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**FACIES ANALYSIS OF LOWER PERMIAN CYCLIC CARBONATES,
WEST-CENTRAL ELLESMERE ISLAND, CANADIAN ARCTIC**

Jean Morin

Thesis

**Submitted to the School of Graduate Studies and Research
in Partial Fulfillment of the Requirement for the
Degree of Master of Science
in Geology**

**Ottawa-Carleton Geoscience Centre
Department of geology
University of Ottawa**



Jean Morin, Ottawa, Canada, 1992



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ABSTRACT

At least 36 decametre-scale, largely symmetric high-frequency cycles spanning approximately 15 Ma make up the carbonate-dominated succession of Lower Permian sequence 3 of the Sverdrup Basin in Fosheim and Hamilton peninsulas. These cycles record a rift pulse characterized by the uplift, passive subsidence, collapse and passive subsidence of the Fosheim-Hamilton subbasin and show that during the rifting phase of the Sverdrup Basin deposition of unconformity-bounded sequences was tectonically rather than eustatically controlled.

The active rifting-phase of the Sverdrup Basin comprises four unconformity-bounded sequences that range in age from Viséan to Kungurian. The third-sequence in Fosheim and Hamilton peninsulas area, west central Ellesmere Island comprises six formations. The Canyon Fiord Formation is composed of lithofacies ranging from basin margin fluvial to marine siliciclastics. The Belcher Channel, Antoinette, Tanquary and Nansen formations are made up of inner- to midshelf carbonates that encompass the Mount Bayley Formation, a thick evaporite succession deposited within the Fosheim-Hamilton subbasin.

Petrographic analysis of the carbonate-dominated facies in sequence 3 has delimited nineteen platformal facies representing lagoonal, barrier and shoals, reefal and non-reefal mid-shelf depositional environments. These facies are organized into high-frequency depositional cycles that record the interplay between eustasy, tectonism and sediment supply. In order to facilitate their regional analysis, cycles were grouped into five idealized cycles. From proximal to distal, these cycles include: Sandstone-Grainstone; Grainstone-Palaeoaplysiniid; Packstone-Phylloid; Wackestone; and Anhydrite cycles. These high-frequency cycles are grouped into a Pre-, Syn- and Post-evaporite cyclic assemblages, each of which possesses an unique stacking pattern. The Pre-evaporite Assemblage comprises 9 cycles characterized by relatively similar thickness and composition. High-frequency cyclicity within this assemblage was controlled by glacio-eustatic oscillations with only local tectonic influence. The Syn-evaporite Assemblage cycles comprises at least 19 cycles characterized by variable composition and thickness and by the occurrence of evaporites in the subbasin centre. High-frequency cyclicity within this assemblage was affected by both syn-depositional faulting and glacio-eustatic variations. The Post-evaporite Assemblage comprises at least 7 cycles characterized by recessive lower and upper shaly units of variable thickness and by a resistant middle carbonate unit of constant thickness and similar composition. High-frequency cyclicity within this assemblage was controlled mainly by glacio-eustasy and to a lesser extent by the local but important siliciclastic influx. The Pre-, Syn- and Post-evaporite assemblages are associated with the initial uplift-passive subsidence, collapse, and passive thermal subsidence of the Fosheim-Hamilton subbasin, respectively.

RÉSUMÉ

Un minimum de 36 cycles decamétriques à haute-fréquences, généralement symétriques, déposés sur une période de 15 Ma composent la séquence 3 (Permien Inférieur) du Bassin de Sverdrup, dans la région des Péninsules de Fosheim et de Hamilton au centre-ouest de l'île d'Ellesmere. Ces cycles se sont déposés lors d'un épisode d'extension caractérisé par un soulèvement suivie d'une période de subsidence passive, d'un effondrement ainsi que d'une autre période de subsidence passive. Ceci suggère que durant la phase de rift du Bassin de Sverdrup, la présence de séquences limitées par des discordances n'est pas contrôlée par l'eustasie globale mais par des phénomènes d'origine tectonique.

La phase active de rift du Bassin de Sverdrup comprend quatre séquences limitées par des discordances qui s'échelonnent du Viséen au Kungurien. La troisième séquence dans la région des Péninsules de Fosheim et de Hamilton est composée de six formations d'âge Assélien à Sakmarien. La Formation de Canyon Fiord est composée de sédiments siliciclastiques variant de fluviale à marin. Les formations de Belcher Channel, Antoinette, Tanquary et de Nansen sont caractérisées par des carbonates de plate-forme peu-profonde et entourent la succession évaporitique de la Formation de Mount Bayley déposée à l'intérieur du sous-bassin de Fosheim-Hamilton.

Suite à l'analyse pétrographique des faciès carbonatés, la séquence 3 a été subdivisée en 19 faciès représentant quatre principaux systèmes de déposition, soit: lagon; barrière et haut-fonds; et faciès récifaux et non-récifaux de la plate-forme moyenne. Ces faciès sont organisés en cycle dépositionnel à haute-fréquence créés par des variations relatives du niveau marin causées par l'interaction de l'eustasie, la tectonique et l'apport sédimentaire. Afin de faciliter leur analyse régionale, ces cycles sont regroupés en cinq cycles idéalisés, soit de proximal à distal: Grès-Grainstone; Grainstone-Palaeoaplysiniid; Packstone-Phylloid; Wackestone; et Anhydrite. Ces cycles à haute-fréquence sont regroupés en trois assemblages de cycle Pré-, Syn-, et Post-évaporite, chacun possédant un patron d'empilement particulier. L'Assemblage Pré-évaporite est composé de 9 cycles caractérisés par des épaisseurs et des compositions relativement constantes. La cyclicité à haute-fréquence dans cet assemblage était contrôlée par des variations glacio-eustatique avec des mouvements tectoniques localisés. L'Assemblage Syn-évaporite comprend au moins 19 cycles caractérisés par d'importantes variations latérales et verticales en composition et épaisseur, ainsi que par la présence d'évaporites au centre du sous-bassin. La cyclicité de haute-fréquence dans cet assemblage était influencée par des failles syn-sédimentaires et par des variations glacio-eustatiques. L'Assemblage Post-évaporite est composé d'au moins 7 cycles caractérisés par des unités inférieure et supérieure récessives d'épaisseur variable et par une unité médiane de carbonate, résistante, de composition et d'épaisseur constante. La cyclicité à haute-

fréquence dans cet assemblage était contrôlée principalement par des variations glacio-eustatiques et, à un moindre degré, par un important apport sédimentaire local. Les Assemblages Pré-, Syn-, et Post-éaporite sont respectivement associés avec le soulèvement initial-subsidence passive, l'effondrement et la subsidence thermique passive du sous-bassin de Fosheim-Hamilton.

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CHAPTER 1: INTRODUCTION

1.1 OBJECTIVES

High frequency cycles are widely developed in upper Paleozoic strata of the world. Numerous studies during the past two decades have shown close similarities in the stacking pattern of carbonate- and clastic-dominated cycles from a variety of depositional settings ranging from glacial (Veevers and Powell, 1988), to fluvial (Busch and Rollins, 1984) to marine (Wilson, 1975; Heckel, 1984). These similarities have led many to believe that glacio-eustasy was the driving mechanism for generating these cycles. This idea appears reasonable considering that vast ice-sheets are known to have formed in Gondwana during the Late Carboniferous to Early Permian interval.

Most of the studies concerning upper Paleozoic high-frequency cycles were performed in areas that experienced relatively little tectonic perturbation during sedimentation. It would be interesting to compare the stacking pattern of such cycles in active areas where tectonically-driven subsidence played an important role in shaping the vertical cyclic succession. Providing that upper Paleozoic high-frequency cycles are indeed of glacio-eustatic origin, one could theoretically use the vertical succession of such cycles as a strip-chart that monitored the tectonic subsidence history of a given basin. The main purpose of this study is to test whether or not high-frequency cycles can be used in such a strip-chart fashion.

In order to achieve this, a vast region of the Sverdrup Basin was examined in detail. The Sverdrup Basin is a rift that was tectonically active in Late Carboniferous-Early Permian time (Beauchamp *et al*, 1989 a, b). A multitude of high-frequency cycles are evident in strata covering a vast area of west-central Ellesmere Island (Fig. 1.1) forming a succession of clastic-, carbonate- and evaporite-dominated formations. This study focussed on carbonate-dominated cycles of the Canyon Fiord, Belcher Channel, Antoinette, Mount Bayley, Tanquary and Nansen formations, which accumulated in a 15 000 km² subbasin (Fosheim-Hamilton Subbasin) of the main Sverdrup Basin. Emphasis is placed on the Asselian and Sakmarian strata of this succession, which constitute one broad 15 M.a. long (third-order) unconformity-bounded sequence. In order to understand the subsidence history using high-frequency cycles of this rift environment, the specific objectives of this study are to: 1) understand the fundamental stratigraphic relationship in the study area; 2) describe and interpret carbonate facies and their environment of deposition; and 3) assess the broad vertical and lateral variations in the cyclic succession to understand mechanisms that controlled the development of this broad third-order sequence.

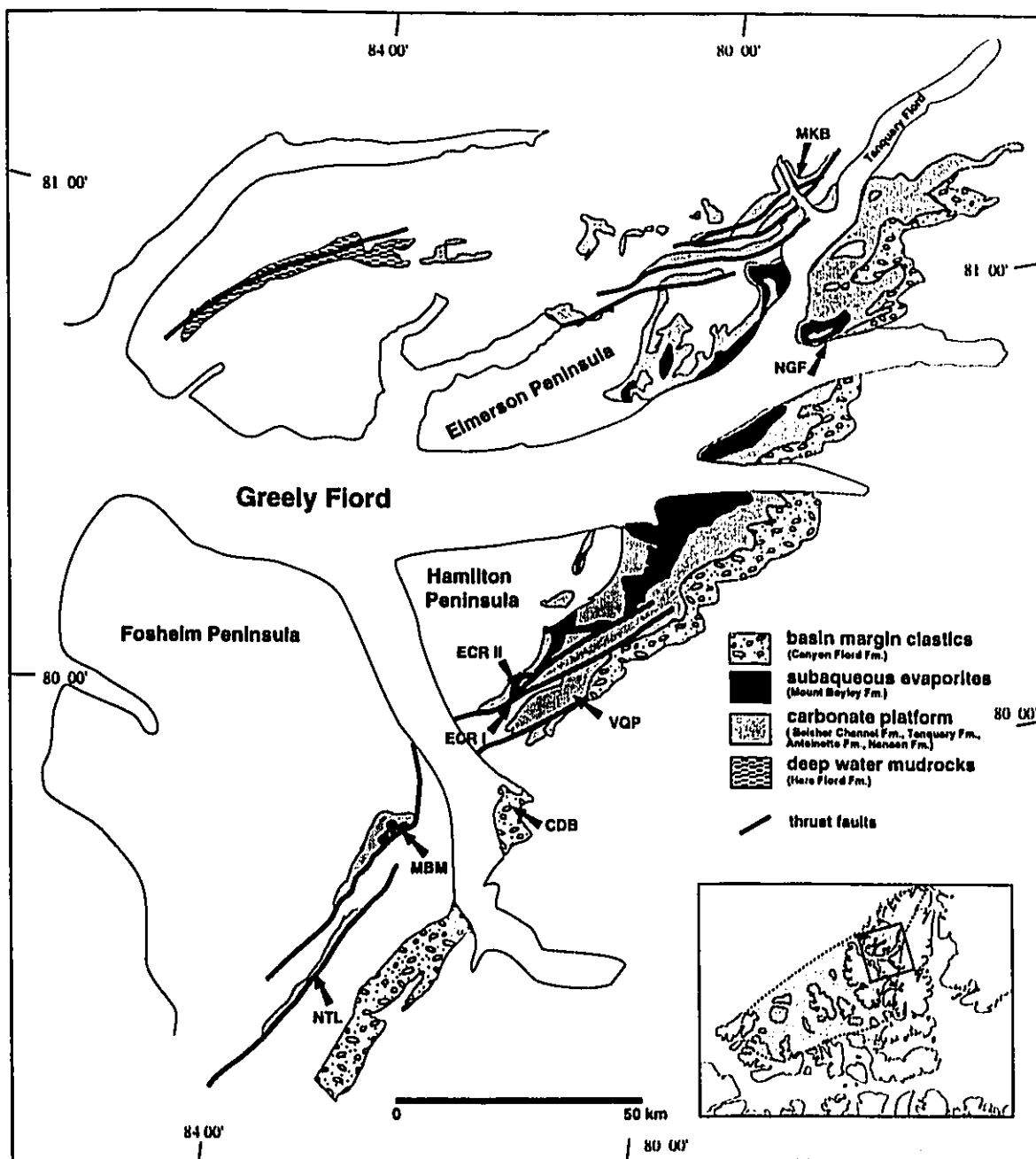


Figure 1.1: Simplified geological map of west-central Ellesmere Island, showing section locations and outcrop distribution of Lower Permian formations. Measured sections are: Notch Lake (N'TL), Mount Bridgman (MBM), Caledonian Bay (CDB), East Cape River I (ECR I), East Cape River II (ECR II), "Vache-qui-pleure" (VQP), North Greely Fiord (NGF), and McKinley Bay (MKB). Geology modified from GSC maps 1308A, 1311A, 1309A, 1306A and 1348A.

1.2 METHODS

Field work was completed in six weeks during the 1990 field season with the logistical and financial support of the Institute of Sedimentary and Petroleum Geology (G.S.C.-Calgary). Almost 5 000 m of strata were measured at 8 localities (e.g. Notch Lake, Mount Bridgman, Caledonian Bay, East Cape River I, East Cape River II, Vache-qui-pleure, North Greely Fiord and McKinley Bay), spread over 250 km (Fig. 1.1). Detailed stratigraphic descriptions of these strata are given in Appendix I.

More than 900 samples were collected for lab examination as polished slabs or thin-sections. A total of 500 thin-sections, stained with alizarin red and potassium ferricyanide (Dickson, 1965), were described using terminology established by Grabau (1904) and Dunham (1962). A small foraminifera biostratigraphic framework for the studied sequence was conducted by Dr. Sylvie Pinard (G.S.C. consultant, Calgary). Conodont biostratigraphy was also carried out by Dr. Charles Henderson at University of Calgary.

1.3 GEOLOGICAL SETTING

Late Paleozoic world paleogeography was characterized by two main cratonic masses Gondwana and Laurussia located in the southern and northern hemispheres respectively. In the northern hemisphere, Laurussia cratonization was completed at the end of Silurian when Laurentia-Greenland accreted to the Fennosarmatian shelf (Ziegler, 1989). At the northern margin of Laurussia, Precambrian to Devonian sedimentary rocks of the Franklinian Mobile Belt were deformed by a series of compressional events (Trettin, 1989). These events occurred between Late Silurian to Late Devonian and ended with the Ellesmerian Orogeny (Late Devonian to Early Carboniferous). During the Early Carboniferous, tensional stresses produced a rift within the orogenic Franklinian Mobile Belt resulting in the development of the Sverdrup Basin.

In the southern hemisphere, the southernmost parts of Gondwana were covered by a widespread continental ice sheet (Early Carboniferous to Late Permian). Variations in ice sheet extension were probably responsible for the worldwide high-frequency cyclic pattern recorded in upper Paleozoic shallow marine sedimentary successions (Crowell, 1978; Veevers and Powell, 1987).

1.3.1 Sverdrup Basin

The Sverdrup Basin represents a rift-initiated pericratonic basin that is 1 000 km long and 400 km wide, containing more than 12 km of Lower Carboniferous to Mid-Tertiary sedimentary and minor volcanic rocks (Thorsteinsson, 1974; Trettin, 1989). During most of its history the Sverdrup Basin was bounded by the Laurussia craton to the south and by a land of unknown

affinities to the north (Crockerland; Fig. 1.2). Only narrow straits connected this basin to the main open ocean, resulting in periodic restriction of the Sverdrup Basin during relative sea-level lowstands (Beauchamp, 1987; Embry 1989b). The axis of the Sverdrup Basin is elongate NE-SW, parallel to the deformed Franklinian Mobile Belt, suggesting that tectonic discontinuities of this orogenic belt may have governed the development of extensional faults within the Sverdrup Basin (Trettin *et al.*, 1972). Scarcity of extensional basalts suggest that the rift development was controlled by a passive rather than active mechanism (Cameron, 1989). Rifting and tectonic subsidence in the Sverdrup Basin took place from Viséan to earliest Kungurian time (Fig. 1.3). This was followed by a regime of passive subsidence that continued until the end of the Permian and into the Mesozoic (Beauchamp *et al.*, 1989a).

The upper Paleozoic succession displays evidence of significant climatic changes ranging from warm, semi-arid conditions in the Early Carboniferous to temperate conditions in the latest Sakmarian, followed by cool in latest Wordian (Beauchamp *et al.*, 1989a). These climatic changes are coeval with the northward drift of Laurussia from 30° to almost 50° N (Ziegler, 1989).

1.3.2 Upper Paleozoic of the Sverdrup Basin

The Upper Paleozoic succession of the Sverdrup Basin is characterized by seven long term transgressive-regressive sequences (Fig. 1.3), bounded at the basin margin by major unconformities that pass basinward into their equivalent conformities (Beauchamp *et al.*, 1989b). These large-scale sequences formed during a rifting phase (sequences 1 to 4) and a passive subsidence phase (sequence 6 and 7), which are separated by the Kungurian Melvilian Disturbance (sequence 5). The sequences that developed during the rifting phase (Fig 1.3) include:

1) Sequence 1 (Viséan) is characterized by lacustrine deposits of the Emma Fiord Formation. It is composed of black carbonaceous shale, siltstone and marlstone with interbedded sandstone, conglomerate, and oolitic and algal limestones (Davies and Nassichuk, 1988). Because of the local occurrence of these strata it has been suggested that deposition took place in locally developed depressions or half-graben basin.

