5 | PS | B2 | X | |
| 04-16 | 310861 | 20 | PS | B2 | X | |
| 04-17 | 310862 | 20.5 | PS | BE2 | X | X |
| 04-18 | 310863 | 21.5 | PS | BE2 | X | |
| 04-19 | 310864 | 23 | GS | BE1 | X | X |
| 04-20 | 310865 | 24.5 | PS-GS | BE1 | X | X |
| 04-21 | 310866 | 26 | GS | BE1 | X | |
| 04-22 | 310867 | 27.5 | GS | C1 | X | X |
| 04-23 | 310868 | 29 | GS | C1 | X | |
| 04-24 | 310869 | 30.5 | PS | B2 | X | X |
| 04-25 | 310870 | 31 | PS | B2 | X | X |
| 04-26 | 310871 | 32 | PS | B2 | X | |
| 04-27 | 310872 | 33.5 | PS | B2 | X | X |
| 04-28 | 310873 | 35 | GS | C1 | X | X |
| 04-29 | 310874 | 36.5 | GS | C1 | X | X |
| 04-30 | 310875 | 38 | PS | C2 | X | X |
| 04-31 | 310876 | 39.5 | GS | C1 | X | X |
| 04-32 | 310876A | 41 | PS | B2 | X | |
| 04-33 | 310877 | 42.5 | PS | B2 | X | |
| 04-34 | 310878 | 43 | PS | B2 | X | |
| 04-35 | 310879 | 44 | PS | B2 | X | |
| 04-36 | 310880 | 45.5 | PS | B2 | X | |
| 04-37 | 310881 | 47 | PS | B2 | X | |
| 04-38 | 310882 | 48.5 | PS | B2 | X | X |
| 04-39 | 310883 | 50 | PS | B2 | X | |
| 04-40 | 310884 | 60.5 | PS | B2 | X | |
| 04-41 | 310885 | 62 | WS-PS | B2 | X | |
| 04-42 | 310886 | 63.5 | WS-PS | B2 | X | X |
| 04-43 | 310887 | 65 | PS | C2 | X | X |
| 04-44 | 310888 | 66.5 | PS | B2 | X | |
| 04-45 | 310889 | 68 | PS | B2 | X | |
| 04-46 | 310890 | 69.5 | PS | B2 | X | |
| 04-47 | 310891 | 71 | PS | B2 | X | |
| 04-48 | 310892 | 72.5 | PS | B2 | X | |
| 04-49 | 310893 | 74 | PS | B2 | X | |
| 04-50 | 310894 | 75.5 | PS | B2 | X | |
| 04-51 | 310895 | 77 | PS | B2 | X | |
| 04-52 | 310896 | 78.5 | PS | B2 | X | X |
| 04-53 | 310897 | 80 | PS | B2 | X | |
| 04-54 | 310898 | 81.5 | PS | B2 | X | X |
| 04-55 | 310899 | 83 | PS | B2 | X | |
| 04-56 | 310900 | 84.5 | PS | B2 | X | |
| 04-57 | 310901 | 86 | WS-PS | B2 | X | |
| 04-58 | 310902 | 87.5 | WS-PS | B2 | X | X |
| 04-59 | 310903 | 89 | PS | B2 | X | |
| 04-60 | 310904 | 90.5 | PS | BE2 | X | |
| 04-61 | 310905 | 92 | PS | BE2 | X | X |
| 04-62 | 310906 | 93.5 | PS | B2 | X | X |
| 04-63 | 310907 | 95 | PS | BE2 | X | |

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|---|---|---|---|---|---|---|
| 04-64 | 310908 | 96.5 | PS | BE2 | X | |
| 04-65 | 310909 | 98 | PS | BE2 | X | |
| 04-66 | 310910 | 99.5 | WS | B2 | X | |
| 04-67 | 310911 | 101 | WS | B2 | X | |
| 04-68 | 310912 | 102.5 | WS | B2 | X | |
| 04-69 | 310913 | 104 | PS | B2 | X | X |
| 04-70 | 310914 | 105.5 | WS | B2 | X | |
| 04-71 | 310915 | 107 | WS | B2 | X | |
| 04-72 | 310916 | 108.5 | PS | B2 | X | |
| 04-73 | 310917 | 110 | PS | B2 | X | |
| 04-74 | 310918 | 111.5 | WS-PS | B2 | X | |
| 04-75 | 310919 | 113 | PS | B2 | X | X |
| 04-76 | 310920 | 114.5 | PS | B2 | X | |
| 04-77 | 310921 | 116 | PS | B2 | X | |
| 04-78 | 310922 | 117.5 | PS | B2 | X | |
| 04-79 | 310923 | 119 | PS | B2 | X | |
| 04-80 | 310924 | 120.5 | PS | B2 | X | |
| 04-81 | 310925 | 122 | PS | B2 | X | |
| 04-82 | 310926 | 123.5 | PS | B2 | X | |
| 04-83 | 310927 | 125 | WS | B2 | X | |
| 04-84 | 310928 | 126.5 | WS | B3 | X | X |
| 04-85 | 310929 | 128 | WS | B2 | X | |
| 04-86 | 310930 | 129.5 | WS | B2 | X | |
| 04-87 | 310931 | 131 | WS | B2 | X | |
| 04-88 | 310932 | 132.5 | WS | B2 | X | |
| 04-89 | 310933 | 134 | WS | B2 | X | |
| 04-90 | 310934 | 135.5 | WS | B2 | X | |
| 04-91 | 310935 | 137 | WS | B2 | X | |
| 04-92 | 310936 | 138.5 | WS | B2 | X | |
| 04-93 | 310937 | 140 | CHERT | | X | |
| 04-94 | 310938 | 141.5 | CHERT | | X | |
| 04-95 | 310939 | 143 | CHERT | | X | |
| 04-96 | 310940 | 144.5 | WS | B2 | X | |
| 04-97 | 310941 | 146 | GS | B1 | X | |
| 04-98 | 310942 | 147.5 | WS | B2 | X | |
| 04-99 | 310943 | 149 | WS | B2 | X | |
| 04-100 | 310944 | 150.5 | CHERT | | X | |
| 04-101 | 310945 | 152 | CHERT | | X | |
| 04-102 | 310946 | 153.5 | PS | B2 | X | |
| 04-103 | 310947 | 155 | WS | B2 | X | |
| 04-104 | 310948 | 156.5 | WS | B3 | X | X |
| 04-105 | 310949 | 158 | WS | B3 | X | |
| 04-106 | 310950 | 159.5 | PS | B2 | X | |
| 04-107 | 310951 | 161 | PS | B2 | X | |

**FIELD LOCATION 5 - SECTION 5**

| SAMPLE# | GSC# | LEVEL (m) | LITH | FACIES | HS | TS |
|---|---|---|---|---|---|---|
| 05-01 | 310952 | 0.75 | MS | H | X | |
| 05-02 | 310953 | 1.5 | MS | H | X | |