2) Sequence 2 (Serpukhovian-Asselian) is composed of marine dominated sediments comprising: marginal-marine clastics (Borup Fiord and Canyon Fiord formations), and platform carbonates (Canyon Fiord, Antoinette and Nansen formations) and laterally equivalent subaqueous anhydrite of the Otto Fiord Formation which accumulated in a deeper water setting. The Otto Fiord Formation (Fig. 1.2) was deposited in three different central subbasins (Nassichuk and Davies, 1980). This formation is overlain by open marine, deep-water mudrocks of the Hare Fiord Formation.

3) Sequence 3 (Asselian-Sakmarian) is relatively similar to the upper part of sequence 2 with marginal-marine clastics (Canyon Fiord Formation), platform carbonate (Belcher Channel,

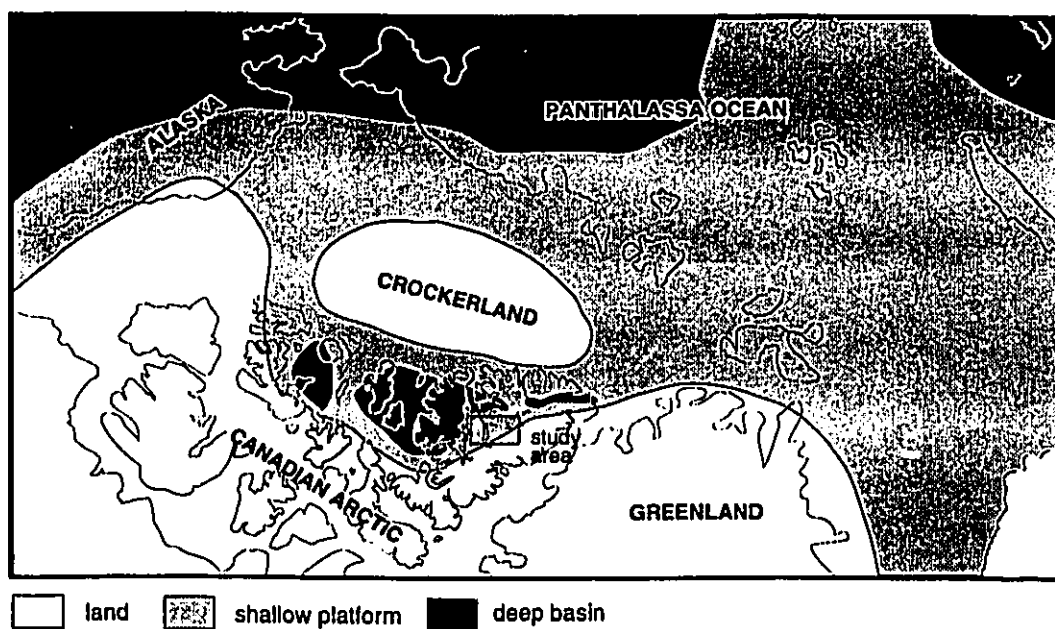


Figure 1.2: Late Paleozoic paleogeography of the Sverdrup Basin characterized by the occurrence of three central deep subbasins located in outcrop regions of Otto Fiord and Hare Fiord formations. The basin is delimited by the Laurussia craton to the south and by a land of unknown origin to the north (Crockerland). Only two narrow straits allowed exchange from the open ocean. Modified from Embry (1989b), Embry (in press) and Ziegler (1989).

Antoinette, Tanquary and Nansen formations) and deep water mudrocks (Hare Fiord Formation). A peculiar stratal relationship, however, is the juxtaposition of subaqueous evaporites (Mount Bayley Formation) surrounded by platform carbonates in Fosheim and Hamilton peninsulas (Thorsteinsson, 1974).

4) Sequence 4 (Sakmarian-Kungurian) comprises shaly platform carbonates ("unnamed" A "green member"), overlain by a carbonate-dominated formation ("unnamed" A "yellow member") both of which display an overall shallowing upward trend. Coeval basinal lithologies comprises deep water mudrocks of the "unnamed" B.

1.3.3 Fosheim-Hamilton subbasin

The Fosheim-Hamilton subbasin occurs along the northeast margin of the Sverdrup Basin, on both Fosheim and Hamilton peninsulas. The existence of this subbasin is based on the presence of up to 400 m of Lower Permian subaqueous evaporites (i.e. upper Antoinette and Mount Bayley formations) covering an area of 7500 km² (Wallace and Beauchamp, 1990), immediately southeast of an area where coeval open marine shelf carbonates (Nansen Formation) and basinal mudrocks (Hare Fiord Formation) are present (Beauchamp *et al.*, 1989a,b). Other evidence includes the presence of Upper Carboniferous westerly derived conglomerates of the Canyon Fiord Formation that were most likely deposited in a half-graben depositional setting (Thériault and Beauchamp, 1991), and the distribution of overlying Artinskian strata on Fosheim and Hamilton peninsulas. The latter strata thin to the southwest and northeast and possibly to the northwest, reflecting closure of the subbasin (Scott *et al.*, 1991).

It has been suggested that the Fosheim-Hamilton subbasin was most likely isolated from the main Sverdrup Basin in order to explain extensive on-shelf evaporite accumulation. Its presence further suggests that a linear high was present between the restricted Fosheim-Hamilton subbasin and the main Sverdrup Basin. This linear high, is referred to as the "Elmerson High" (Morin *et al.*, 1991a; Beauchamp *et al.*, 1991; Thériault and Beauchamp, 1991; Scott *et al.*, 1991). This topographic feature existed in the environs of Elmerson Peninsula and extended for some distance in a southwest direction, roughly parallel to the elongation of the subbasin (Fig. 1.4). The Fosheim-Hamilton subbasin is also limited to the northeast by the Tanquary High (Maurel, 1989), in the southwest by the "Bay Fiord High" (Beauchamp *et al.*, 1989a), and in the southeast by the Franklinian basement (Fig. 1.4).

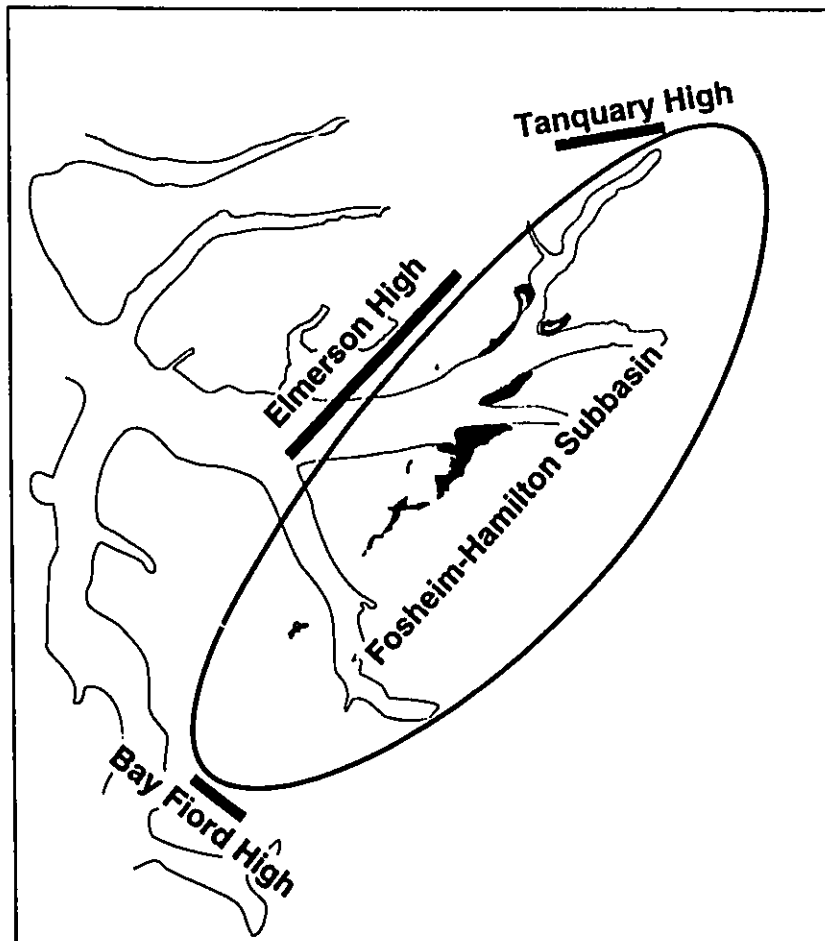


Figure 1.4: Location map of the Fosheim Hamilton subbasin in west-central Ellesmere Island showing paleotopographic highs. Black areas correspond to Mount Bayley Formation. Paleogeography based on work of Morin et al. (1991), Beauchamp et al. (1991), Thériault et al. (1991), Scott et al. (1991) and Wallace and Beauchamp (1990).

CHAPTER 2: STRATIGRAPHY

2.1 INTRODUCTION

This chapter outlines the stratigraphy of the Asselian-Sakmarian sequence near the Fosheim and Hamilton peninsulas and adjacent McKinley Bay area (Fig. 1.1). The stratigraphic framework used in the present study of Fosheim-Hamilton subbasin is partly based on the work of Thorsteinsson (1974) and Beauchamp *et al.* (1989a,b). Sequence 3 as defined by Beauchamp *et al.* (ibid.; see Fig. 1.3) is composed of marginal clastics (Canyon Fiord Formation), platformal carbonates (Belcher Channel, Tanquary, Antoinette, and Nansen formations) and basinal deep-water mudrocks (Hare Fiord Formation). A peculiar feature of the Fosheim-Hamilton subbasin, however, is the occurrence of subaqueous anhydrite (Mount Bayley Formation) within the platformal carbonate sequence. This evaporite unit separates two platformal carbonate units; the underlying Antoinette Formation and overlying Tanquary Formation respectively. All the formations that make up sequence 3 are characterized by high-frequency sedimentary cycles.

Eight sections were measured representing approximately 5000 m of strata (Figs. 2.1a and b; Appendix I) and include: Notch Lake (NTL); Mount Bridgman (MBM), Caledonian Bay (CDB); East Cape River I (ECR I); East Cape River II (ECR II); "Vache-qui-pleure" (VQP); North Greely Fiord (NGF), and McKinley Bay (MKB). All but one stratigraphic sections (McKinley Bay) were located within the Fosheim-Hamilton subbasin. The formations under investigation include: Canyon Fiord; Belcher Channel; Antoinette; Mount Bayley; Tanquary; and Nansen formations (Figs. 2.2a and b).

Small foraminifera (Pinard, 1990) and conodont (Henderson, 1988) have been used as a biostratigraphic framework. The small foraminifera and conodont zonations do not correspond exactly but provide sufficient biostratigraphic resolution (Fig. 2.1). For instance, the Asselian-Sakmarian boundary using small foraminifera zones is relatively older than that defined by conodonts. The small foraminifera and conodont zones identified in the present study (Pinard, pers. comm.; Henderson, pers. comm.) are listed in Appendix I beside their respective stratigraphic position in measured sections.

2.2 STUDIED FORMATIONS

2.2.1 Canyon Fiord Formation

General

The Canyon Fiord Formation outcrops on northern Melville Island, northwest Devon Island and along western Ellesmere Island. The type section is located on the west-central part of

Ellesmere Island on the north side of the Cañon Fiord. The formation as defined by Thorsteinsson (1974) is mainly composed of marginal continental and marine clastics. The formation in Raanes Peninsula is subdivided by Beauchamp (1987) into three informal members, a lower clastic member, a middle limestone member, and an upper clastic member. This informal subdivision is not as well defined on Fosheim and Hamilton peninsulas, where the overall succession has been subdivided into three facies assemblages: CF1, CF2, CF3 (Thériault and Beauchamp, 1991). CF3 comprises the middle limestone and upper clastic members.

The Canyon Fiord Formation is highly variable in thickness across the Sverdrup Basin. On Raanes Peninsula, thicknesses vary from 545 m to more than 1000 m (Beauchamp, 1987). On Fosheim and Hamilton peninsulas, the thickness varies from a few tens of metres at the head of Tanquary Fiord to 1650 m at the type section (Thériault and Beauchamp, 1991).

In the present study, incomplete sections of Canyon Fiord Formation have been measured (Fig 2.2) at Caledonian Bay (342 m) and at Notch Lake (275 m). The Caledonian Bay section was measured in the vicinity of the type section.

Lithologies

The Canyon Fiord Formation comprises a wide range of lithologies varying from conglomerate to sandstone, siltstone and shales with various limestone and mixed limestone-siliciclastic facies. Thériault (1991) and Thériault and Beauchamp (1991) have subdivided the Canyon Fiord Formation into three facies assemblages: CF1, CF2 and CF3. CF1 or conglomerate assemblage is commonly located at the base of the formation and comprises mainly red pebble to cobble conglomerate. The CF2 or sandstone assemblage overlies the conglomerates and is composed of interbedded sandstone/pebbly sandstone and of interbedded sandstone/ mudstone/ caliche. CF3 or sandstone/limestone assemblage overlies the sandstone assemblage. CF3 is composed of asymmetric high-frequency cycles made up of sandstone, mudstone and limestone facies.

In the study area, the Caledonian Bay section is composed of the CF3 assemblage. This section is made up of light gray fine to medium grained sandstone with parallel and cross stratification interbedded with red and dark gray silty shale. This clastic-dominated assemblage is punctuated by wackestone, packstone and grainstone units of various compositions. The carbonate units occur in different positions within individual clastic-dominated cycles. The Canyon Fiord Formation at Notch Lake section is made up of CF1 and CF2 assemblages.

Age

The base of the Canyon Fiord Formation is diachronous, regionally with a maximum age range from Bashkirian to Sakmarian (Thorsteinsson, 1974; Beauchamp, 1987). In this study (Fig. 2.2), the Canyon Fiord Formation at Caledonian Bay ranges from Middle to Late Sakmarian and,

at Notch Lake possibly Late Bashkirian (small foraminifera zone #22) to Moscovian age (small foraminifera zone #24).

Relation to other formations

The Canyon Fiord Formation is in erosional contact with the Franklinian basement and probably also in erosional contact with the Borup Fiord Formation (Thériault, 1991). The Canyon Fiord Formation passes basinward into the Belcher Channel and Antoinette formations.

2.2.2 Belcher Channel Formation

General

The type section of the Belcher Channel Formation is located near Lyall River on Devon Island. This formation was first described by Harker and Thorsteinsson (1960). Successive modifications by Nassichuk (1965), Nassichuk and Davies (1975) and finally, by Beauchamp (1987) and Beauchamp and Henderson (work in progress) have restricted the Belcher Channel to the carbonate dominated strata overlying the Canyon Fiord Formation and underlying the "unnamed" A "lower green unit". The Belcher Channel Formation is exposed on Devon and Ellesmere islands. This formation varies in thickness from 0 m to 500 m. According to Beauchamp (1987), a large part of this 500 m thick section should be ascribed to the unnamed A "lower green unit".

In this study, only the Vache-qui-pleure and Notch Lake sections are part of the Belcher Channel Formation, these incomplete sections are 250 m and 90 m thick respectively (Fig. 2.2).

Lithologies

The Belcher Channel Formation is made up of high-frequency depositional cycles with important compositional variations from base to top within individual cycles. Cycle thickness ranges from 5 to 35 m. Each cycle is composed of carbonates with minor amounts of siliciclastics.

The resistant parts of these cycles in the Belcher Channel Formation are composed of light grey grainstone and palaeoaplysiniid boundstone forming tabular bioherms. Phylloid boundstone bioherms occur locally. The recessive parts are composed of dark coloured shaly to silty nodular to wavy bedded packstone and wackestone, and dark coloured calcareous mudstone. Fine-grained sandstone beds are present.

Age

The Belcher Channel Formation ranges in age from Asselian to Late Sakmarian (Beauchamp, 1987; Thorsteinsson, 1974). The base of the formation is diachronous regionally, while the top is probably synchronous (Beauchamp, 1987). In this study, the Belcher Channel Formation is of Sakmarian age only (Fig. 2.2).