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|---|---|---|---|---|---|---|
| 05-03 | 310954 | 3 | MS-WS | H | X | X |
| 05-04 | 310955 | 4.5 | MS | H | X | |
| 05-05 | 310956 | 6 | MS | H | X | |
| 05-06 | 310957 | 6.05 | MS | H | X | |
| 05-07 | 310958 | 7.5 | MS | H | X | |
| 05-08 | 310959 | 9 | MS | H | X | |
| 05-09 | 310960 | 15 | MS | H | X | |
| 05-10 | 310961 | 12 | MS | H | X | X |
| 05-11 | 310962 | 13.5 | MS | H | X | |
| 05-12 | 310963 | 15 | MS | H | X | |
| 05-13 | 310964 | 15 | MS | H | X | |
| 05-14 | 310965 | 16.5 | MS | H | X | |
| 05-15 | 310966 | 18 | MS | H | X | |
| 05-16 | 310967 | 19.5 | WS | B2 | X | X |
| 05-17 | 312064 | 19 | WS | B2 | X | |
| 05-18 | 310968 | 21 | WS | B2 | X | |
| 05-19 | 310969 | 22.5 | WS | B2 | X | |
| 05-20 | 310970 | 23 | WS | B2 | X | |
| 05-21 | 310971 | 23.5 | WS | B2 | X | |
| 05-22 | 310972 | 25 | WS | B2 | X | |
| 05-23 | 310973 | 26.5 | WS | B2 | X | X |
| 05-24 | 310974 | 28 | WS | B2 | X | |
| 05-25 | 310975 | 29.5 | WS | B2 | X | |
| 05-26 | 310976 | 31 | WS | B2 | X | |
| 05-27 | 310977 | 32.5 | WS | B2 | X | |
| 05-28 | 310978 | 34 | WS | B2 | X | |
| 05-29 | 310979 | 35.5 | WS | B2 | X | X |
| 05-30A | 310980 | 37 | PS | B2 | X | |
| 05-30B | 310981 | 37 | PS | B2 | X | |
| 05-31 | 310982 | 38.5 | PS | B2 | X | |
| 05-32 | 310983 | 40 | PS | B2 | X | X |
| 05-33 | 310984 | 41.5 | WS | B2 | X | |
| 05-34 | 310985 | 43 | WS | B2 | X | |
| 05-35A | 310986 | 44.5 | WS | B2 | X | |
| 05-35B | 310987 | 44.5 | WS | B2 | X | |
| 05-36 | 310988 | 46 | PS | B2 | X | |
| 05-37 | 310989 | 47.5 | WS | B2 | X | |
| 05-38 | 310990 | 49 | WS | B2 | X | |
| 05-39A | 310991 | 50.5 | WS | B2 | X | X |
| 05-39B | 310992 | 50.5 | WS | B2 | X | |
| 05-40 | 310993 | 52 | WS | B2 | X | |
| 05-41 | 310994 | 53.5 | PS | B2 | X | X |
| 05-42 | 310995 | 55 | PS | B2 | X | |
| 05-43 | 310996 | 56.5 | PS | B2 | X | |
| 05-44 | 310997 | 58 | PS | B2 | X | |
| 05-45 | 310998 | 59.5 | PS | B2 | X | X |
| 05-46 | 310999 | 61 | PS | B2 | X | |
| 05-47 | 311000 | 62.5 | WS | B2 | X | |
| 05-48 | 311001 | 64 | WS | B2 | X | X |
| 05-49 | 311002 | 65.5 | WS | B2 | X | |
| 05-50 | 311003 | 67 | WS | B2 | X | |
| 05-51 | 311004 | 68.5 | WS | B2 | X | |
| 05-52 | 311005 | 70 | WS | B2 | X | |

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|---|---|---|---|---|---|---|
| 05-53 | 311006 | 71.5 | PS | B2 | X | X |
| 05-54 | 311007 | 73 | WS | B2 | X | |
| 05-55 | 311008 | 75.5 | WS | BE3 | X | X |
| 05-56 | 311009 | 75.9 | WS | B2 | X | X |
| 05-57 | 311010 | 76.4 | WS | BE3 | X | X |
| 05-58 | 311011 | 77.4 | WS | B2 | X | |
| 05-59 | 311012 | 78.9 | CHERT | | X | |
| 05-60 | 311013 | 80.4 | WS | B2 | X | |
| 05-61 | 311014 | 81.9 | WS | B2 | X | |
| 05-62 | 311015 | 83.4 | WS | B2 | X | |
| 05-63 | 311016 | 84.9 | WS | B2 | X | |
| 05-64 | 311017 | 86.4 | WS | B2 | X | |
| 05-65 | 311018 | 87.9 | WS | B2 | X | |
| 05-65A | 311111 | 108.9 | WS | B2 | X | |
| 05-65C | 311118 | 111.9 | WS | BE3 | X | |
| 05-65D | 311119 | 114.9 | WS | B2 | X | |
| 05-65E | 311120 | 119.4 | WS | BE3 | X | X |
| 05-65F | 311121 | 120.5 | WS | B2 | X | |
| 05-66 | 311019 | 0 | WS | B2 | X | X |
| 05-67 | 311020 | 1.5 | WS | BE3 | X | X |
| 05-68 | 311021 | 3 | WS | B2 | X | |
| 05-69 | 311022 | 4.5 | WS | B2 | X | X |
| 05-70 | 311023 | 4.6 | WS | B2 | X | |
| 05-71 | 311024 | 6 | WS | B2 | X | |
| 05-72 | 311025 | 9 | WS | B2 | X | |
| 05-73 | 311026 | 10.5 | PS | B2 | X | |
| 05-74 | 311027 | 12 | PS | BE2 | X | X |
| 05-75 | 311028 | 13.5 | PS | BE2 | X | |
| 05-76 | 311029 | 15 | WS-PS | B2 | X | |
| 05-77 | 311030 | 16.5 | WS | B2 | X | X |
| 05-78 | 311031 | 18 | WS | B2 | X | |
| 05-79 | 311032 | 19.5 | WS | B2 | X | |
| 05-80 | 311033 | 21 | WS | B2 | X | |
| 05-81 | 311034 | 21.5 | WS | BE3 | X | X |
| 05-82 | 311035 | 23 | WS | B2 | X | |
| 05-83 | 311036 | 24.5 | WS | B2 | X | X |
| 05-84 | 311037 | 26 | WS | B2 | X | |
| 05-85 | 311038 | 27.5 | WS | B2 | X | |
| 05-86 | 311038A | 29 | WS | B2 | X | |
| 05-87 | 311039 | 31.5 | WS | B2 | X | X |
| 05-88 | 311040 | 33 | WS | B2 | X | |
| 05-89 | 311041 | 33 | WS | B2 | X | |
| 05-90 | 311042 | 34.5 | WS | B2 | X | |
| 05-91 | 311043 | 36 | WS | B2 | X | |
| 05-92 | 311044 | 37.5 | WS | B2 | X | |
| 05-93 | 311045 | 39 | WS | B2 | X | |
| 05-94 | 311046 | 40.5 | WS | B2 | X | X |
| 05-95 | 311047 | 42 | WS | B2 | X | |
| 05-96 | 311048 | 43.5 | WS | B2 | X | |
| 05-97 | 311049 | 45 | WS | B2 | X | |
| 05-98 | 311050 | 46.5 | WS | B2 | X | |
| 05-99 | 311051 | 48 | WS | B2 | X | |
| 05-100 | 311052 | 49.5 | WS | B2 | X | |

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|---|---|---|---|---|---|---|
| 05-101 | 311053 | 51 | WS | B2 | X | |
| 05-102 | 311054 | 52.5 | WS | B2 | X | |
| 05-103 | 311055 | 54 | WS | B2 | X | |
| 05-104 | 311056 | 55.5 | PS | B2 | X | |
| 05-105 | 311057 | 67 | WS | B2 | X | |
| 05-106 | 311058 | 68.5 | WS | B2 | X | |
| 05-107 | 311059 | 70 | WS | B2 | X | |
| 05-108 | 311060 | 71.5 | WS | B2 | X | X |
| 05-109 | 311061 | 73 | WS | B2 | X | |
| 05-110 | 311062 | 74.5 | WS | B2 | X | |
| 05-111 | 311063 | 76 | WS | B2 | X | |
| 05-112 | 311064 | 77.5 | WS | B2 | X | |
| 05-113 | 311065 | 79 | WS | B2 | X | |
| 05-114 | 311066 | 80.5 | WS | B2 | X | |
| 05-115 | 311067 | 82 | PS | B2 | X | X |
| 05-116 | 311068 | 83.5 | WS | B2 | X | |
| 05-117 | 311069 | 85 | WS | B2 | X | |
| 05-118 | 311070 | 86.5 | WS | B2 | X | |
| 05-119 | 311071 | 88 | PS | B2 | X | X |
| 05-120 | 311072 | 89.5 | WS | B2 | X | |
| 05-121 | 311073 | 92 | WS | B2 | X | |
| 05-122 | 311074 | 93.5 | WS | B2 | X | |
| 05-123 | 311075 | 95 | PS | B2 | X | X |
| 05-124 | 311076 | 97.5 | WS | B2 | X | |
| 05-125 | 311077 | 99 | WS | B2 | X | X |
| 05-126 | 311078 | 100.5 | PS | B2 | X | |
| 05-127 | 311079 | 102 | PS | B2 | X | |
| 05-128 | 311080 | 103.5 | WS | B3 | X | X |
| 05-129 | 311081 | 105 | WS | B2 | X | |
| 05-130 | 311082 | 106.5 | WS | B2 | X | X |
| 05-131 | 311083 | 108 | WS | B2 | X | X |
| 05-132 | 311084 | 109.5 | WS | B2 | X | |
| 05-133 | 311085 | 111 | WS | B2 | X | |
| 05-134 | 311086 | 112.5 | WS | B2 | X | |
| 05-135 | 311087 | 114 | WS | BE3 | X | X |
| 05-136 | 311088 | 115.5 | WS | B2 | X | |
| 05-137 | 311089 | 117 | WS | B2 | X | X |
| 05-138 | 311090 | 118.5 | WS | B2 | X | |
| 05-139 | 311091 | 120 | WS | B2 | X | |
| 05-140 | 311092 | 121.5 | WS | B2 | X | X |
| 05-141 | 311093 | 123 | WS | B2 | X | |
| 05-142 | 311094 | 124.5 | WS | B2 | X | |
| 05-143 | 311095 | 126 | WS | B2 | X | |
| 05-144 | 311096 | 127.5 | WS | B2 | X | |
| 05-145 | 311097 | 129 | WS | B2 | X | |
| 05-146 | 311098 | 130.5 | WS | B2 | X | X |
| 05-147 | 311099 | 132 | WS | B2 | X | |
| 05-148 | 311100 | 133.5 | WS | B2 | X | |
| 05-149 | 311100A | 135 | WS | B2 | X | |
| 05-150 | 311101 | 136.5 | PS | BE2 | X | X |
| 05-151 | 311102 | 138 | PS | BE2 | X | |
| 05-152 | 311103 | 139.5 | WS | B2 | X | |
| 05-153 | 311104 | 141 | WS | B2 | X | X |

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|---|---|---|---|---|---|---|
| 05-154 | 311105 | 142.5 | WS | B2 | X | |
| 05-155 | 311106 | 144 | WS | B2 | X | |
| 05-156 | 311107 | 145.5 | WS | B2 | X | |
| 05-157 | 311108 | 147 | WS | B2 | X | |
| 05-158 | 311109 | 148.5 | WS | B2 | X | |
| 05-159 | 311110 | 150 | WS | B2 | X | |
| 05-160 | 311112 | 150 | PS | B2 | X | X |
| 05-161 | 311113 | 151.5 | WS | B2 | X | |
| 05-162 | 311114 | 153 | WS-PS | B2 | X | X |
| 05-163 | 311115 | 154.5 | WS | B2 | X | X |
| 0 -164 | 311116 | 156 | WS | B2 | X | |
| 05-165 | 311117 | 157.5 | WS | B2 | X | X |
| 05-166 | 311122 | 159 | WS | B2 | X | X |
| 05-167 | 311123 | 161.5 | WS | B2 | X | |
| 05-168 | 311124 | 163 | WS | B2 | X | |
| 05-169 | 311125 | 164.5 | WS | B2 | X | |
| 05-170 | 311126 | 166 | PS | B2 | X | |
| 05-171 | 311127 | 167.5 | PS | B2 | X | |
| 05-172 | 311128 | 169 | PS | B2 | X | |
| 05-173 | 311129 | 171.5 | PS | B2 | X | |
| 05-174 | 311130 | 173 | PS | B2 | X | |
| 05-175 | 311131 | 174.5 | PS | B2 | X | |
| 05-176 | 311132 | 175 | WS | B2 | X | |
| 05-177 | 311133 | 176 | WS | B2 | X | |
| 05-178 | 311134 | 177.5 | WS | B2 | X | |
| 05-179 | 311135 | 179 | PS | B2 | X | X |
| 05-180 | 311136 | 180.5 | PS | B2 | X | X |
| 05-181 | 311137 | 182 | WS | B2 | X | |
| 05-182 | 311138 | 183.5 | CHERT | | X | |
| 05-183 | 311139 | 185 | PS | B2 | X | |
| 05-184 | 311140 | 186.5 | PS | B2 | X | |
| 05-185 | 311141 | 188 | WS | B2 | X | |
| 05-186 | 311142 | 189.5 | WS | B2 | X | |
| 05-187 | 311143 | 191 | WS | B2 | X | |
| 05-188 | 311144 | 192.5 | WS | B2 | X | |
| 05-189 | 311145 | 194 | WS | B2 | X | |
| 05-190 | 311146 | 195.5 | WS | B2 | X | |
| 05-191 | 311147 | 197 | CHERT | | X | |
| 05-192 | 311148 | 198.5 | WS | B2 | X | |
| 05-193 | 311149 | 200 | WS | B2 | X | |
| 05-194 | 311150 | 201.5 | WS | B2 | X | |
| 05-195 | 311151 | 203 | WS | B2 | X | |
| 05-196 | 311152 | 204.5 | PS | B2 | X | X |
| 05-197 | 311153 | 206 | CHERT | | X | |
| 05-198 | 311154 | 207.5 | CHERT | | X | |
| 05-199 | 311155 | 209 | CHERT | | X | |
| 05-200 | 311156 | 210.5 | WS | B2 | X | |
| 05-201 | 311157 | 212 | WS | B2 | X | |
| 05-202 | 311158 | 213 | WS | B2 | X | |
| 05-203 | 311159 | 215 | PS | B2 | X | X |
| 05-204 | 311160 | 216.5 | PS | B2 | X | |
| 05-205 | 311161 | 218 | PS | B2 | X | |
| 05-206 | 311162 | 219.5 | PS | B2 | X | |