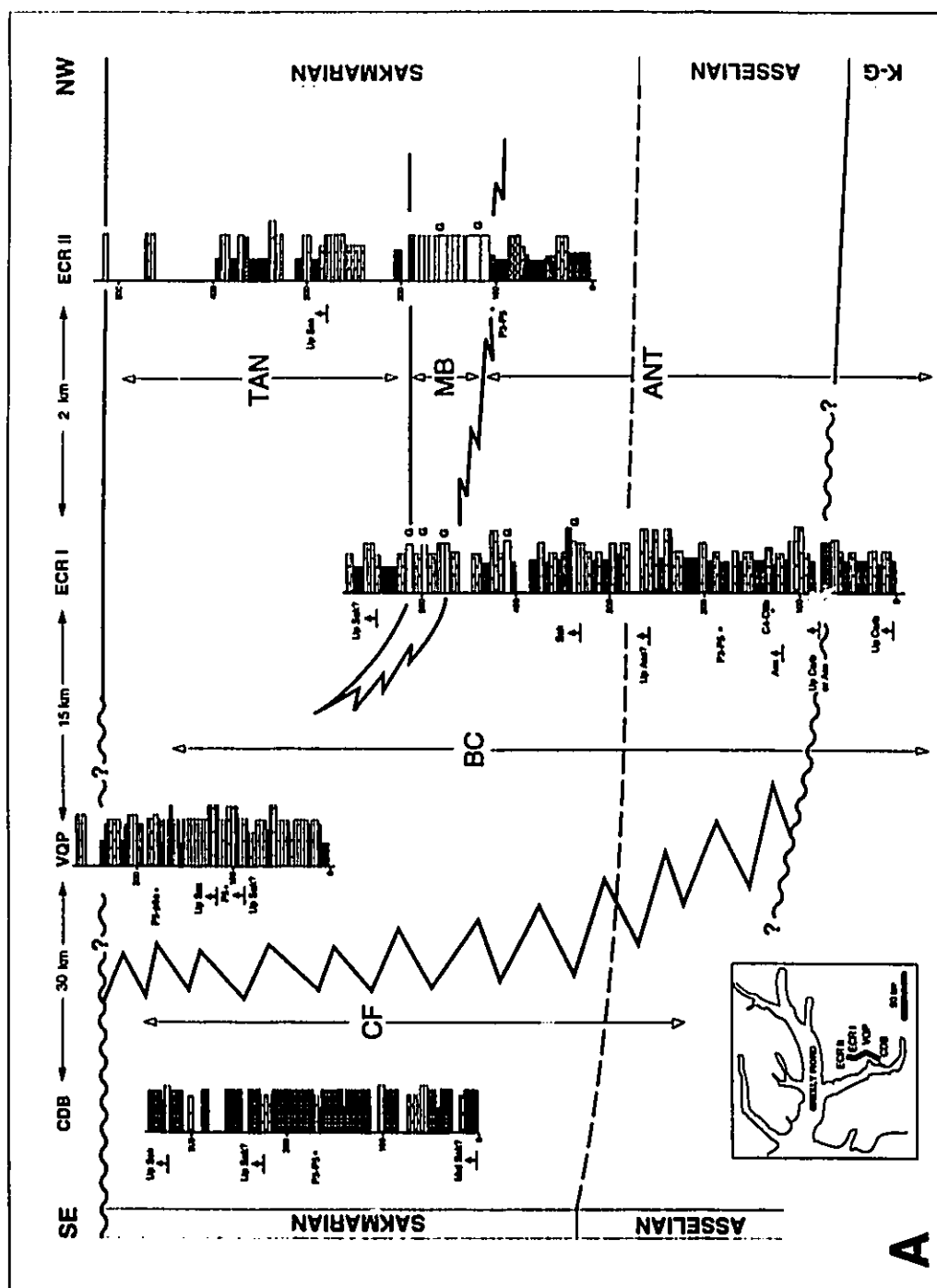
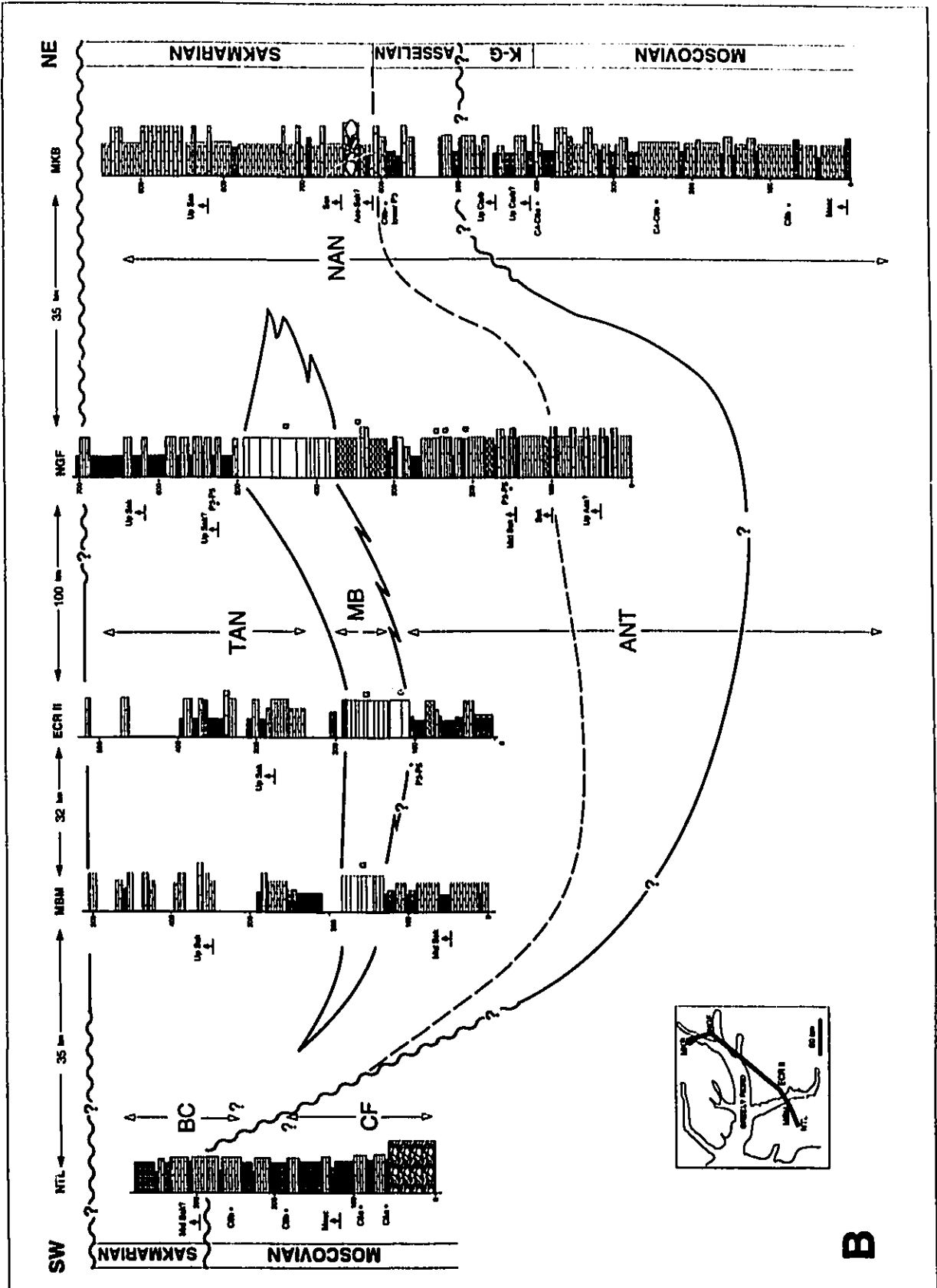


Figure 2.2: Diagrams showing stratigraphic relationships of Asselian-Sakmarian sequence 3 of Beauchamp (1989a,b) present in the study area. Part A shows sections oriented perpendicular to the general facies belt; Part B shows sections parallel to the facies belt. The formation names are Canyon Fjord (CF), Belcher Channel (BC), Antoinette (ANT), Mount Bayley (MB), Tanquary (TAN), and Nansen (NAN). The section names are Caledonian Bay (CDB), Vache-qui-pleure (VQP), East Cape River I (ECR I), East Cape River II (ECR II), Notch Lake (NTL), Mount Bridgman (MBM), North Greely Fjord (NGF) and McKinley Bay (MKB). Biostratigraphic data are indicated with arrows (small foraminifer) and dots (conodont) beside each section. Solid lines are for formation limits and sequence boundaries, and dotted line is for chronostratigraphic correlation. G = gypsum (lithological symbols in Appendix I).



B

Relation to other formations

The Belcher Channel Formation conformably overlies the Canyon Fiord Formation or unconformably overlies the Franklinian basement. In rare occurrence, the Belcher Channel Formation may be unconformably on the Canyon Fiord Formation; this situation is present in the Notch Lake section. The "unnamed" A "lower green unit" is generally unconformably overlain by the Belcher Channel Formation (Beauchamp, 1987). The Belcher Channel Formation passes landward into the Canyon Fiord Formation and basinward into the Antoinette, Mount Bayley and Tanquary, and/or Nansen formations

2.2.3 Antoinette Formation

General

The type section of the Antoinette Formation (465 m thick) is located on the north side of and at the head of Greely Fiord. Thorsteinsson (1974) named the formation after Antoinette Bay which is located near the type section. The Antoinette Formation was defined as a carbonate-dominated unit overlying the Canyon Fiord Formation and underlying the Mount Bayley Formation. The Antoinette Formation outcrops widely on Fosheim and Hamilton peninsulas but is unknown elsewhere in the Sverdrup Basin.

Thorsteinsson (1974) also measured more than 800 m of an incomplete section of the Antoinette Formation at East Cape River. In this study, incomplete sections of the Antoinette Formation (Fig 2.2) have been measured at East Cape River I (470 m), at East Cape River II, (108 m), at Mount Bridgman (130 m) and at North Greely Fiord (375 m).

Lithologies

The Antoinette Formation comprises high-frequency depositional cycles expressed in the field by the occurrence of resistant-recessive, ledge-forming couplets showing important compositional variations from base to top within individual cycle. Cycles range from 5 to 50 m in thickness and are composed of carbonates with minor amounts of siliciclastics and evaporites.

The resistant parts of the Antoinette Formation are represented by dark coloured fusulinid-rich packstone and phylloid algal boundstone forming tabular to lenticular bioherms. Grainstone and palaeoaplysiniid boundstone bioherms occur locally. The recessive parts are composed of dark coloured nodular to wavy bedded shaly to silty wackestone, and dark coloured calcareous mudstone. Fine-grained sandstone beds are rare. At North Greely Fiord and East Cape River I, the upper part of the Antoinette Formation is characterized by scattered occurrences of 1-5 m thick laminated anhydrite beds. Evaporites are generally associated with abundant dolomitized wackestone, common dark calcareous shale and rare packstone.

Age

The base of the Antoinette Formation (contact with the underlying Canyon Fiord) and possibly the top (contact with overlying Mount Bayley Formation) are regionally diachronous. The base of the Antoinette Formation is as old as Moscovian (Thorsteinsson, 1974). In this study, the oldest Antoinette strata (East Cape River I) is Upper Carboniferous. The top of the formation, is Middle Sakmarian age, and possibly diachronous throughout the subbasin because the number of cycles and the thickness of the Mount Bayley Formation decreases from northeast to southwest (Fig. 2.2). The diachronism at the top of the formation, if existent, is below the present detection limit of biostratigraphic zones.

Relation to other formations

The Antoinette Formation conformably overlies the Canyon Fiord Formation (Thorsteinsson, 1974) and is conformably overlain by the Mount Bayley Formation. The Antoinette Formation passes laterally into the Belcher Channel, and Nansen formations, and lower part of the Mount Bayley Formation. The contact between the Antoinette and the Canyon Fiord formations was not observed. The contact between the Antoinette and Mount Bayley formations is sharp to gradational. It is sharp at Mount Bridgman and East Cape River II, where packstone to shaly wackestone pass upward into anhydrite and shale. The contact is gradational at North Greely Fiord and East Cape River I, where several beds of anhydrite occur in the upper part of the Antoinette Formation.

2.2.4 Mount Bayley Formation

General

The Mount Bayley Formation was named by Thorsteinsson (1974) after Mount Bayley, which is located at the intersection of Tanquary and Greely fiords. This formation is mainly composed of deep water evaporites (Wallace and Beauchamp, 1990), is enclosed by carbonate dominated formations. The Mount Bayley Formation occurs on Fosheim and Hamilton peninsulas, over an area of 7500 km².

The thickness of the Mount Bayley Formation varies from 42 m at East Cape River to more than 400 m (Wallace, pers. comm.) on Elmerson Peninsula. In the present study, four complete sections of the Mount Bayley Formation were measured (Fig. 2.2): North Greely Fiord (135 m); East Cape River I (42 m); East Cape River II (68 m), and Mount Bridgman (55 m).

Lithologies

The Mount Bayley Formation is made up of interbedded evaporite and carbonate with minor amounts of shale. At Mount Bridgman and East Cape River II sections, the carbonate layer is limited to laminated dolostone of a few centimetres to 2 m thick, whereas in other sections the carbonate layer is 10 m thick and commonly composed of wackestone and packstone with rare

boundstone. The evaporite is mainly composed of anhydrite that occurs in parallel laminae of less than a centimetre thick. The anhydrite laminae are separated by very fine layers (100 μm) of alternating dolostone and silt-sized quartz. The diagenetic transformation of the primary laminated evaporite into discontinuous nodules, crinkled laminae, bedded and massive mosaics is common (Wallace and Beauchamp, 1990).

Age

The base of the Mount Bayley Formation is possibly diachronous as suggested by the decreasing numbers of anhydrite cycles and by decreasing thickness of the formation from northeast to southwest in the Fosheim-Hamilton subbasin. As mentioned earlier, this diachronism, if present, is below the actual biostratigraphic resolution. The base of the formation, however, is Middle Sakmarian. The top of Mount Bayley Formation is synchronous (Wallace and Beauchamp, 1990) and appears to coincide with the contact between Middle and Late Sakmarian (Fig. 2.2).

Relation to other formations

The Mount Bayley Formation overlies conformably the Antoinette Formation and underlies the Tanquary Formation. The Mount Bayley Formation passes laterally into the Belcher Channel, Antoinette and Nansen formations.

2.2.5 Tanquary Formation

General

The Tanquary Formation is named after Tanquary Fiord, with the type section located on the north side and at head of the Greely Fiord (Thorsteinsson, 1974). The Tanquary Formation was defined as interbedded carbonate and clastic strata that overly evaporites of the Mount Bayley Formation. The Tanquary Formation is present exclusively on Fosheim and Hamilton peninsulas.

The Tanquary Formation is 200 m thick at the type section (North Greely Fiord section), 315 m at East Cape River II and reaches its maximum thickness of 323 m at Mount Bridgman.

Lithologies

The Tanquary Formation consists of 7 or 8 high-frequency depositional cycles which vary in thickness from 12 to 90 m. The resistant part of a cycle is relatively constant in thickness while the recessive part is extremely variable. The resistant part is generally composed of either grainstone-dominated strata with common palaeoaplysiniid boundstone or packstone-dominated strata with phylloid boundstone. The recessive part is composed of green mudstone that gradually changes into fine sandstone to siltstone.

Age

The base and the top of the Tanquary Formation are both regionally synchronous and the formation is of Late Sakmarian age (Fig. 2.2).

Relation to other formations

The Tanquary Formation conformably overlies the Mount Bayley Formation and generally underlies the Artinskian sequence 4 of Beauchamp *et al.* (1989a,b). The contact with the Mount Bayley Formation is sharp and synchronous (Wallace and Beauchamp, 1990). The contact between the Artinskian strata and the Tanquary Formation is conformable at East Cape River II and Mount Bridgman. At North Greely Fiord, however, the Tanquary Formation is directly overlain by Triassic strata (Thorsteinsson, 1974).

2.2.6 Nansen Formation

General

The type section of the Nansen Formation is located near the head of Hare Fiord on northwestern Ellesmere Island. Thorsteinsson (1974) defined the Nansen Formation as a limestone-dominated succession with minor amounts of siliciclastic material. The Nansen Formation crops out in two belts; the first occurs on the northwest of Axel Heiberg and Ellesmere islands and the second on the western part of Ellesmere Island (Thorsteinsson, 1974).

Thicknesses vary greatly in the Nansen Formation and range from 700 m in northern Axel Heiberg Island (Beauchamp, 1987) to 2300 m at the type section (Thorsteinsson, 1974). In this study, an incomplete section of 950 m of Nansen Formation have been measured at McKinley Bay.

Lithologies

The Nansen Formation is made up of high-frequency depositional cycles of varying thicknesses (2-50 m) that comprises of a wide spectrum of carbonate-dominated lithologies showing important compositional variations from base to top within individual cycles. The depositional cycles are outlined by the occurrence of alternating resistant and recessive units. The resistant unit is composed of packstone or grainstone with minor scattered bioherm occurrences. Siltstone and sandstone beds are locally common. The recessive part consists of calcareous mudstone and common nodular wackestone. The cycle composition is variable throughout the formation.

In the study area, only the McKinley Bay section is part of the Nansen Formation. This section shows three distinctive cycle successions. The basal succession (first 500 m) is made up of packstone-dominated resistant and shaly recessive units, followed by phylloid boundstone resistant and nodular wackestone recessive units. The basal succession is limited at its base and its top by sandstone beds. The middle succession is 100 m thick, and consists of packstone-dominated cycles. The basal part of the upper succession is 350 m thick composed of a black siltstone and shale cycles capped by a 30 m thick olistostrome containing blocks up to 5 m in

diameter. The olistostrome is overlain by cycles composed of thick fusulinid-rich packstone and bioherms forming the remainder of the upper succession (270 m thick).

Age

The Nansen Formation extends from Moscovian (possibly older) to Sakmarian (Beauchamp, 1987; Thorsteinsson, 1974). In this study, the Nansen Formation at McKinley Bay ranges from the base of the Moscovian (small foraminifera zone #23) to Late Sakmarian (Fig. 2.2).

Relation to other formations

The Nansen Formation is conformably overlain the Borup Fiord and Canyon Fiord formations and is either conformably or unconformably overlain by the "unnamed" A formation (Beauchamp and Henderson, in press). The Nansen Formation passes basinward into the Otto Fiord and Hare Fiord formations and landward into either the Antoinette, Mount Bayley and Tanquary formations or the Canyon Fiord and Belcher Channel formations. In the study area, the Nansen at McKinley Bay section is in unconformable contact with the overlying "unnamed" A "lower green member" (Beauchamp pers. comm.)