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|---|---|---|---|---|---|---|
| 05-207 | 311163 | 221 | WS | B2 | X | |
| 05-208 | 311164 | 222.5 | PS | B2 | X | |
| 05-209 | 311165 | 224 | PS | B2 | X | |
| 05-210 | 311166 | 225.5 | PS | B2 | X | |
| 05-211 | 311167 | 227 | WS | B2 | X | |
| 05-212 | 311168 | 228.5 | WS | B2 | X | |
| 05-213 | 311169 | 230 | WS | B2 | X | |
| 05-214 | 311170 | 231.5 | PS | B2 | X | |
| 05-215 | 311171 | 233 | PS | B2 | X | |
| 05-216 | 311172 | 234.5 | GS | BE1 | X | |
| 05-217 | 311173 | 234.5 | GS | BE1 | X | |
| 05-218 | 311174 | 236 | GS | BE1 | X | |
| 05-219 | 311175 | 237.5 | GS | BE1 | X | |
| 05-220 | 311176 | 239 | GS | BE1 | X | X |
| 05-221 | 311177 | 240.5 | GS | BE1 | X | |
| 05-222 | 311178 | 242 | GS | BE1 | X | |
| 05-223 | 311179 | 243.5 | GS | BE1 | X | |
| 05-224 | 311180 | 245 | GS | BE1 | X | |
| 05-225 | 311181 | 246.5 | GS | BE1 | X | |
| 05-226 | 311182 | 248 | GS | BE1 | X | |
| 05-227 | 311183 | 249.5 | GS | BE1 | X | |
| 05-228 | 311184 | 251 | GS | BE1 | X | |
| 05-229 | 311185 | 251 | GS | BE1 | X | |
| 05-230 | 311186 | 252.5 | GS | BE1 | X | |
| 05-231 | 311187 | 254 | GS | BE1 | X | |
| 05-232 | 311188 | 255.5 | GS | BE1 | X | |
| 05-233 | 311189 | 257 | GS | BE1 | X | |
| 05-234 | 311190 | 258.5 | GS | BE1 | X | |
| 05-235 | 311191 | 260 | PS | BE2 | X | |
| 05-236A | 311192 | 261.5 | GS | BE1 | X | X |
| 05-236B | 311193 | 261.5 | GS | BE1 | X | |
| 05-237 | 311194 | 263 | GS | BE1 | X | |
| 05-238 | 311195 | 264.5 | GS | BE1 | X | |
| 05-239 | 311196 | 266 | GS | BE1 | X | X |
| 05-240 | 311197 | 267.5 | GS | BE1 | X | |
| 05-241 | 311198 | 269 | PS | BE2 | X | |
| 05-242 | 311199 | 270.5 | GS | BE1 | X | |
| 05-243 | 311200 | 272 | GS | B1 | X | |
| 05-244 | 311201 | 273.5 | GS | B1 | X | |
| 05-245 | 311202 | 275 | GS | B1 | X | |
| 05-246 | 311203 | 276.5 | GS | B1 | X | X |
| 05-247 | 311204 | 278 | GS | B1 | X | |
| 05-248 | 311205 | 279.5 | GS | B1 | X | |
| 05-249 | 311206 | 281 | GS | B1 | X | |
| 05-250 | 311207 | 282.5 | GS | B1 | X | X |
| 05-251 | 311208 | 284 | GS | B1 | X | |
| 05-252 | 311209 | 285.5 | GS | B1 | X | |
| 05-253 | 311210 | 287 | GS | B1 | X | |
| 05-254 | 311211 | 288.5 | GS | B1 | X | |
| 05-255 | 311212 | 290 | GS | BE1 | X | |
| 05-256 | 311213 | 291.5 | GS | B1 | X | |
| 05-257 | 311214 | 293 | GS | B1 | X | |
| 05-258 | 311215 | 296 | GS | B1 | X | |

| | | | | | | |
|---|---|---|---|---|---|---|
| 05-259 | 311216 | 330.5 | GS | B1 | X | |
| 05-260 | 311217 | 373 | GS | B1 | X | |
| 05-261 | 311218 | 379 | GS | B1 | X | |
| 05-262 | 311219 | 389.5 | GS | B1 | X | X |
| 05-263 | 311220 | 413.5 | GS | B1 | X | |
| 05-264 | 311221 | 476.5 | GS | B1 | X | |
| 05-265 | 311222 | 481 | GS | B1 | X | |

**FIELD LOCATION 6 - SECTION 2**

| SAMPLE# | GSC# | LEVEL (m) | LITH | FACIES | HS | TS |
|---|---|---|---|---|---|---|
| 06-01 | 311223 | 0 | MS | H | X | |
| 06-02 | 311224 | 39 | MS | H | X | |
| 06-03 | 311225 | 61.5 | MS | H | X | |
| 06-04 | 311226 | 105 | MS | H | X | X |
| 06-05 | 311227 | 145.5 | MS | H | X | X |
| 06-06 | 311228 | 222 | MS | H | X | |
| 06-07 | 311229 | 279 | MS | H | X | X |
| 06-08 | 311230 | 423 | MS | H | X | X |
| 06-09 | 311231 | 500.5 | MS | H | X | X |
| 06-10 | 311232 | 546 | WS | B3 | X | X |
| 06-11 | 311233 | 574.5 | WS | B3 | X | |
| 06-12A | 311234 | 582 | WS | B3 | X | X |
| 06-12B | 311235 | 582 | WS | B3 | X | X |
| 06-13 | 311236 | 588 | WS | B3 | X | |
| 06-14 | 311237 | 607.5 | PS | H | X | X |
| 06-15 | 311238 | 621 | WS | B3 | X | X |
| 06-16 | 311239 | 645 | WS | B3 | X | |
| 06-18A | 311240 | 666 | WS | B3 | X | X |
| 06-18B | 311241 | 666 | WS | B3 | X | |
| 06-19 | 311242 | 667.5 | WS | B3 | X | X |
| 06-20 | 311243 | 670.5 | WS | B3 | X | |
| 06-21 | 311244 | 687.75 | WS | B3 | X | X |
| 06-22 | 311245 | 699 | WS | B3 | X | X |
| 06-23 | 311246 | 717 | WS | B3 | X | X |
| 06-24 | 311247 | 718.5 | MS | H | X | X |
| 06-25 | 311248 | 726 | MS | H | X | X |
| 06-26 | 311249 | 729.75 | MS | H | X | X |
| 06-27 | 311250 | 732.75 | MS | H | X | X |
| 06-28 | 311251 | 750 | MS | H | X | X |

**FIELD LOCATION 7 - SECTION 15**

| SAMPLE# | GSC# | LEVEL (m) | LITH | FACIES | HS | TS |
|---|---|---|---|---|---|---|
| 07-01 | 311252 | 0 | MS | H | X | |
| 07-1A | 311253 | 1.5 | MS | H | X | |
| 07-02 | 311254 | [illegible] | MS | H | X | |
| 07-03 | 311255 | [illegible] | MS | H | X | |

| | | | | | | |
|---|---|---|---|---|---|---|
| 07-04 | 311256 | 4.5 | MS | H | X | |
| 07-05 | 311257 | 6 | MS | H | X | |
| 07-06 | 311258 | 7.5 | MS | H | X | |
| 07-07 | 311259 | 9 | MS | H | X | |
| 07-08 | 311260 | 10.5 | MS | H | X | |
| 07-09 | 311261 | 12 | MS | H | X | |
| 07-10 | 311262 | 13.5 | MS | H | X | |
| 07-11 | 311263 | 15 | MS | H | X | |
| 07-12 | 311264 | 16.5 | MS | H | X | X |
| 07-13 | 311265 | 18 | MS | B3 | X | |
| 07-14 | 311266 | 19.5 | MS | B3 | X | |
| 07-15 | 311267 | 21 | MS | B3 | X | |
| 07-16 | 311268 | 22.5 | MS | B3 | X | |
| 07-17 | 311269 | 24 | MS | B3 | X | |
| 07-18 | 311270 | 26.5 | MS | B3 | X | |
| 07-19 | 311271 | 28 | MS | B3 | X | |
| 07-20 | 311272 | 29.5 | MS | B3 | X | |
| 07-21 | 311273 | 35 | MS | B3 | X | |
| 07-22 | 311274 | 32.5 | MS | B3 | X | X |
| 07-23 | 311275 | 34 | MS | B3 | X | |
| 07-24 | 311276 | 35.5 | WS | B3 | X | X |
| 07-25 | 311277 | 37 | WS | B3 | X | |
| 07-26 | 311278 | 38.5 | WS | B3 | X | |
| 07-27 | 311279 | 40 | WS | B3 | X | X |
| 07-28A | 311280 | 41.5 | WS-PS | B2 | X | X |
| 07-28B | 311281 | 42.2 | WS-PS | B2 | X | X |
| 07-30 | 311282 | 43 | WS-PS | B2 | X | X |
| 07-31 | 311283 | 44.2 | WS-PS | B2 | X | X |
| 07-31A | 311284 | 44 | WS | B2 | X | X |
| 07-31B | 311285 | 44.5 | WS | B2 | X | X |
| 07-32 | 311286 | 44.6 | WS | B3 | X | X |
| 07-33 | 311287 | 45.7 | PS | B2 | X | X |
| 07-34 | 311288 | 47.5 | PS | B2 | X | |
| 07-35 | 311289 | 49 | PS | B2 | X | |
| 07-36 | 311290 | 50.1 | PS | B2 | X | X |
| 07-37 | 311291 | 50.5 | PS | B2 | X | |
| 07-38 | 311292 | 52 | PS | B2 | X | |
| 07-39 | 311293 | 53.5 | WS-PS | B3 | X | X |
| 07-40 | 311294 | 55 | WS | B3 | X | |
| 07-41 | 311295 | 56.5 | WS | B3 | X | |
| 07-42 | 311296 | 58 | WS | B3 | X | |
| 07-43 | 311297 | 59.5 | MS | H | X | |
| 07-44 | 311298 | 61 | MS | H | X | |
| 07-45 | 311299 | 62.5 | WS | B3 | X | |
| 07-46 | 311300 | 64 | MS-WS | H | X | X |
| 07-47 | 311301 | 65.5 | PS | DT | X | |
| 07-48 | 311751 | 67 | PS | DT | X | |
| 07-49 | 311752 | 68.5 | PS | DT | X | X |
| 07-50 | 311753 | 69 | WS | H | X | X |

**FIELD LOCATION 8 - SECTION 9**

| SAMPLE# | GSC# | LEVEL (m) | LITH | FACIES | HS | TS |
|---|---|---|---|---|---|---|
| 08-25 | 311824 | 358.5 | PS | DT | X | X |
| 08-26 | 312065 | 360 | MS | H | X | |
| 08-27 | 311825 | 367.5 | MS | H | X | X |
| 08-28 | 312066 | 376.5 | MS | H | X | |
| 08-29 | 311826 | 379.5 | MS | H | X | X |
| 08-30 | 311827 | 373.5 | MS | H | X | X |
| 08-31 | 312067 | 403 | MS | H | X | |
| 08-32 | 311829 | 417.5 | WS | B3 | X | X |
| 08-33 | 312068 | 421.5 | WS | B3 | X | |
| 08-34 | 311830 | 426 | WS | B3 | X | X |
| 08-35 | 312069 | 429.5 | MS | FS | X | |
| 08-36 | 311831 | 446.5 | WS | B3 | X | X |
| 08-36B | 311832 | 446.5 | PS-GS | DT(B2, C2) | X | X |
| 08-36C | 311833 | 446.5 | WS-PS | DT(B2, C2) | X | X |
| 08-37 | 311834 | 430.5 | MS | FS | X | X |
| 08-38 | 312070 | 441 | WS | B3 | X | |
| 08-39 | 311835 | 458 | WS | DT(B2, C2) | X | X |
| 08-40 | 312071 | 458.25 | PS | DT(B2, C2) | X | |
| 08-41 | 311836 | 457.5 | GS | DT(B2, C2) | X | X |
| 08-42 | 312072 | 489 | MS | H | X | |
| 08-43 | 311837 | 505.5 | MS | H | X | X |
| 08-44 | 312073 | 530.4 | MS | H | X | |
| 08-45 | 311838 | 531 | MS | H | X | X |
| 08-46 | 312074 | 547 | MS | H | X | |
| 08-47 | 311839 | 556.5 | MS | H | X | X |
| 08-48 | 312075 | 570 | MS | H | X | |
| 08-49 | 311840 | 571.5 | PS | B2 | X | X |
| 08-50 | 312076 | 595 | MS | H | X | |
| 08-51 | 311841 | 630 | WS | DT(B2) | X | X |
| 08-52 | 311842 | 660 | MS | H | X | X |
| 08-53 | 312077 | 772 | MS | H | X | |
| 08-54 | 311843 | 772.8 | MS | H | X | X |