2.3 STRATIGRAPHIC SEQUENCES

These studied formations are part of two broad stratigraphic sequences (3rd order sequence in the sense of Vail *et al.*, 1977) that are correlated across the Sverdrup Basin (Beauchamp, 1989a, b). These sequences are bounded at the basin margin by unconformities at the basin margin passing basinward into their equivalent conformities. In the study area, the boundaries between sequences 2/3 and 3/4 are recognized (Fig. 2.2 a,b).

The boundary between sequences 2 and 3 is present in the study area within the Belcher Channel, Antoinette and Nansen formations at Notch Lake, East Cape River I and McKinley Bay respectively. At Notch Lake, the boundary is a major unconformity separating Middle Sakmarian from underlying Moscovian (C5b) strata. The rocks at the boundary are composed of medium sandstone overlain by a 10 m thick unit of massive grainstone (see Appendix I, NTL, 272-286 m). At ECR I, the limit between the two sequences coincides with dark colored calcilutite that is overlain, with an erosive contact, by a 15 cm thick intraformational conglomerate with rounded limestone cobble into an orthoquartzite matrix (Plate 15a). At McKinley Bay, the boundary corresponds with an important increase in siliciclastic material and the occurrence of a thick grainstone unit (see Appendix I, MKB, 487-500 m). The boundary of sequences 2/3 at McKinley Bay section is possibly an unconformity because of the thin succession of Asselian strata and by the smaller number of depositional cycles present (see Chapter 4). The age of the boundary

between sequence 2 and 3 at East Cape River I and McKinley Bay coincides approximately with Late Carboniferous (Kasimovian-Gzhelian) and Early Permian (Asselian) boundary.

The boundary between sequences 3 and 4 is present in the study area at Mount Bridgman, East Cape River II, North Greely Fiord and Vache-qui-pleure sections (Fig. 2.2). At Mount Bridgman and East Cape River II sections, the boundary corresponds to the contact between the Tanquary Formation and the "unnamed" A "lower green member". This contact is conformable at Mount Bridgman and East Cape River II and is placed at the top of the last resistant limestone bed of the Tanquary Formation. At North Greely Fiord, the upper part of the Tanquary Formation is unconformably overlain by Triassic strata (Thorsteinsson, 1974). At Vache-qui-pleure section the boundary between sequences 3 and 4 corresponds to the contact between the Belcher Channel Formation and the "lower green member". The contact is an unconformity in which a complete conodont zone is missing at the base of sequence 4 (Scott, 1991). The boundary between sequences 3 and 4 at McKinley Bay section is a major unconformity represented by thin red beds (Beauchamp, pers. comm.).

CHAPTER 3: CARBONATE FACIES ANALYSIS

3.1 FACIES DESCRIPTION AND INTERPRETATION

3.1.1 Introduction

Nineteen carbonates facies are recognized in the Asselian-Sakmarian succession of the study area. This chapter contains descriptions and interpretations of these facies each of which are defined and named on the basis of the most common features combining either microfacies characteristics such as grain composition and texture (Flügel, 1982) or megascopic features such as sedimentary structures, colour and bioturbation. The nineteen facies are grouped into four categories based on their interpreted depositional setting: inner shelf lagoonal, barrier and shoals; and non-reefal and reefal mid-shelf deposits (Fig. 3.1).

The shelf as used in this study is subdivided into two broad parts, inner and mid-shelf, that correspond with their position relative to the paleoshoreline (Fig. 3.2). The inner shelf is shallow marine environment located above the fair-weather wave action zone. The mid shelf is a deeper marine environment extending from wave base to below the photic zone. The barrier and shoals of the inner-shelf are relatively shallow sedimentary bodies that form a positive topography relative to the surrounding sea floor, and are within or close to the fair-weather wave action zone. The barrier and shoals are characterized by lithofacies with relatively high energy features including a lack of lime mud, abundance of abraded grains, occurrence of ooids and high angle ($>20^\circ$) cross-bedding. The lagoon was a relatively shallow marine setting characterized by various levels of restriction. Lagoonal lithofacies are characterized by low diversity biotic assemblages and by relatively low energy depositional textures. The barrier and shoal lithofacies are probably responsible for the restrictive nature of lagoonal lithofacies. The mid-shelf is limited landward by barrier and shoals, and basinward by deeper water outer-shelf/basin lithofacies. The mid shelf comprises a wide variety of lithofacies with open marine biotic assemblages and relatively low energy depositional textures, varying from mudstone-wackestone to packstone (non-reefal facies) with very common boundstone (reefal facies).

The composition of carbonate facies is compiled in Figure 3.3, and their compositional transition with other facies is shown in Figure 3.4. The facies analysis is based on examination of polished slabs and more than 500 thin-sections from hand specimens collected in the study area. In the following descriptions, allochem concentrations are provided on a semi-quantitative scale that include four subdivisions, absent, rare, common and abundant, representing 0%, 0-5%, 5-20%, and $>20\%$ respectively.

INNER SHELF		MID SHELF	
RESTRICTED	OPEN MARINE SHELF		
LAGOON	BARRIER AND SHOALS	NON-REEFAL	REEFAL (AND RELATED)
PELOIDAL FORAMINIFERAL	BIOCLASTIC DASYCLADACEAN ONCOIDAL OOLITIC	FUSULINACEAN BRYOZOAN MICRITIC	PALAEOAPLISINID BOUNDSTONE (PALAEOAPLISINID-DASYCLAD) PALAEOAPLISINID-PHYLLOID BOUNDSTONE PHYLLOID BOUNDSTONE (PHYLLOID-FUSULINID) BRYOZOAN-TUBIPHYTES BOUNDSTONE (BRYOZOAN-TUBIPHYTES) SYRINGOPORID BOUNDSTONE BERESELLID BOUNDSTONE SPONGIOSTROMID BOUNDSTONE

Figure: 3.1: Table summarizing the classification of depositional facies recognized in Asselian-Sakmarian strata in the study area.

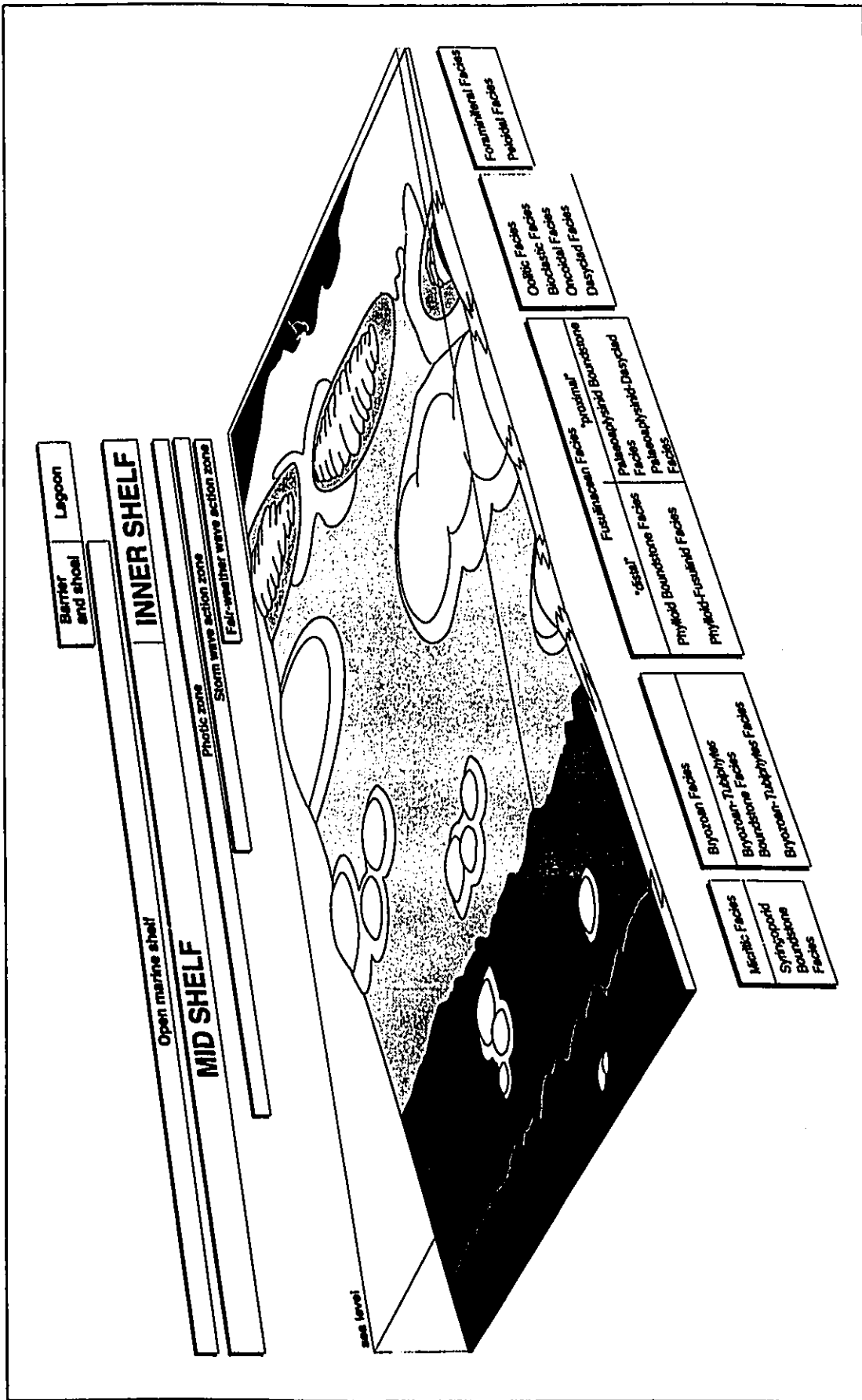


Figure 3.2: Paleogeographic reconstruction of showing the distribution of carbonate shelf facies. The relative facies proportion of the different facies in the diagram approximates their relative importance in the field. The idealized shelf is approximately of 100 km in width.

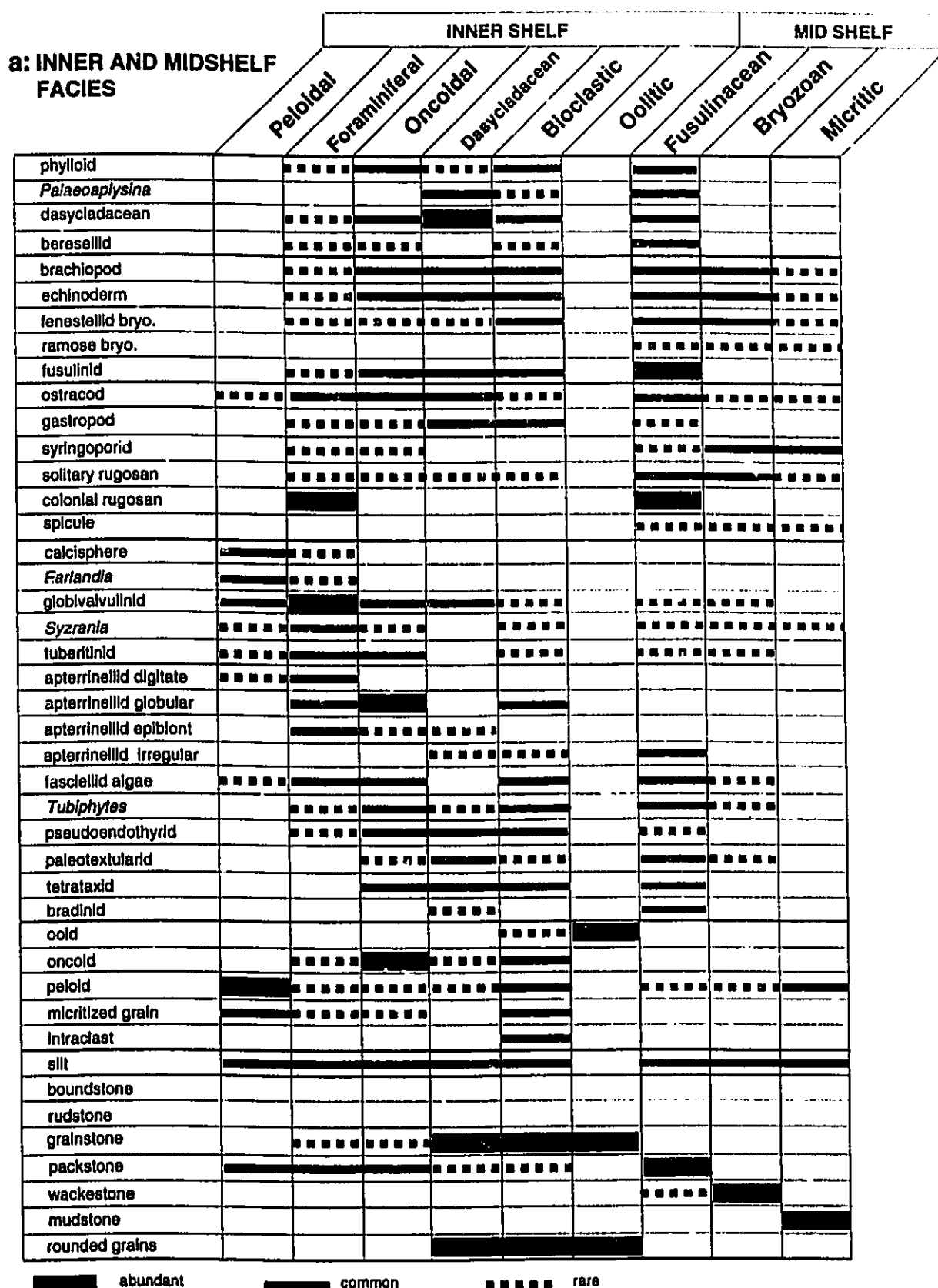


Figure 3.3: Microfacies attributes of carbonate facies. This figure represents variation in abundance of allochem grains in: **a)** inner and mid-shelf facies; **b)** mid-shelf reef facies; and **c)** associated reef (flank) facies. Relative abundances are shown by changes in line thickness. Textural data are listed at the bottom of the figure.

b: REEFAL FACIES

	Palaeoaplysinaid	Palaeoaplysinaid- Phylloid	Phylloid	Bryozoan- Tubiphytes	Syringoporida	Spongiostromid	Beresellid
phylloid			■■■■■				
<i>Palaeoaplysina</i>	■■■■■	■■■■■	■■■■■				
dasycladacean	■■■■■	■■■■■	■■■■■				
beresellid		■■■■■					■■■■■
brachlopod	■■■■■		■■■■■	■■■■■			
echinoderm	■■■■■	■■■■■	■■■■■	■■■■■			
fenestellid bryo.	■■■■■	■■■■■	■■■■■	■■■■■			
ramose bryo.			■■■■■	■■■■■			
fusulinid	■■■■■	■■■■■	■■■■■			■■■■■	
ostracod	■■■■■	■■■■■	■■■■■				
gastropod	■■■■■	■■■■■	■■■■■				
syringoporida				■■■■■			
solitary rugosan				■■■■■			
colonial rugosan							
epicula	■■■■■		■■■■■	■■■■■			
calcsphere							
<i>Eurandria</i>							
globivalvulinid		■■■■■	■■■■■			■■■■■	
<i>Syzrania</i>	■■■■■	■■■■■	■■■■■			■■■■■	
tuberitid	■■■■■	■■■■■	■■■■■	■■■■■		■■■■■	
apterrinellid digitate						■■■■■	
apterrinellid globular						■■■■■	
apterrinellid epibiont							
apterrinellid irregular		■■■■■	■■■■■	■■■■■			
fascicled algae	■■■■■	■■■■■	■■■■■	■■■■■	■■■■■		
<i>Tubiphytes</i>	■■■■■	■■■■■	■■■■■	■■■■■		■■■■■	
pseudoendothyrid		■■■■■	■■■■■			■■■■■	
paleotextularid	■■■■■	■■■■■	■■■■■				
tetrataxid	■■■■■	■■■■■	■■■■■				
bractinid	■■■■■	■■■■■	■■■■■			■■■■■	
oid							
oncolid							
peloid	■■■■■	■■■■■	■■■■■	■■■■■	■■■■■		
micritized grain							
intraclast							
silt	■■■■■	■■■■■	■■■■■	■■■■■	■■■■■		
boundstone	■■■■■	■■■■■	■■■■■	■■■■■	■■■■■	■■■■■	
rudstone							
grainstone							
packstone							
wackestone							
mudstone							
rounded grains							



abundant



common



rare

**C: ASSOCIATED REEF
(FLANK) FACIES**

	Palaeoaplysiniid- Dasyclad	Phylloid- Fusulinid	Bryozoan- Tubiphytes
phylloid		■ ■ ■ ■ ■	■ ■ ■ ■ ■
<i>Palaeoaplysina</i>	■ ■ ■ ■ ■		
dasycladacean	■ ■ ■ ■ ■		
beresellid		■ ■ ■ ■ ■	
brachiopod			■ ■ ■ ■ ■
echinoderm			■ ■ ■ ■ ■
fenestellid bryo.	■ ■ ■ ■ ■	■ ■ ■ ■ ■	■ ■ ■ ■ ■
ramose bryo.			■ ■ ■ ■ ■
fusulinid		■ ■ ■ ■ ■	
ostracod	■ ■ ■ ■ ■	■ ■ ■ ■ ■	
gastropod	■ ■ ■ ■ ■	■ ■ ■ ■ ■	■ ■ ■ ■ ■
syringoporiid			
solitary rugosan	■ ■ ■ ■ ■	■ ■ ■ ■ ■	■ ■ ■ ■ ■
colonial rugosan			
spicule			
calcsphere			
<i>Eartandia</i>			
globivalvulinid		■ ■ ■ ■ ■	■ ■ ■ ■ ■
<i>Syzranla</i>		■ ■ ■ ■ ■	■ ■ ■ ■ ■
tuberitlinid		■ ■ ■ ■ ■	
apterrinelid digitate			
apterrinelid globular			
apterrinelid epibiont			
apterrinelid irregular		■ ■ ■ ■ ■	■ ■ ■ ■ ■
fasciellid algae		■ ■ ■ ■ ■	■ ■ ■ ■ ■
<i>Tubiphytes</i>		■ ■ ■ ■ ■	■ ■ ■ ■ ■
pseudoendothyrid			
paleotextularid		■ ■ ■ ■ ■	■ ■ ■ ■ ■
tetrataxid		■ ■ ■ ■ ■	■ ■ ■ ■ ■
bradlinid		■ ■ ■ ■ ■	
oid			
oncolid			
peloid	■ ■ ■ ■ ■	■ ■ ■ ■ ■	
micritized grain			
intraclast			
silt	■ ■ ■ ■ ■	■ ■ ■ ■ ■	■ ■ ■ ■ ■
boundstone			
rudstone			
grainstone	■ ■ ■ ■ ■		
packstone	■ ■ ■ ■ ■	■ ■ ■ ■ ■	■ ■ ■ ■ ■
wackestone			
mudstone			
rounded grains	■ ■ ■ ■ ■		