**FIELD LOCATION 9 - SECTION 10**

| SAMPLE# | GSC# | LEVEL (m) | LITH | FACIES | HS | TS |
|---|---|---|---|---|---|---|
| 09-01 | 311981 | 1 | PS | DT | X | X |
| 09-02 | 311982 | 4.5 | MS | FS | X | X |
| 09-03 | 311983 | 33.5 | WS | DT(B2) | X | X |
| 09-04 | 311984 | 36 | MS | FS | X | X |
| 09-05 | 312078 | 51 | MS | FS | X | |
| 09-06 | 311985 | 63 | MS | H | X | X |
| 09-07 | 312079 | 73.5 | MS | H | X | |
| 09-08 | 312080 | 127.5 | MS | H | X | |
| 09-09 | 311986 | 160.5 | MS | H | X | X |

| | | | | | | |
|---|---|---|---|---|---|---|
| 09-10 | 312081 | 161 | MS | H | X | |
| 09-11 | 312082 | 183 | MS | H | X | |
| 09-12 | 312083 | 189 | MS | H | X | |
| 09-13 | 312084 | 192.5 | MS | H | X | |
| 09-14 | 312085 | 201.5 | MS | H | X | |
| 09-16 | 312087 | 217.5 | MS | H | X | |
| 09-17 | 311987 | 226.5 | WS | B3 | X | X |
| 09-18 | 311988 | 278.5 | WS | B3 | X | X |
| 09-19 | 311989 | 282 | WS | B3 | X | X |
| 09-20 | 312088 | 309 | WS | B2 | X | |
| 09-21 | 311990 | 322 | WS | B2 | X | X |
| 09-22 | 311991 | 328.5 | WS | B2 | X | X |
| 09-23 | 311992 | 330 | WS | B2 | X | X |
| 09-24 | 312089 | 342 | PS | B2 | X | |
| 09-25 | 311993 | 352.5 | GS | B1 | X | X |
| 09-26 | 311994 | 357 | GS | B1 | X | X |
| 09-27 | 312090 | 363 | GS | B1 | X | |
| 09-28 | 311995 | 364.5 | GS | B1 | X | X |
| 09-29 | 312091 | 373.5 | GS | B1 | X | |
| 09-30 | 312092 | 381 | GS | B1 | X | |
| 09-31 | 312093 | 396 | GS | B1 | X | |
| 09-32 | 311996 | 400.5 | PS | B2 | X | X |
| 09-33 | 312094 | 403.5 | PS | B2 | X | |
| 09-34 | 312095 | 411 | PS | B2 | X | |
| 09-35 | 312096 | 421.5 | PS | B2 | X | |
| 09-36 | 312097 | 426 | PS | B2 | X | |
| 09-37 | 312098 | 432 | PS | B2 | X | |
| 09-38 | 311997 | 433.5 | PS | B2 | X | X |
| 09-39 | 312099 | 435 | PS | B2 | X | |
| 09-40 | 312100 | 447 | PS | B2 | X | |
| 09-41 | 312101 | 454.5 | WS | B2 | X | |
| 09-42 | 311998 | 469.5 | WS | B2 | X | X |

## FIELD LOCATION 10 - SECTION 11

| SAMPLE# | GSC# | LEVEL (m) | LITH | FACIES | HS | TS |
|---|---|---|---|---|---|---|
| 10-LSB | 311922 | 1.5 | PS | BE2 | X | X |
| 10-LSB | 311923 | 1.5 | PS | BE2 | X | X |
| 10-01 | 311924 | 0 | GS | B1 | X | X |
| 10-02 | 311925 | 1.4 | GS | BE1 | X | X |
| 10-03 | 311926 | 1.6 | GS | B1 | X | X |
| 10-04 | 311927 | 3 | PS | B2 | X | X |
| 10-05 | 311928 | 4.5 | PS | B2 | X | X |
| 10-06 | 312102 | 6 | PS | B2 | X | |
| 10-08 | 311929 | 7.5 | PS | B2 | X | X |
| 10-09 | 312104 | 9 | PS | B2 | X | |
| 10-10 | 311930 | 17.5 | WS | B2 | X | X |
| 10-11 | 311931 | 19 | WS | B2 | X | X |
| 10-12 | 311932 | 23.5 | WS | B2 | X | X |
| 10-13 | 312105 | 25 | WS | B2 | X | |

| | | | | | | |
|---|---|---|---|---|---|---|
| 10-14 | 312106 | 28 | WS | B2 | X | |
| 10-15 | 311933 | 29.5 | WS | B2 | X | X |
| 10-16 | 312107 | 33 | WS | B2 | X | |
| 10-17 | 312108 | 34.5 | WS | B2 | X | |
| 10-18 | 312109 | 36 | WS | B2 | X | |
| 10-19 | 312110 | 37.5 | WS | B2 | X | |
| 10-20 | 311934 | 39 | WS | B2 | X | X |
| 10-21 | 312111 | 40.5 | WS | B2 | X | |
| 10-22 | 311935 | 42 | WS | B2 | X | X |
| 10-23 | 311936 | 59 | PS | B2 | X | X |
| 10-24 | 312112 | 60.5 | PS | B2 | X | |
| 10-25 | 312113 | 62 | PS | B2 | X | |
| 10-26 | 311937 | 63.5 | PS | B2 | X | X |
| 10-27 | 312114 | 65 | PS | B2 | X | |
| 10-28 | 311938 | 66.5 | PS | B2 | X | X |
| 10-29 | 312115 | 68 | PS | B2 | X | |
| 10-30 | 311939 | 69.5 | PS | B2 | X | X |
| 10-31 | 312116 | 71 | PS | B2 | X | |
| 10-31A | 312117 | 71 | PS | B2 | X | |
| 10-32 | 312118 | 72.5 | PS | B2 | X | |
| 10-32A | 312119 | 72.5 | PS | B2 | X | |
| 10-33 | 311940 | 74 | PS | B2 | X | X |
| 10-33A | 312120 | 74 | PS | B2 | X | |
| 10-34 | 311941 | 75.5 | PS | B2 | X | X |
| 10-34B | 311942 | 76.3 | PS | B2 | X | X |
| 10-35 | 311943 | 77.3 | PS | BE2 | X | X |
| 10-36 | 312121 | 78.3 | PS | BE2 | X | |
| 10-37 | 311944 | 79.8 | PS | BE2 | X | X |
| 10-38 | 311945 | 81.3 | GS | B1 | X | X |
| 10-39 | 311946 | 82.8 | PS | BE2 | X | X |
| 10-40 | 311947 | 84.3 | PS | BE2 | X | X |
| 10-41 | 311948 | 85.3 | PS | BE2 | X | X |
| 10-42 | 311949 | 86.3 | | SANDST | X | X |
| 10-43 | 311950 | 86.8 | | SANDST | X | X |

**FIELD LOCATION 11 - SECTION 8**

| SAMPLE# | GSC# | LEVEL (m) | LITH | FACIES | HS | TS |
|---|---|---|---|---|---|---|
| 11-01 | 311951 | 1.5 | MS | H | X | X |
| 11-4.5 | 311952 | 6.75 | PS | DT(C2) | X | X |
| 11-17 | 312122 | 25.5 | MS | H | X | |
| 11-19 | 311953 | 28.5 | PS | DT(C2) | X | X |
| 11-20 | 311954 | 30 | MS | H | X | X |
| 11-34 | 311955 | 51 | MS | H | X | X |
| 11-36 | 311956 | 54 | MS | H | X | X |
| 11-38 | 311957 | 57 | GS | DT(C1) | X | X |
| 11-45 | 312123 | 67.5 | MS | FS | X | |
| 11-50 | 311958 | 75 | PS | DT(C2) | X | X |
| 11-54 | 311959 | 81 | PS | DT(C2) | X | X |
| 11-64 | 311960 | 96 | PS | DT(C2) | X | X |

| | | | | | | |
|---|---|---|---|---|---|---|
| 11-67 | 311961 | 100.5 | PS | DT(C2) | X | X |
| 11-75 | 311962 | 112.5 | PS | DT(C2) | X | X |
| 11-81 | 312124 | 120.5 | MS | H | X | |
| 11-82 | 311963 | 123 | MS-PS | H | X | X |
| 11-85 | 311964 | 127.5 | WS | B3 | X | X |
| 11-86 | 311965 | 129 | WS | B3 | X | X |
| 11-91.5 | 311966 | 137.25 | WS | DT(C2) | X | X |
| 11-95 | 311967 | 142.5 | MS | FS | X | X |
| 11-97 | 311968 | 145.5 | MS-WS | H | X | X |
| 11-101 | 311969 | 151.5 | WS-PS | DT(C2) | X | X |
| 11-102 | 311970 | 153 | GS | DT(C1) | X | X |
| 11-107 | 311971 | 160.5 | PS | DT(C2) | X | X |
| 11-107B | 311972 | 160.5 | GS | DT(C1) | X | X |
| 11-111.5 | 311973 | 167.25 | PS | DT(C2,BE2) | X | X |
| 11-115 | 311974 | 172.5 | MS | H | X | X |
| 11-131B | 311975 | 196.5 | PS | DT(C2) | X | X |
| 11-131A | 311976 | 196.5 | PS | DT(BE2) | X | X |
| 11-137 | 311977 | 205.5 | MS | H | X | X |
| 11-148 | 311978 | 222 | WS | DT(C2) | X | X |
| 11-150 | 312125 | 225 | MS | H | X | |
| 11-151 | 311979 | 226.5 | MS | H | X | X |
| 11-176 | 312126 | 264 | WS-PS | DT | X | |
| 11-187 | 311980 | 280.5 | MS | FS | X | X |
| 11-199 | 312127 | 298.5 | MS | FS | X | |
| 11-329 | 312128 | 493.5 | MS | H | X | |

**FIELD LOCATION 12 - SECTION 1**

| SAMPLE# | GSC# | LEVEL (m) | LITH | FACIES | HS | TS |
|---|---|---|---|---|---|---|
| 12-0 | 311844 | 0 | MS | H | X | X |
| 12-1 | 311845 | 1.5 | WS | B3 | X | X |
| 12-2 | 311846 | 3 | WS | B3 | X | X |
| 12-4 | 311847 | 6 | MS | H | X | X |
| 12-16 | 311848 | 24 | MS | H | X | X |
| 12-18 | 311849 | 27 | MS | H | X | X |
| 12-25 | 311850 | 37.5 | MS | H | X | X |
| 12-50 | 311851 | 75 | MS | H | X | X |

**FIELD LOCATION 13 - SECTION 14**

| SAMPLE# | GSC# | LEVEL (m) | LITH | FACIES | HS | TS |
|---|---|---|---|---|---|---|
| 13-1 | 311852 | N/A | WS | BE3-F | X | X |
| 13-2 | 311853 | N/A | WS | BE3-F | X | X |
| 13-3 | 311854 | N/A | WS | BE3-F | X | X |
| 13-6 | 311855 | N/A | WS | BE3-F | X | X |
| 13-8 | 311856 | N/A | WS | BE3 | X | X |
| 13-7 | 311857 | N/A | WS | BE3 | X | X |
| 13-9 | 311858 | N/A | WS | BE3 | X | X |

| | | | | | | |
|---|---|---|---|---|---|---|
| 13-15 | 311859 | N/A | PS | B2 | X | X |

**FIELD LOCATION 14 - SECTION 6**

| SAMPLE# | GSC# | LEVEL (m) | LITH | FACIES | HS | TS |
|---|---|---|---|---|---|---|
| 14-13 | 311915 | 19.5 | GS | B1 | X | X |
| 14-15 | 311914 | 22.5 | GS | B1 | X | X |
| 14-20 | 311913 | 30 | GS | B1 | X | X |
| 14-23 | 311912 | 34.5 | GS | B1 | X | X |
| 14-28 | 311911 | 42 | GS | B1 | X | X |
| 14-33 | 311910 | 49.5 | GS | B1 | X | X |
| 14-37 | 311860 | 55.5 | PS | B2 | X | X |
| 14-38 | 311861 | 57 | PS | B2 | X | X |
| 14-39 | 311862 | 58.5 | PS | B2 | X | X |
| 14-41 | 311863 | 61.5 | PS | B2 | X | X |
| 14-44 | 311864 | 66 | PS | B2 | X | X |
| 14-45 | 311865 | 67.5 | PS | B2 | X | X |
| 14-46 | 311866 | 69 | PS | B2 | X | X |
| 14-48 | 311867 | 70.5 | PS | B2 | X | X |
| 14-50 | 311868 | 75 | PS | B2 | X | X |
| 14-51.5 | 311869 | 77.25 | PS | B2 | X | X |
| 14-54 | 311870 | 81 | MS | H | X | X |
| 14-59 | 311871 | 88.5 | PS | B2 | X | X |
| 14-59.5 | 311872 | 89.25 | GS | B1 | X | X |
| 14-65 | 311873 | 97.5 | GS | B1 | X | X |
| 14-67 | 311874 | 100.5 | GS | B1 | X | X |
| 14-70 | 312129 | 105 | GS | B1 | X | |