■ ■ ■ ■ ■ abundant ■ ■ ■ ■ ■ common ■ ■ ■ ■ ■ rare

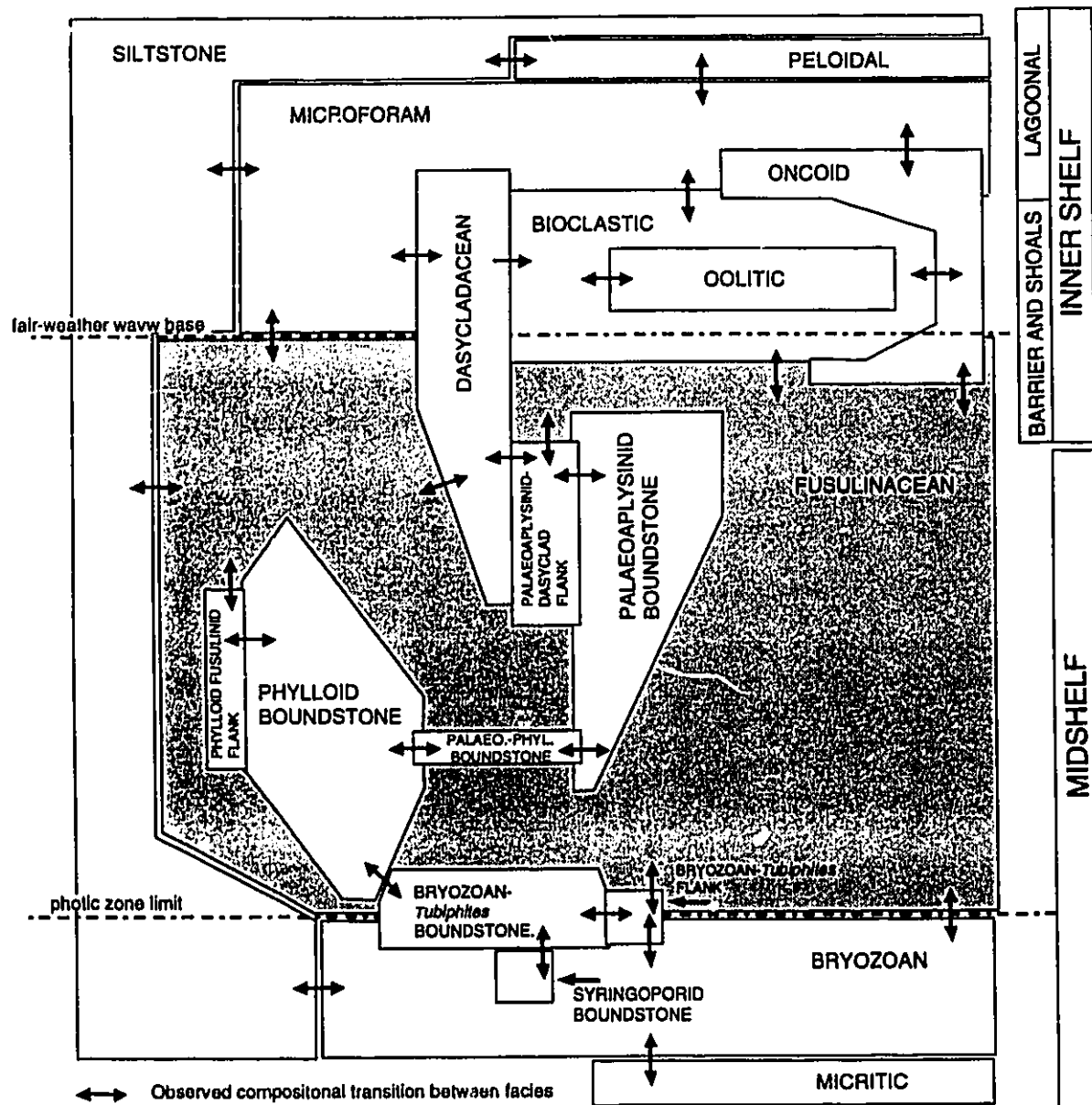


Figure 3.4: Conceptual plan view of shelf carbonates and related facies relationships. Boxes represent facies that are positioned across a hypothetical shelf and arrows show the facies transitions. Vertical axis represents the relative water depths with fair-weather wave base and photic zone limits as a reference. The box areas are approximately proportional to the relative facies abundance. Transitions with siltstone to Bioclastic, Oolitic, Oncoid and Dasyclad Facies present in microfacies are not shown within the diagram. The transition from Oncoid to Dasyclad Facies present within microfacies is also not shown.

INNER SHELF

3.1.2 Lagoonal deposits

Lagoonal deposits are subdivided into Peloidal and Foraminiferal Facies (Fig. 3.3) both characterized by the presence of a low diversity biotic assemblage indicative of a semi-restricted depositional environment.

3.1.2.1 Peloidal Facies

Description

The Peloidal Facies comprises silt to fine sand-sized packstone containing abundant peloids and an ubiquitous low diversity assemblage (Fig. 3.5). The small foraminifers *Earlandia*, globivalvulinids, tuberitinids, in addition to calcispheres, fasciellid algae (encrusting red algae) and ostracods are rare to common (Plate 1a and b). *Earlandia* is a tubular foraminifer common in low diversity lagoonal assemblages (Fig. 3.5). Irregular nodular apterrinellids are also present. Silt-sized quartz fragments are ubiquitous. Peloids are elongate in shape, subangular to subrounded in roundness, and average 0.1 mm in size. Although some peloids are similar to fecal pellets (Flügel, 1982), most have an irregular shape suggesting that they are either fragments of micritized allochems, or algae or even small intraclasts (Tucker and Wright, 1990).

The transition from Peloidal Facies to more "open marine" facies (i.e. Foraminiferal Facies) are characterized by increasing biotic diversity and decreasing peloid content (Figs. 3.5 and 3.6).

Interpretation

This facies represents sediments deposited in a relatively low energy lagoonal environment characterized by restricted water circulation (Fig. 3.2). This is indicated by the presence of micrite and by the low diversity biotic assemblage composed mainly of euryhaline taxa.

3.1.2.2 Foraminiferal Facies

Description

The Foraminiferal Facies is made up of packstone with rare wackestone and grainstone. A typical biotic assemblage is composed of common to abundant small foraminifers (e.g. globivalvulinids, tuberitinids, *Earlandia*, *Syzrania* and apterrinellids). Irregular nodular apterrinellids are present in the most restricted assemblages while globular nodular apterrinellids are common in "open marine" assemblages (see discussion on apterrinellids, section 3.2). Fasciellid algae, ostracods, calcispheres, peloids and echinoderm fragments are also common (Plates 1c, 1d and 2a). Other components include rare skeletal fragments (listed in Fig. 3.3a) and silt-sized quartz fragments. The overall biotic variation in this facies is summarized in Figure 3.5. Clusters of closely spaced colonial rugosan corals are locally abundant in this facies (Plate 2b).

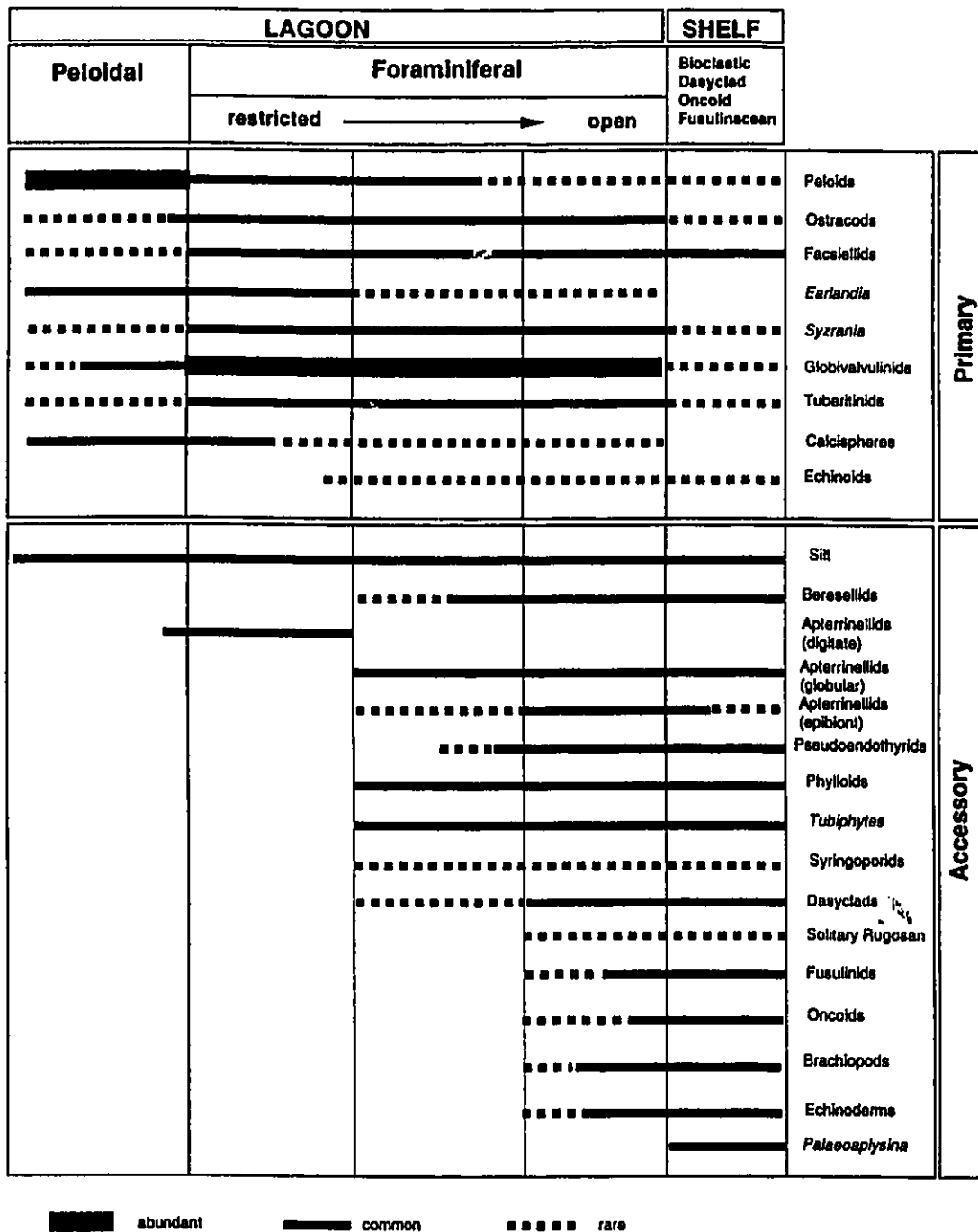


Figure 3.5: Figure showing allochem variations between lagoonal facies (Peloidal and Foraminiferal) and open shelf facies. Biotic variations in lagoonal facies are schematically represented from the restricted assemblage of the Peloid Facies to "more open" assemblage of Foraminiferal Facies. Lateral variation from left to right in the diagram reflects increasing water circulation and more open marine conditions. Allochems are subdivided into two major groups based on their relative abundance; "primary" and "accessory" organisms. Allochem content primary taxa is average while accessory taxa content is the maximum present. The relative abundance is shown by horizontal line thickness.

Facies transitions (Fig. 3.4) are from restricted to high energy, or open shelf facies (e.g. Dasycladacean, Bioclastic, and Oncoidal Facies) or to more quiet, open shelf facies (e.g. Fusulinacean Facies). These transitions are characterized by an increase in open marine stenohaline taxa (i.e. fusulinids, brachiopods, echinoderms, pseudoendothyrids, bradynids, tetrataxids, paleotextularids, dasyclads, *Palaeoaplysina*...)

Interpretation

The Foraminiferal Facies represents lagoonal lithofacies deposited in a shallow, low energy environment ranging from restricted to more open conditions (Fig 3.2). The facies is characterized by variable levels of water restriction as reflected in variations in the diversity of the biotic assemblage. The overall energy level is low but variable according to the variations in the depositional textures (mainly packstone-wackstone but locally grainstone).

3.1.3 Barrier and Shoal deposits

Barrier and shoal facies represent well winnowed sediments deposited under relatively high energy conditions within an inner carbonate shelf and include: Oolitic, Bioclastic, Dasycladacean and Oncoidal Facies.

3.1.3.1 Oolitic Facies

Description

The Oolitic Facies is generally characterized in outcrop by large scale (>1 m) cross-beds with low-angle (< 15°) and rare high-angle (>20°) foresets. This facies is mainly composed of oolitic grainstone with rare peloids and abraded, rounded bioclasts (Plate 2c and d). Ooids are well sorted but range locally from 0.08 to 0.5 mm in size. Ooids are generally dissolved or recrystallized. Nuclei consist of either peloids, rounded bioclasts or quartz silt grains. Peloidal nuclei are most likely derived from the breakdown and partial abrasion of micritized bioclasts, as suggested by their irregular shape. Bioclast transformation into peloids is probably a function of exposure time (i.e. sediment transport) on the sea floor, where as the amount of quartz silt is probably a function of river input and later dispersion. A gradual transition from Oolitic Facies to Bioclastic Facies and to siltstone is present (Fig. 3.4).

Interpretation

The Oolitic Facies represents well winnowed oolitic sand accumulating in a high energy shoal environment (Fig.3.2). Active oolitic sand shoals have been reported from several Holocene carbonate platforms occurring either as beach-barrier islands, nearshore sands or shelf-margin sands (Tucker and Wright, 1990). Most of these shoals formed only a few meters below sea level. The Oolitic Facies in the study area are interpreted as representing beach barrier island deposits,

because of their overall depositional setting dictated by associated inner shelf facies. The occurrence of high energy sedimentary structures and the well-sorted and well-winnowed depositional textures confirm this interpretation.

3.1.3.2 Bioclastic Facies

Description

This facies consists of large scale, low angle cross bedded sand-sized grainstone and rare packstone in which individual grains show evidence of intense abrasion. Grains are well-sorted, rounded and composed of skeletal fragments from numerous taxa, peloids, ooids, oncoids and intraclasts (Plate 3a to d). The most common bioclasts are phylloid and dasycladacean algae, echinoderms, brachiopods, fusulinids, globular apterrinellids, fasciellid algae, *Tubiphytes* and pseudoendothyrids. Other biota are listed in Figure 3.3a. Silt to sand-sized quartz grains are also present. A whole spectrum from small rounded peloids (0.05 mm) to larger micritic irregular grains (0.3 mm) as well as partially micritized to pristine bioclasts are present (Plate 3a), suggesting that most peloids originated from the breakdown of bioclasts.

Important variations in allochem content occur within the Bioclastic Facies with distinct gradual transitions into Oolitic, Dasycladacean, Oncoidal, Foraminiferal Facies and siltstone (Fig. 3.4).

Interpretation

Sediments of the Bioclastic Facies were deposited in a relatively high-energy environment based on their depositional texture, intense grain abrasion and the presence of high energy sedimentary structures. The association of the Bioclastic Facies and its gradual transition with the Oolitic Facies suggest that it represents shallow active shoals (Fig. 3.2) forming above fair-weather wave base where ooid production was more limited, most likely related to a lower energy level.

3.1.3.3 Dasycladacean Facies

Description

The Dasycladacean Facies is characterized by the predominance of *Epimastopora*, a dasycladacean algae together with other bioclasts. Although, the original skeleton of this dasycladacean algae is never preserved, its internal structure is partially outlined by micritic pore infills. This facies is generally made up of grainstone with diverse abraded bioclastic grains (Plate 4a and b). A typical biotic assemblage consists of globivalvulinids, pseudoendothyrids, paleotextularids, *Tetrataxis*, echinoderms, brachiopods, fusulinids, *Tubiphytes*, *Palaeoaplysina*, ostracods, gastropods and rare phylloids, bradynids, solitary rugosans, oncoids and fenestellid bryozoans.