**FIELD SECTION 14A - SECTION 6**

| SAMPLE# | GSC# | LEVEL (m) | LITH | FACIES | HS | TS |
|---|---|---|---|---|---|---|
| 14A-23 | 311921 | 111.5 | GS | B1 | X | X |
| 14A-24 | 311920 | 112.5 | PS | B2 | X | X |
| 14A-25 | 311919 | 113.5 | PS | B2 | X | X |
| 14A-26 | 311918 | 114.5 | PS | B2 | X | X |
| 14A-27 | 311917 | 115.5 | PS | B2 | X | X |
| 14A-28 | 311916 | 116.5 | MS | H | X | X |

**FIELD LOCATION 15 - SECTION 7**

| SAMPLE# | GSC# | LEVEL (m) | LITH | FACIES | HS | TS |
|---|---|---|---|---|---|---|
| 15-0.5 | 312139 | 0.5 | GS | C1 | X | |
| 15-2 | 311879 | 2 | PS | C2 | X | X |
| 15-5.5 | 311880 | 5.5 | PS | BE2 | X | X |
| 15-6 | 312140 | 6 | WS-PS | BE2 | X | |
| 15-9 | 311881 | 9 | WS-PS | BE2 | X | X |

| | | | | | | |
|---|---|---|---|---|---|---|
| 15-13 | 312141 | 13 | WS | B2 | X | |
| 15-15 | 312142 | 15 | WS | B2 | X | |
| 15-19 | 311882 | 19 | WS | C2 | X | X |
| 15-25 | 311883 | 25 | WS | C2 | X | X |
| 15-33.5 | 312143 | 33.5 | PS | BE2 | X | |
| 15-42 | 311884 | 42 | PS | BE2 | X | X |
| 15-43.8 | 312144 | 43.8 | PS | B2 | X | |
| 15-44.5 | 311885 | 44.5 | PS | B2 | X | X |
| 15-58.5 | 312145 | 58.5 | PS | B2 | X | |
| 15-61.5 | 311886 | 61.5 | PS | C2 | X | X |
| 15-71.5 | 311887 | 71.5 | PS | C2 | X | X |
| 15-94.5 | 312146 | 94.5 | WS | B2 | X | |
| 15-105 | 311888 | 105 | PS | B2 | X | X |
| 15-112 | 311889 | 112 | PS | B2 | X | X |
| 15-120 | 312147 | 120 | PS | B2 | X | |
| 15-138 | 311890 | 138 | WS | BE3 | X | X |
| 15-151.5 | 311891 | 151.5 | WS | BE3 | X | X |
| 15-195 | 311892 | 195 | WS | BE3 | X | X |
| 15-231 | 311893 | 231 | WS-PS | B2 | X | X |
| 15-240 | 311894 | 240 | WS | B2 | X | X |
| 15-246 | 311895 | 246 | WS | B2 | X | X |
| 15-261 | 312148 | 261 | WS | B2 | X | |
| 15-271.5 | 312149 | 271.5 | WS | B3 | X | |
| 15-282 | 311896 | 282 | MS | H | X | X |
| 15-294 | 311897 | 294 | MS | H | X | X |
| 15-301.5 | 312150 | 301.5 | WS | B3 | X | |
| 15-315 | 312151 | 315 | WS | B3 | X | |
| 15-330 | 311898 | 330 | WS | B3 | X | X |
| 15-339 | 312156 | 339 | WS | B2 | X | |
| 15-343.5 | 311899 | 343.5 | WS | B2 | X | X |
| 15-359 | 311900 | 359 | PS | B2 | X | X |

**FIELD LOCATION 15A - SECTION 7**

| SAMPLE# | GSC# | LEVEL (m) | LITH | FACIES | HS | TS |
|---|---|---|---|---|---|---|
| 15B-05 | 311901 | 0.5 | PS | B2 | X | X |
| 15B24 | 311902 | 24 | CHERT | | X | X |
| 15B-36 | 311903 | 36 | GS | B1 | X | X |
| 15B-51 | 311904 | 51 | GS | B1 | X | X |
| 15B-53 | 311905 | 53 | GS | B1 | X | X |
| 15B-67.5 | 311906 | 67.5 | PS | B2 | X | X |
| 15B70.5 | 311907 | 70.5 | PS | B2 | X | X |
| 15B-81 | 312157 | 81 | WS | B3 | X | |

## APPENDIX 4: CONODONT SAMPLES

| SECTION | GSC NUMBER | FIELD NUMBER | LEVEL (m) | CONODONT ASSEMBLAGE* |
|---|---|---|---|---|
| 3 | 311705 | 94-01 | 1024-1025 | b |
| 3 | 311706 | 94-01 | 1083 | P8 |
| 4 | 311708 | 94-03 | 4-5 | b |
| 5 | 311709 | 94-05 | 25 | P6-P7 |
| 5 | 311710 | 94-05 | 0-1 | P6-P7 |
| 5 | 311711 | 94-05 | 130 | b |
| 5 | 311712 | 94-05 | 171 | b |
| 5 | 311713 | 94-05 | 231 | upper P7-P8 |
| 6 | 311733 | 94-14 | 54-56 | b |
| 6 | 311734 | 94-14 | 57-59 | b |
| 6 | 311735 | 94-14 | 73.5-75 | P8 |
| 6 | 311736 | 94-14 | 88.5-90.8 | b |
| 6 | 311737 | 94-14 | 123-124.5 | upper P8 |
| 9 | 311714 | 94-08 | 307 | P5 |
| 9 | 311715 | 94-08 | 320 | P5 |
| 9 | 311716 | 94-08 | 358 | P5 |
| 9 | 311717 | 94-08 | 422 | P6 |
| 9 | 311718 | 94-08 | 431 | in |
| 9 | 311719 | 94-08 | 478-480 | P6-P7 |
| 9 | 311720 | 94-08 | 630 | b |
| 10 | 311721 | 94-09 | 0 | P5a |
| 10 | 311722 | 94-09 | 138 | P5b |
| 10 | 311723 | 94-09 | 190 | P5b |
| 10 | 311724 | 94-09 | 216 | P6 |
| 10 | 311725 | 94-09 | 318 | P7 |
| 11 | 311726 | 94-10 | 2-3 | b |
| 11 | 311727 | 94-10 | 6-7 | b |
| 11 | 311728 | 94-10 | 12-13 | b |
| 11 | 311729 | 94-10 | 37-39 | b |
| 11 | 311730 | 94-10 | 80 | b |
| 11 | 311731 | 94-10 | 83 | P10 |
| 12 | 311707 | 94-02 | 13-14 | P6b |
| 14 | 311732 | 94-13 | Eastern Flanks | b |
| 15 | 311701 | 94-07 | 40.5-42 | P8 |
| 15 | 311702 | 94-07 | 43.9-44.6 | P8 |
| 15 | 311703 | 94-07 | 55 | b |
| 15 | 311704 | 94-07 | 67-68 | b |

* Conodont assemblage codes are explained in Table 1 on page 28. Analysis of conodonts for this study was done by Dr. Charles Henderson at the University of Calgary.