Although the amount of dasyclads can be highly variable locally, gradual transitions are evident from Dasycladacean Facies to Foraminiferal, Oncoidal, Bioclastic and Palaeoaplysiniid-Dasyclad Facies are present (Fig. 3.4). The transition with Foraminiferal Facies is generally characterized by a fine sand-sized dasyclad grainstone to packstone with relatively restricted biota including "flat single-layered epibiont" apterrinellids (see section 3.2), ostracods, globivalvulinids, gastropods, brachiopods, *Syzyrnia* and peloids. The transition with Oncoidal Facies is defined by dasyclad grainstone to packstone containing mm-sized apterrinellid-fasciellid oncoids. Skeletal grains associated with this transition show little abrasion and consist of common "globular nodular" apterrinellids and echinoderms. The transition with the Bioclastic Facies is the most common and consists of an abraded grainstone with a diverse biotic assemblage similar to that of the Bioclastic Facies but containing dasycladacean fragments. The Palaeoaplysiniid-Dasyclad Facies transition represents a gradual change to Palaeoaplysiniid buildup flank facies. This grainstone is clearly dominated by dasycladacean grains with common to rare *Palaeoaplysina* and *Tubiphytes* fragments. Minor fusulinids, *Tetrataxis*, echinoderms, pseudoendothyrids and paleotextularids are also present.

Interpretation

The Dasycladacean facies was deposited in relatively turbulent environments spatially associated with shoals, probably close to the fair-weather wave action zone but certainly within the storm wave action zone (Fig 3.2). Dasycladacean algae (*Epimastopora*) are always found in association with relatively open marine biotic assemblages but are more common in relatively high-energy shoal facies such as the Bioclastic and Oncoidal Facies. Dasycladacean fragments are abundant in coarse grainstone of the Palaeoaplysiniid bioherms flank facies but also present in flank facies of Bryozoan-*Tubiphytes* bioherms (Morin *et al.*, 1991b). Dasycladacean algae favoured the positive topography of shoals and buildup margins where water circulation was more vigorous. The low abrasion of dasyclad fragments and the grainstone texture suggest that the sand-sized dasyclad fragments at the sediment-water interface were only slightly winnowed. The largely monospecific composition of Dasycladacean Facies suggests that the dasyclads were deposited *in situ* (relatively little transportation) and therefore able to grow on a mobile substrate. Under conditions of high sedimentation, as seen today for green algae (Tucker and Wright, 1990), their ability to grow on mobile substrates may have enabled them to colonize sediments that other organisms could not such as colonial rugosans, syringoporids and certain echinoderms.

3.1.3.4 Oncoidal Facies

Description

The Oncoidal Facies is defined by the presence of foraminiferal/algal oncolitic encrustment on fossil fragments. The oncoid size ranges from 1 mm to 15 cm in diameter. The encrusting

organisms are mainly composed of globular apterrinellid foraminifers, fasciellid red algae and *Tubiphytes*, with rare *Asphaltina*, *Cuneiphipicus* and *Nansenella*. Syringoporidae corals encrust the outer layers in some large oncoids. The bioclastic nuclei are generally dasycladacean and phylloid algal plate fragments, globular nodular apterrinellid (auto-encrusting) or gastropods.

The Oncoidal Facies is subdivided into informal "open" and "restricted" subfacies based on associated biota. The restricted subfacies consists of a packstone matrix containing biota similar to that of the Foraminiferal Facies (i.e. ostracods, tuberitids, globivalvulinids, *Syzrania*, phylloids and *Tubiphytes*; Plate 4c). The "open" subfacies is generally composed of slightly abraded bioclastic grainstone to packstone with biota similar to that of the Fusulinacean and Bioclastic Facies assemblages: dasycladacean, echinoderms, brachiopods, fenestellids, pseudoendothyrids, *Tetrataxis*, paleotextularids, gastropods and rare ooids (Plate 4d). Transitional biotic compositions between these two subfacies are present.

Interpretation

Oncoid formation requires a relatively turbulent environment (at least periodically), to cause overturning (Tucker and Wright, 1990). The energy level may have influenced oncoid size and shape. For instance, the agitation level was relatively high when oncoids are oblong and reach 15 cm in diameter, whereas the level was lower where oncoids are spherical, and less than 1 cm in diameter. This suggests that the sediments of the Oncoidal Facies were deposited in depositional environments ranging from shallow (within the fair-weather wave action zone) to the lower limit of storm wave action zone. The allochem composition and the transition with Oolitic, Bioclastic and Dasycladacean facies, however, indicate a depositional environment relatively close to fair-weather wave base (Fig. 3.2).

3.1.4 Non-reefal mid-shelf deposits

Non-reefal, mid-shelf sediments were deposited in open marine, low energy depositional environments below the fair-weather wave base. These facies include: Fusulinacean, Bryozoan and Micritic Facies. They are generally darker coloured, bioturbated, argillaceous packstone or wackestone with rare sedimentary structures. Other facies were deposited in the mid-shelf setting but will be described later in the sections on reefal mid-shelf facies.

3.1.4.1 Fusulinacean Facies

Description

The Fusulinacean Facies is the most variable in composition and widespread in distribution. This facies is generally dark grey to black, bioturbated and consists of packstone or wackestone with a diverse biotic assemblage in which clusters of large colonial rugosans are

locally abundant. Fusulinacean Facies contain various amounts of fusulinids, fenestellid bryozoans, echinoderms and brachiopods. These organisms are usually associated with diverse stenohaline taxa such as: phylloid, dasycladacean and fasciellid algae, *Palaeoaplysina*, *Tubiphytes*, solitary rugosans, globular and irregular apterrinellids and others (Fig. 3.3a). Bradynids, paleotextularids, and *Tetrataxis* foraminifers are relatively common. Depositional textures range from packstone (Plate 5a) to wackestone (Plate 5b), or more typically, to a "poorly sorted" packstone (Plate 5c).

There is a gradual transition between Fusulinacean Facies and flanking reef facies. For instance, when reef builders and associated organisms (e.g. Dasycladacean, *Palaeoaplysina*, *Tubiphytes*, phylloids, irregular apterrinellids, fenestellid and ramose bryozoan) are more common within the Fusulinacean Facies, their presence is systematically related to buildup proximity. In fact, the large majority of carbonate buildups present in the Asselian-Sakmarian shelf on Fosheim-Hamilton peninsulas formed within or near the depositional limits of the Fusulinacean Facies (Fig. 3.5). This spatial distribution best explains variations in composition within the Fusulinacean Facies.

Complete facies transitions are present from mid-shelf Fusulinacean Facies to inner shelf Bioclastic, Oncoidal and Foraminiferal Facies (Fig. 3.5). Facies transitions with Bryozoan Facies are also common and characterized by the disappearance of numerous taxa (Fig. 3.3a). These transitions are important because the Fusulinacean Facies can be subdivided into informal "proximal" and "distal" subfacies. The "proximal" subfacies corresponds with a compositional transition to inner-shelf facies including: Foraminiferal, Oolitic, Oncoidal, Bioclastic and Dasycladacean Facies, and is characterized by a diversified biota. The "distal" subfacies represents a compositional transition with the Bryozoan Facies.

Interpretation

The lack of high energy sedimentary structures, open marine biotic assemblages, abundance of micrite and the presence of calcareous green algae, suggest an open shelf depositional setting below fair-weather wave base but within the photic zone (Fig. 3.2).

The most peculiar feature in this facies is the occurrence of packstone composed exclusively of fusulinids (Plate 5d). This "fusulinite" rock occurs either as capping phylloid bioherms or as massive beds up to 15 m thick. Beauchamp (1987) suggested that the latter, thick fusulinite deposits observed on Raanes Peninsula, were related to selective taphonomic transportation of shelf sediments by storms to deeper offshore environments. On Fosheim and Hamilton peninsulas thick fusulinid-rich beds are usually massive and structureless suggesting that their origin is most likely related to a particularly favourable environment for the growth of this huge unicellular organism. Wilson (1975) described similar facies from Mid-Continent cyclothems

(i.e. microfacies P-5) and interpreted them as accumulating under normal open marine conditions, on carbonate platforms ranging from "*a few meters to a few tens of meter deep*".

3.1.4.2 Bryozoan Facies

Description

The Bryozoan Facies is generally composed of fenestellid and ramose bryozoans, with echinoderms and brachiopods, within a bioturbated wackestone (Plate 6a). Ostracods, fasciellid algae, tuberitinids, *Syzrania* , *Tubiphytes*, sponge spicules, solitary rugosans and syringoporids are also present but are rare. Quartz silt grains occur in variable amounts and bitumen is also present. This facies is dark grey to black in outcrop and has a strong hydrocarbon smell in freshly broken rocks.

Interpretation

Sediments of the Bryozoan Facies were deposited in relatively deep water, mid shelf setting. The lack of calcareous green algae, *Palaeoaplysina* and encrusting foraminifer, wackestone texture, lack of sedimentary structures, presence of Fasciellids (red algae) and common bioturbation altogether suggest a relatively quiet depositional environment below wave base and probably below the penetration limits of green light (Fig. 3.2). Dominant biota of this facies are similar to those present in modern and ancient cool water shelf carbonates but in warm water settings these biota are restricted to deeper cooler water shelf environments (Nelson, 1988).

3.1.4.3 Micritic Facies

Description

The Micritic Facies is characterized by dark gray to black, bioturbated calcilutite mudstone. This facies is largely dominated by micrite with rare to common quartz silt grains, small peloids and rare skeletal elements such as brachiopods, fenestellids, fasciellid algae and others (Plate 6b). Laminations in silt-rich facies (Plate 6c), and gypsum pseudomorphs crystals floating in a micritic matrix are locally present (Plate 6d). These structures and mineral assemblages probably reflect a facies transition between the evaporite related facies: Laminated Siltstone-Dolostone Facies (see Anhydrite cycle, Chapter 4).

The Micritic Facies is often completely dolomitized. It is made up of microcrystalline dolomite with rare to common silt-sized quartz grains. Relict peloids and rare brachiopods are present. A peculiar feature is the common occurrence of gypsum crystals "floating" in the dolomitic matrix (Plate 7a). Gypsum crystals, are either replaced by spar or are inferred by preserved crystal habit. In some thin-sections silt laminations are interpreted as the dolomitized equivalent of the transition of Micritic Facies to Laminated Siltstone-Dolostone Facies (Plate 7b; see Anhydrite cycle, Chapter 4). In fact most of the dolomitized rocks in the study area are

transitional from Micritic Facies (locally dolomitized) to Laminated Siltstone-Dolostone Facies and to Laminated Anhydrite Facies (see Anhydrite cycle, Chapter 4) suggesting that dolomitization is possibly related to the saline fluids that were responsible for gypsum precipitation.

Interpretation

The Micritic Facies represents sediment deposited under low energy conditions in deep water (below photic zone) as evidenced by the lack of green algae, the scarcity of biotic elements, and the muddy depositional texture (Fig. 3.2). Nevertheless, the occurrence of anhydrite crystals in some samples suggests that this facies was also spatially and temporally associated with anhydrite deposition.

3.1.5 Reefal mid-shelf deposits

The Carboniferous and Early Permian was a time of crisis for reef-framework building organisms (Newell, 1972). The reef ecosystem is characterized by smaller branching and encrusting taxa able to form mound-like structures (James, 1983) and by the presence of smaller branching or encrusting taxa able to form mound-like structures. These organisms include phylloid algae, bryozoans (mainly fenestellids), *Tubiphytes*, *Palaeoaplysina* and *Archeolithoporella*. The latter two taxa are mutually exclusive and grew in boreal and tethyan regions respectively (Davies *et al.*, 1989).

Dozens of reef buildups are present within the Asselian-Sukmariian sequence in the study area. These buildups display three distinct shapes or morphology types: patch reefs, tabular banks and reef mounds (Beauchamp, in press). Patch reefs are lenticular in shape, less than 15 m thick and 50 m wide. Tabular banks are massive to coalescent flat bodies, less than 20 m thick, and as large as 6 km. Reef mounds or pinnacle reefs are 150 m thick and reach up to 500 m in width. Beauchamp (in press) suggested that the reef morphology is mainly controlled by the vertical space available for reef growth, and therefore, a relation exists between shelf position and reef shape.

Upper Paleozoic buildups of the Sverdrup Basin consist of several boundstone types identified according to the major reef building taxa (Beauchamp, 1987; Davies *et al.*, 1989; Beauchamp *et al.*, 1989c; Beauchamp, 1989a,b; Beauchamp, in press; Nassichuk and Davies, 1992). In the present study area, boundstone types in various buildups are similar to those previously reported elsewhere in the Sverdrup Basin but some differences are recognized, as well as, a new boundstone type is introduced here and named Syringoporid boundstone.

This section describes boundstone facies (Fig. 3.3b) and their associated facies, if present, (Fig. 3.3c) that occur in an open marine mid-shelf setting (Fig. 3.1). These include: Palaeoaplysiniid Boundstone and Palaeoaplysiniid-Dasyclad Facies; Phylloid Boundstone and Phylloid-Fusulinid Facies; Palaeoaplysiniid-Phylloid Boundstone Facies, Bryozoan-*Tubiphytes* Boundstone and Bryozoan-*Tubiphytes* Facies; Syringoporid Boundstone Facies; Spongiostromid

Boundstone Facies; and Beresellid Boundstone Facies. Palaeoaplysiniid and Phylloid Boundstones are the most abundant ($\approx 95\%$), whereas Bryozoan-*Tubiphytes* and Beresellid Boundstones are rare and other boundstones are very rare.

3.1.5.1 Palaeoaplysiniid Boundstone and related Facies

Palaeoaplysiniid Boundstone Facies

Description

Palaeoaplysiniid boundstones occur as small patch reefs (<10 m large) or as large flat topped tabular reefs up to 10 m thick. The palaeoaplysiniid reefs are generally present in the resistant part of proximal cycles containing shallow inner shelf grainstones and most abundant in Fosheim-Hamilton subbasin marginal sections (e.g. VQP, ECR I)

The Palaeoaplysiniid Boundstone Facies is made up of an *in situ* accumulation of *Palaeoaplysina* plates generally encrusted by abundant *Tubiphytes* and more rarely by apterrinellids, tuberitids and fasciellid algae. *Palaeoaplysina* plates are locally superimposed forming up to 85% of the reef facies (Plate 7d) but more commonly occur as a loose framework. Growth cavities are filled with wackestone-packstone matrix (Plate 8a) containing peloids and various skeletal fragments similar to those of the Fusulinacean Facies assemblage. Common dasycladacean algae, echinoderms, fusulinids and *Syzrania* are present. Brachiopods, fenestellids, paleotextularids, *Tetrataxis*, bradynids, ostracods, gastropods, solitary rugosans and rare sponge spicules are minor constituents (Fig. 3.3b).

Palaeoaplysina is a peculiar organism of unknown affinity possibly assigned to the sponges or algae but more probably related to hydrozoans (Breuninger, 1976). This organism is platy in shape, 3 to 6 mm thick, and up to 1 m long but generally occurs as decimetre-sized skeletal fragments. *Palaeoaplysina* plates, originally aragonitic, are now spar-filled but some plates are well preserved possessing polygonal internal cells that form a complex pore network (Plate 7c).

Palaeoaplysiniid-Dasyclad Facies

Description

Palaeoaplysiniid-Dasyclad Facies is characterized by grainstone, or more rarely packstone texture (Plate 8b). This facies is mainly composed of abundant abraded skeletal fragments of *Palaeoaplysina* (≈ 1 cm in size) and *Epimastopora*, and dasycladacean algae (≈ 3 mm in diam.). Common *Tubiphytes*, echinoderms, brachiopods, fenestellids, fasciellids, and rare fusulinids, globivalvulinids, *Syzrania* sp (Fig. 3.3c) are also present. This reef related facies is transitional with Fusulinacean Facies and Dasycladacean Facies (Fig. 3.5).

Interpretation

Palaeoaplysina plates played an important role in bioherm construction by baffling and trapping sediment. The Palaeoaplysiniid-Dasyclad Facies, is characteristic of bioherm flank area. The abraded grains and common grainstone texture of the flank facies are indicative of a relatively high-energy environment, within or close to the fair-weather wave base. This argument is supported by the abundance of dasycladacean algae, an organism which seems to proliferate in relatively turbulent environments (see Dasycladacean Facies). The energy level interpreted from grain texture was relatively high but lower than that of Oolitic and Bioclastic Facies. The latter two facies are usually present either at the base or at the top of the palaeoaplysiniid buildups, suggesting that the depositional environment of the Palaeoaplysiniid Boundstone Facies and the Palaeoaplysiniid-Dasyclad Facies was close to the lower limits of fair-weather base and within storm wave action zone. The presence of bioherms above and below strata either made up of "proximal" Fusulinacean Facies, or underlain by shallow shelf sediment as Oolitic, Bioclastic, Oncoidal or Dasycladacean Facies (see Appendix I: VQP, 55-70 m, 130-140 m; NTL, 320-325 m; MKB, 245-260 m). The common occurrence of *Palaeoaplysina* buildups in subbasin marginal sections (see Appendix I: VQP, CDB) also suggests that *Palaeoaplysina* buildups were deposited in relatively shallow shelf setting. Breuninger *et al.* (1989) in a study of a small bioherms in Idaho suggested that turbulent conditions favoured the growth of *Palaeoaplysina* plates over fragile but fast growing phylloid plates. A similar interpretation is reported for a *Palaeoaplysina* buildup in the Yukon (Davies, 1989). In the study area, the only vertical transition from Palaeoaplysiniid to Phylloid Boundstone is part of an overall deepening upward facies succession (see Appendix I: VQP 100-129 m) confirming a shallower depositional environment for Palaeoaplysina.

3.1.5.2 Phylloid Boundstone and related Facies

Phylloid Boundstone Facies

Description

Phylloid boundstones are interpreted as large patch reefs (10 to 50 m large, 15 m thick) or as tabular reefs with irregular top and various thickness (1 to 10 m thick to up to 6 km large). This reefal facies is generally present in the transgressive part of relatively distal cycles associated with deeper shelf packstone lithofacies (see Idealized Cycles 3; Chapter 4).

Phylloid Boundstone Facies is made up of a relatively open framework of phylloid plates. Phylloid thalli are encrusted by abundant *Tubiphytes* and common irregular apterrinellids. The aragonitic phylloid plates are generally poorly preserved. Mamet *et al.* (1987) assigned phylloid algae to platy codiaceans (green algae) and recognized three different genera within the Sverdrup Basin: *Eugonophyllum*, *Neoanchicodium* and *Ivanovia*.

In general, sediment-filled growth cavities represent more than 80% of the facies volume and consist (Plates 8c and d) of peloidal packstone to wackestone with biotic assemblages similar to that of Fusulinacean Facies. Biotic elements include common fusulinids, echinoderms, brachiopods, fenestellids, *Syzrania*, tuberitinids, irregular apterrinellids, pseudoendothyrids, paleotextularids and tetrataxids, and rare dasyclads, beresellids, ostracods, gastropods, globivalvulinids, fasciellids and bradinids (Fig. 3.3b).

Phylloid-Fusulinid Facies

Description

This flank facies is associated with Phylloid Boundstone Facies and comprises abundant phylloid platy fragments, up to 1 cm long, and fusulinid in a packstone texture (Plate 9a). This facies contains common echinoderms, brachiopods, tuberitinids, irregular apterrinellids, fasciellids, *Tubiphytes* and peloids, and rare beresellids, fenestellids, gastropods, solitary rugosan, globivalvulinids, *Syzrania*, paleotextularids, tetrataxids and bradinids (Fig. 3.3c). This flank facies is transitional with the Fusulinacean Facies (Fig. 3.3).

Interpretation

The phylloid algae thalli played an important role in bioherm construction by baffling and trapping sediment. The encrusters present on phylloid thalli, are rare and played a negligible role in mound development. The Phylloid-Fusulinid Facies mainly occurs as flank deposits surrounding phylloid buildups. Phylloid platy fragments become progressively smaller away from the bioherm. The predominance of phylloid buildups in central subbasin sections, the presence of mud, abundance of fusulinids, lack of abraded skeletal grains, and transition to Fusulinacean Facies all indicate an open marine, relatively deep and quiet depositional environment for phylloid buildups and associated flank facies, with periodic higher energy events (storms?) capable of disturbing phylloid thalli. Thus, the depositional setting was located within the photic zone, probably below the fair-weather wave base but within the lower limits of storm wave base.

In some cases, the accessory biotic assemblage associated with phylloid boundstone is somewhat similar to that of the Foraminiferal Facies, and made up of a packstone-grainstone containing common fecal-like peloids, globivalvulinids, *Syzrania*, tuberitinids, globular apterrinellids, *Tubiphytes*, pseudoendothyrids and ostracods. The restricted character of this biotic assemblage suggests that phylloid boundstone developed also within relatively restricted lagoonal environments.

3.1.5.3 *Palaeoaplysina*-Phylloid Boundstone Facies

Description and interpretation

Phylloid and *Palaeoaplysina* plates rarely occur together within the same buildup. In the study area, a single example (see Appendix I: VQP section) of this boundstone has been yet recognized. It is characterized by a loose framework of *Palaeoaplysina* plates on which phylloid plates locally grew. Apterrinellids and *Tubiphytes* also encrust both reef-building taxa. Internal sediment fill is composed of grainstone-packstone (Plate 9b) containing common dasyclad, globivalvulinids, fenestellids, echinoderms, peloids and fusulinids (Fig. 3.3b). The depositional environment of this facies is probably transitional between those of the Phylloid Boundstone Facies and *Palaeoaplysina* Boundstone Facies.

3.1.5.4 Bryozoan-*Tubiphytes* Boundstone and related Facies

Bryozoan-*Tubiphytes* Boundstone Facies

Description

The Bryozoan-*Tubiphytes* Boundstone Facies comprises an open framework of fenestellid and ramose bryozoans and rare sponges, encrusted by *Tubiphytes*, fasciellids algae, tuberitinids, apterrinellids and fistuliporid bryozoan. *Tubiphytes*, other encrusters and probably sponges played a secondary, stabilizing role in the reefal construction. Growth cavities are infiltrated by pelleted lime mud containing common brachiopods, echinoderms and spicules, and rare dasyclad and phylloid algae, and *Palaeoaplysina* (Plate 9c and d).

In the study area, Bryozoan-*Tubiphytes* Boundstone Facies occurs as two small bioherms less than 5 m thick. The Bryozoan-*Tubiphytes* Boundstone Facies present, however, are more similar with younger Artinskian bioherms from Raanes Peninsula described by Beauchamp (1989b) and characterized by abundant fenestellid bryozoan and common sponges. Beauchamp (1987, 1989a), documented similar facies forming bioherms up to 12 m thick that are dominated by ramose bryozoans with rare fenestellids, but lack sponges. They are interpreted as relatively shallow mid-shelf reefs.

Bryozoan-*Tubiphytes* Facies

Description

The Bryozoan-*Tubiphytes* Facies is mainly composed of echinoderms, *Tubiphytes*, fenestellids and ramose bryozoan fragments in a packstone to grainstone-packstone texture (Plate 10a). Common brachiopods, fasciellids, and solitary rugosans are present. Rare components include globivalvulinids, irregular apterrinellids, *Syzrania*, paleotextularids and *Tetrataxis*. Dasycladacean algae and fusulinids are either common or absent. This related boundstone facies is transitional to the Bryozoan and Fusulinacean Facies (Fig. 3.5).

Interpretation

Delicate branching ramose and fenestellid bryozoans acted as sediment trappers and bafflers during reef growth. The spatial distribution of the Bryozoan-*Tubiphytes* Facies to the buildups, and the large size of bryozoan fragments suggest that this facies flanked the buildups. The packstone texture of the Bryozoan-*Tubiphytes* Facies suggests also a relatively quiet, low energy environment. The rare occurrence of dasyclads and fusulinids, and the presence of common red fasciellid algae indicate a depositional environment close to the lower limit of the photic zone (Fig. 3.4). Morin *et al.* (1991b) reported a vertical zonation within an individual bioherm from Phylloid to Bryozoan-*Tubiphytes* and to Syringoporiid Boundstone, this transition as part of a deepening upward trend ranging from below fair-weather wave action base to below the photic zone. Phylloids and syringoporids represent the shallowest and the deepest reefal subfacies respectively. In this study the Bryozoan-*Tubiphytes* Boundstone is characterized by the occurrence of green algae (dasyclad and phylloid) at the base, whereas fasciellid algae are common at both the base and in the top of the Bryozoan-*Tubiphytes* reef mounds. Therefore Bryozoan-*Tubiphytes* Boundstone Facies developed close to the limit of photic zone. The shelf position of the Bryozoan-*Tubiphytes* Boundstone Facies corresponds with the limit of proliferation of photophilic builders such as phylloid algae.

3.1.5.5 Syringoporiid Boundstone Facies

Description and interpretation

This Boundstone Facies in which syringoporids played a major role as reef builders is an unusual facies in the Sverdrup Basin and possibly worldwide (Morin *et al.*, 1991b). This facies represents small coalescent bioherms within the Asselian Antoinette Formation at North Greely Fiord. Another occurrence has been reported recently from the north side of Greely Fiord-Tanquary Fiord (Beauchamp, pers. comm.). The facies is dominated by abundant hemispheric and fasciculate syringoporiid corals, 5 to 25 cm in diameter. Other reef builders include ramose and fenestellid bryozoans, and rare sponges and solitary rugosans. Reef building syringoporids encrust ramose bryozoans, solitary rugosans and other syringoporids (Plate 10b and 10c). *Tubiphytes*, fasciellid algae, tuberitinids and fistuliporiid bryozoans are also present. The matrix is composed of spicule-rich pelleted lime mud containing various bioclasts (mainly echinoderms and brachiopods; Fig. 3.3b). Marginal facies are composed of coarse packstone containing common solitary rugosans, echinoderms, fenestellid and ramose bryozoans, and rare brachiopods and syringoporiid fragments.

During reef development, syringoporiid corals acted as frame constructors and sediment trappers, and the small encrusters played only a minor role in reef stabilization due to of their

relative scarcity. The Syringoporid Boundstone Facies, in association with decreasing content in green algae, apterrinellids and fusulinids, and increasing amount of fasciellid algae and solitary coral is coeval with the flooding surface of a high-order cycle (Morin *et al.*, 1991). This suggests that the small coalescent bioherms in this facies represent patch reefs that developed in a relatively deep shelf setting below the photic zone at least for the green light where syringoporids were more prolific and efficient as reef-builders.

3.1.5.6 Spongiostromid Boundstone Facies

Description and interpretation

The Spongiostromid Facies is also rare within the study area. It is characterized by a peculiar texture of dark peloidal grains arranged like a "stretched chicken-skin" texture. This fabric is also called "structure grumeleuse", spongiostromate or clotted fabric but its origin is still unknown and probably multiple. In the present study, "stromatactid" cavities are present and partially filled with lime mud (Plate 10d) and drusy fibrous cement. Beauchamp (in press) recognized spongiostromid mats within all buildup types of the Sverdrup Basin up to latest Artinskian time. According to Beauchamp (*ibid.*) spongiostromid mat may have acted as a great sediment stabilizer and possibly as binder. In the study area, however, only three occurrences of Spongiostromid Facies are recognized; all three in the Upper Sakmarian strata at McKinley Bay section. In outcrop, the Spongiostromid Facies forms a massive and resistant unit, overlain by phylloid biostrome near a major syn-sedimentary fault. Occurrence with other reef building taxa has not been yet observed, but important thickness of Spongiostromate Facies (see Appendix I: MKB, 870-910 m) on the uplifted block nearby a syn-sedimentary fault may suggest an efficient stabilizing role, given that such depositional setting was most likely tectonically unstable.

3.1.5.7 Beresellid Boundstone Facies

Description and interpretation

The Beresellid Boundstone Facies is a peculiar type of boundstone present mainly in Moscovian strata, but also locally in Asselian and Sakmarian strata. The Beresellid Boundstone Facies is dominated by beresellid algae (Plate 11a) and forms thin (<5 m) biostromes. The interskeletal pores are filled either with packstone or with cement characterized by a thin isopachous rim covering the algal thalli. The remaining pore space is filled with equant spar. This facies contains rare to common fusulinids, *Tubiphytes*, pseudoendothyrids, bradynids, globular apterrinellids (see discussion on apterrinellids) and globivalvulinids (Fig. 3.3b), suggesting a relatively shallow shelf environment probably equivalent to those of the "proximal" Fusulinid Facies and/or the "open" Foraminiferal Facies. The relative paleobathymetric position of the Beresellid Boundstone Facies deduced from vertical succession in well defined high-frequency

cycles (see Chapter 4) suggests a relatively shallow shelf setting at, or near, fair-weather wave base (see Appendix I: NTL, 230-250 m, 260-270 m; ECR I, 330-340 m).

Beresellids are small tubular green algae that are abundant in Carboniferous strata but also present in younger deposits of the Sverdrup Basin (Beauchamp, 1987). A "beresellid event" associated with their widespread occurrence is believed to exist at the Asselian-Sakmarian boundary (S. Pinard, pers. comm.). This stratigraphic "event", however, is observed only locally (one section) throughout the study area. Beresellid algae are locally present in several facies. For example beresellids are present in Foraminiferal, Fusulinid, Phylloid-Fusulinid and Phylloid Boundstone Facies. On the other hand, beresellid algae are systematically absent from Peloidal and "restricted" Foraminiferal Facies, suggesting that they grew in normal marine environments ranging from relatively shallow depths to the lower limit of the photic zone.

3.1.5.8 Boundstone Summary

The variety of boundstone facies form mound-like structures ranging from small patch reefs to large tabular reefs and developed from shallow subtidal setting to below the photic zone. Their relative position on the shelf was controlled, at least in part, by water depth (see individual description and interpretation). In general, the different boundstone facies are mutually exclusive suggesting that their occurrence in a particular shelf environment was related to the growth efficiency of the various reef building taxa under specific environment conditions.

The reef shelf location are interpreted as following (Fig. 3.6): 1) Palaeoaplysiniid buildups in relatively shallow water setting at the lower limit of fair-weather wave base, to deeper subtidal setting, where the fragile but fast growing phylloid algae was less efficient as reef constructor; 2) Phylloid buildups developed from below storm wave base to the lower limits of the photic zone, where favourable conditions existed for growth of photophilic green algae with fragile growth forms; 3) Bryozoan-*Tubiphytes* buildups grew at or near the base of the photic zone; 4) Syringoporiid buildups developed in relatively deep waters below the photic zone, where bryozoans were inefficient builders and supplanted by syringoporiids. The depositional environments of the Spongiostromid Boundstone and Beresellid Boundstone Facies are not well constrained at this time. The Spongiostromid Boundstone Facies is associated with active syn-sedimentary faulting suggesting possibly that it played a stabilizing role. The Beresellid Boundstone Facies was probably deposited in shallow waters below fair-weather wave base.

3.2 SIGNIFICANCE OF APTERRINELLID FORAMINIFERA

As seen in the previous section, apterrinellids are foraminifers with an encrusting habit that are common to abundant in nearly all shallow water facies. Morphological differences in apterrinellid growth forms have been observed from facies to facies, and even within some facies,

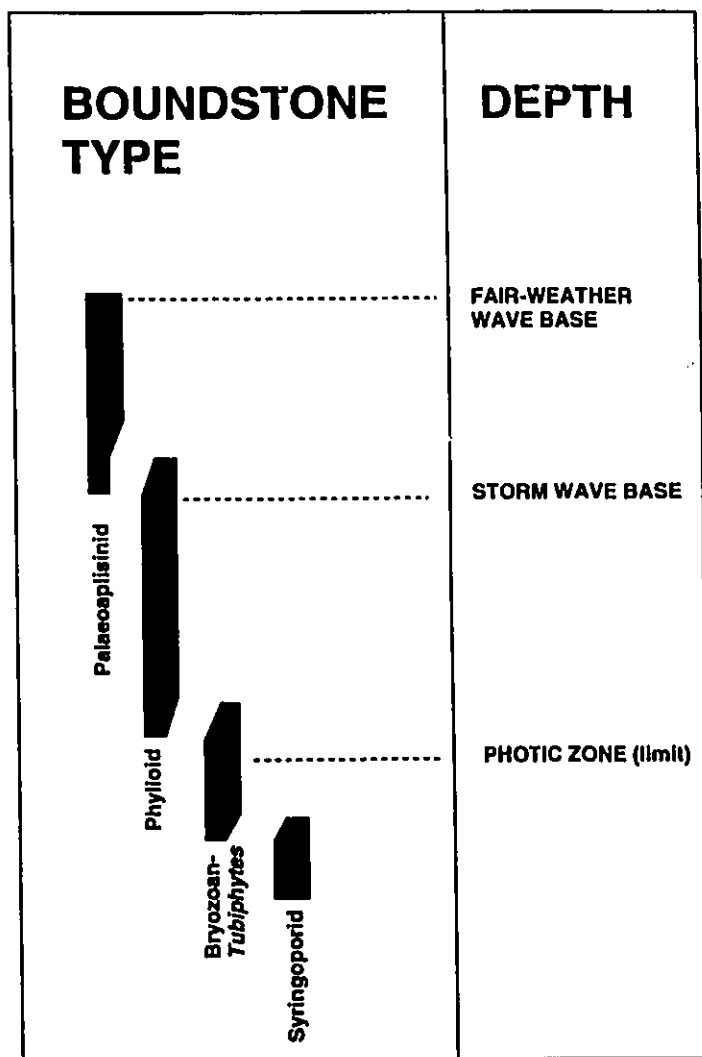


Figure 3.6: Schematic diagram showing the relative shelf position of major Asselian-Sakmurian boundstone facies in the study area.

suggesting a link between morphology and environments. Two major types of apterrinellids have been recognized: 1) an epibiont type, recognizable by their flat-base morphology growing attached to other organisms but were later detached from their support, and 2) nodular type, growing freely on the sea floor and forming multi-layered nodules similar in appearance to oncoids.

3.2.1 Epibiont apterrinellids

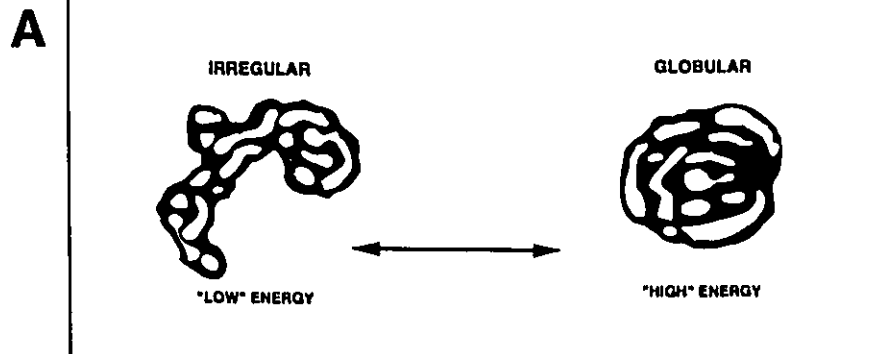
Epibiont apterrinellids are characterized by two basic morphologies: 1) flat single layered; and 2) multi-layered irregular morphologies. Single-layered epibiont apterrinellids are made up of a single "layer" of apterrinellids with a flat base and irregular top (Fig. 3.7 and Plate 11d). Their size varies from 0.4 to 1.4 mm. These apterrinellids are locally abundant within the Foraminiferal Facies and dominant in some samples (Plate 12a). Epibionts are associated with fasciellid algae, dasycladacean algae, ostracods, gastropods, echinoids, globivalvulinids and other foraminifers. The well preserved flat base of the single-layered suggests that the support has disappeared as would happen with post-mortem decay of soft-body organisms (non-calcified algae ?). Single-layered epibiont apterrinellids are closely related to modern epibionts growing on the sea grass blades of *Thalassa*. The small modern epibionts are mainly composed of red algae, foraminifera and serpulids (Tucker and Wright, 1990) and their associated biota include: gastropods, bivalves, echinoids, foraminifers, small fish, corals fecal pellets and calcareous algae. The presence of marine sea-grass is relatively recent in the rock record (Post-Jurassic), however, several soft-bodied algae could have played a similar role in ancient setting.

Multi-layered epibiont apterrinellids are similar to single-layered epibiont types, but are made of several encrusting "layers" and present in growth position on phylloid blades and *Palaeoplysina* plates (Fig. 3.7 and Plate 8c). As bioclasts detached from their growing substrate, these encrusters show broken edges and relatively irregular bases, probably resulting from the rupture from a strongly bonded substrate. These apterrinellids are generally smaller (0.2-1 mm) and "rounder" than the single-layered apterrinellids. Multi-layered apterrinellids occur as bioclasts within Fusulinacean, Phylloid, *Palaeoplysina* and Bryozoan-*Tubiphytes* Boundstones and related facies.

3.2.2 Nodular apterrinellids

Nodular apterrinellids are an auto-encrustment of the apterrinellids and subdivided into irregular and globular types. Irregular nodular apterrinellids are characterized by an irregular growth shape (Fig. 3.7) and range from 0.3 to 1 mm in size. Irregular nodular apterrinellids are present in packstone of the Peloidal Facies and restricted sediments of the Foraminiferal Facies (Plate 11b).

NODULAR APTERRINELLIDS (ONCOID-LIKE)



FLAT-BASED APTERRINELLIDS (EPIBIONT)

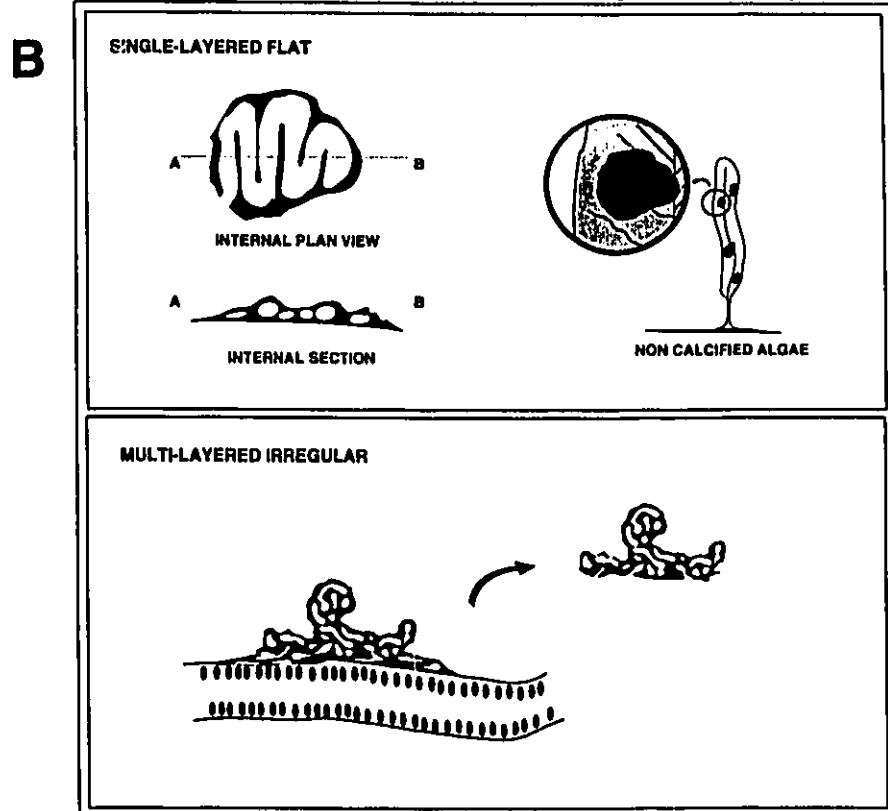


Figure 3.7: Diagram illustrating different growth shapes of encrusting apterrinellid foraminifera. A) Irregular to globular nodular apterrinellids are end-members of the auto-encrusting foraminifer. Irregular forms are rarely overturned and grew in low energy environments whereas globular nodular forms are often overturned and occurred higher energy settings (see Plate 13a and b). B) Single-layered flat-based apterrinellids are characterized by a well preserved flat base and a single "layer" of encrusting soft bodied organisms such as non-calcified algae (see Plate 13 c and d). Multi-layered flat-based apterrinellids occur in boundstone as encrusting builders. As bioclasts their base are irregular and show broken edges due to a strong bond between the encruster and supporting calcified organisms (see Plate 8c).

Globular nodular apterrinellids have a sub-spheric shape (Plate 11c) and are 0.3 to 1.0 mm in size. Globular apterrinellids are present in grainstones of relatively diversified assemblages ranging from the Foraminiferal Facies, Oncoidal, Bioclastic, Dasycladacean Facies to "proximal" Fusulinacean Facies.

Globular and irregular nodular apterrinellids are interpreted as representing end-members of an auto-encrusting process. The differences in growth forms are probably related to variations in energy level. The irregular nodular apterrinellids were present in low energy settings because they are rarely overturned. The globular nodular apterrinellids preferred a more turbulent setting where they were often overturned as suggested by their association with higher energy facies. A similar situation occurs in modern carbonate shelf environments with rhodoliths. Rhodoliths are made up of an encrustment by coralline red algae on selected nuclei and their variable growth shapes are environmentally controlled (Bosellini and Ginsburg, 1970). Low energy rhodoliths are digitate and become more rounded with increasing wave agitation on the sea floor. Thus the shape of nodular apterrinellids can be used as indicator of energy level. The energy level is relatively low in facies of Foraminiferal Facies with irregular nodular apterrinellids as evidenced by their "muddy" texture. The energy is moderate to high in open shelf facies of Foraminiferal, Bioclastic, Oncoidal, Dasyclad and "proximal" Fusulinacean Facies where globular apterrinellids are present. Irregular nodular apterrinellids have not yet been observed in Fusulinacean Facies.

CHAPTER 4: HIGH-FREQUENCY CYCLES

4.1 INTRODUCTION

The nineteen carbonate facies described and interpreted in chapter 3 recur in a cyclical fashion throughout the study area. Approximately 36 high-frequency cycles (i.e. fourth order of Vail *et al.*, 1977) are present within the Asselian-Sakmarian succession of the Fosheim-Hamilton subbasin. Each cycle was influenced by fluctuations in : 1) eustasy, 2) subsidence, and 3) sediment input. The combination of these variables resulted in relative sea-level variations that can be expressed through time on a relative sea-level curve. Such curves have been derived for each measured section using the carbonate facies interpretation presented in chapter 3. As shown in Appendix I, the relative sea-level curve swings back and forth between deep water and shallow water facies reflecting high-frequency fluctuations (cycles) on the order of 250 000 years on average*. An individual cycle is herein defined as the succession of strata between two flooding surfaces and similar to the cycles defined by Wilson (1975), Anderson *et al.* (1984), Goodwin and Anderson (1985), and Goldhammer *et al.* (1990) and is also similar to the parasequence concept used mainly for siliciclastic-dominated sequences by the Exxon group (Van Wagoner *et al.*, 1990).

4.2 IDEALIZED CYCLES

The cyclic succession of each measured section is complex, and important variations in the composition of cycles are present. In order to facilitate the analysis of large scale spatial and temporal fluctuations in the study area, the whole spectrum of carbonate cycles are grouped into three idealized categories. As shown in chapter 2, the carbonate succession passed from clastic-dominated strata at the basin margin, to evaporite-dominated strata toward the centre of the Fosheim-Hamilton subbasin. In addition to the carbonate-dominated cycles, idealized cycles are defined for the clastic and evaporite successions. Together, the five idealized cycles reported in a proximal to distal transect include (Fig. 4.1): Sandstone-Grainstone (#1); Grainstone-Palaeoaplysiniid (#2); Packstone-Phylloid (#3); Wackestone (#4) and Anhydrite (#5). Cycles are nearly symmetric in facies organization so that both transgressive and regressive portions in a depositional cycle are generally developed. A few cycles, however, display better development of the regressive or transgressive parts. The five idealized cycles are named according to their dominant facies (Fig. 4.1). As indicated by their appellation, idealized cycles correspond with an idealized cyclic facies succession, so that not all cycles fall readily into these five categories.

* Sakmarian time represents approximately 7 Ma (Cowie and Bassett, 1989), thus there is 27 high-order cycles averaging each 250 000 years in duration.

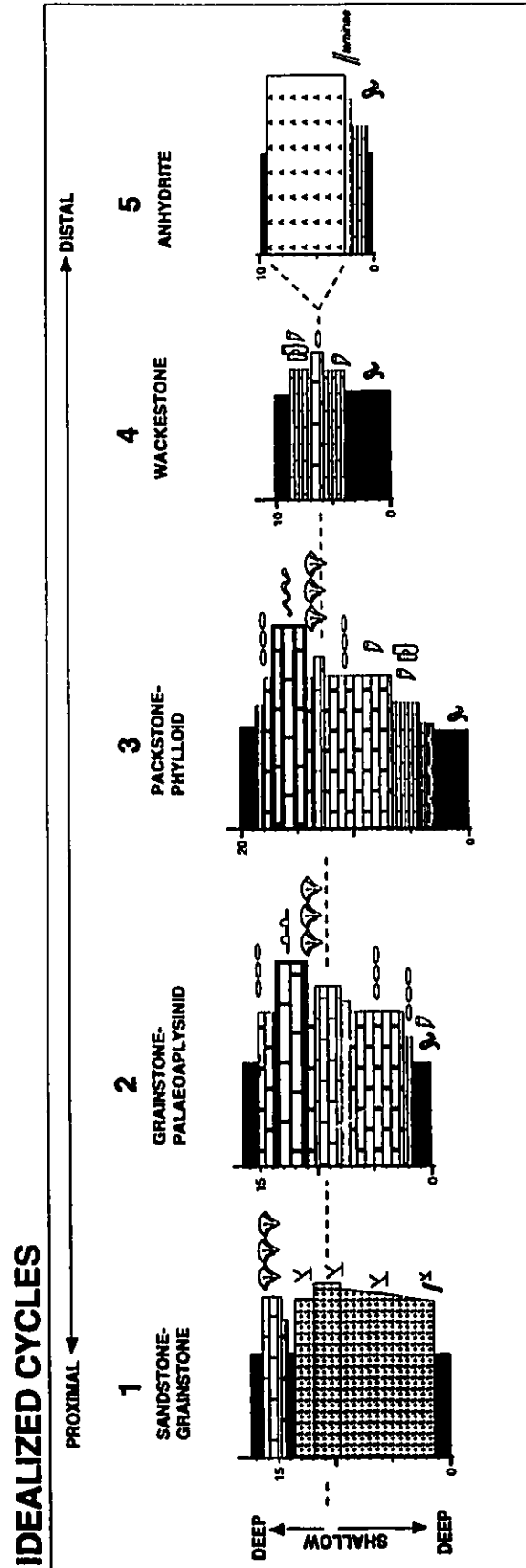


Figure 4.1: Diagram showing idealized high frequency cycles present in study area. Idealized cycles represent laterally equivalent complete cycles occurring across the shelf. Ideal cycles are placed in relation to their relative position on the shelf with Sandstone-Grainstone cycle being proximal and Anhydrite cycle being distal. Dotted line corresponds with the maximum regressive phase. Thicknesses are approximate. See Appendix I for symbols.

Idealized cycles, however, are a representative synthesis of most of the depositional cycles that are present in the study area.

4.2.1 Sandstone-Grainstone cycle

Sandstone-Grainstone cycles are generally composed of fine to medium grade sandstone with some grainstone beds. These cycles are predominant in sections near the basin margin (e.g. Caledonian Bay and Notch Lake sections).

Idealized Sandstone-Grainstone Cycle (Fig. 4.1) consists of a basal grey shale unit overlain by a thick sandstone unit. This unit is composed of medium bedded sandstone with parallel laminations and small scale cross-beds grading upward into thicker bedded coarser sandstone near the top (Plate 13d). The overlying unit is made up of medium bedded, medium to coarse sandstone (shallow marine nearshore deposits) with large scale low angle cross-beds representing a maximum regression. The uppermost sandstone unit is made of medium sand with large scale and low angle cross-beds. The overlying bed is generally recessive and composed of grey shale. A transgressive carbonate unit is commonly enclosed within the shale unit and comprises bioclastic grainstone to packstone from the Dasycladacean (commonly rich in *Palaeoaplysina* fragments), Oncoidal, and "proximal" Fusulinacean Facies in which clusters of large colonial rugosan are common.

The Sandstone-Grainstone cycles are extremely variable in composition with capping carbonate facies that are sometimes thin or even replaced by mixed siliciclastic-carbonate facies. In some cases, packstone or wackestone is also present within the basal regressive part. Rare cycles composed exclusively of siliciclastic sediment are also present in the study area (see Appendix I: NTL, (possibly) 350-364 m; CDB, 120-141 m, 199-205 m, 252-264 m).

4.2.2 Grainstone-Palaeoaplysiniid Cycle

Grainstone-Palaeoaplysiniid cycles, however, are characterized by the occurrence of relatively thick grainstone beds that are generally overlain or underlain by a palaeoaplysiniid boundstone. These cycles are abundant in carbonate-dominated sections from basin marginal areas such as Vache-qui-pleure but are also present at McKinley Bay, East Cape River I and II, and at North Greely Fiord sections.

In an **Idealized Grainstone-Palaeoaplysiniid Cycle** (Fig. 4.1) the basal facies is composed of a grey alcareous mudstone that is generally bioturbated and contains rare to common solitary rugosan. This mudstone unit is recessive and rarely exposed but is clearly absent in some well exposed cycles from basin marginal sections. The overlying strata are composed of wackestone/packstone of the Fusulinacean Facies. The wackestone is nodular to wavy bedded and the packstone is massive and medium to thickly bedded. The Fusulinacean Facies is "distal" in

character at the base of the packstone unit but "proximal" at the top (see Fusulinacean Facies, Chapter 3). Relatively thin, massive siltstone to sandstone beds are ubiquitous within the regressive part. The maximum regression facies is represented by grainstones with common large scale, low angle cross beds. The grainstones are composed of Foraminiferal, Dasycladacean, Bioclastic or Oolitic Facies. These grainstones are overlain by a thin massive packstone to packstone-grainstone of "proximal" Fusulinacean Facies, Palaeoaplysiniid-Dasyclad Flank Facies or Oncoidal Facies. Clusters of large colonial rugosans are common. These rugosan clusters were probably used as a stable substrate that were capped by palaeoaplysiniid boundstone. Palaeoaplysiniid boundstones occur commonly as flat-topped tabular banks, and more rarely as coalescent small patch reefs, up to 10 m thick (Plate 14a). The boundstones are overlain by a thin packstone unit of the Fusulinacean Facies. Palaeoaplysiniid boundstones are also present within the regressive part or during the maximum regressive stage of the cycle. In addition some cycles with thick grainstone units are lacking palaeoaplysiniid boundstone.

4.2.3 Packstone-Phylloid Cycle

Packstone-Phylloid cycles are mainly composed of a relatively thick packstone unit generally associated with phylloid boundstones. These cycles are abundant in more basinward sections such as at East Cape River II, Mount Bridgman, North Greely Fiord and McKinley Bay.

The basal facies of an **Idealized Packstone-Phylloid Cycle** (Fig 4.1) is composed of calcareous silty grey shale, overlain by thin wavy bedded calcilutite with wackestone to mudstone typical of the Micritic Facies. The calcilutite unit is overlain by nodular to wavy bedded wackestone to packstone of the Bryozoan Facies containing common solitary rugosan and syringoporid corals. This unit is overlain by a massive medium to thick bedded packstone of the Fusulinacean Facies. The Fusulinacean Facies is "distal" at the base and progressively more "proximal" at the top. The "proximal" Fusulinacean Facies represents the maximum regression level, but "shallower" grainstone-packstone of the Oncoidal Facies are locally present. The maximum regression unit is overlain by packstone of "proximal" Fusulinacean Facies containing clusters of large colonial rugosans. These clusters also acted as a stable substrate for phylloid boundstones. Phylloid algae form bioherms of various shapes ranging from large patch reefs (≤ 100 m width and ≤ 15 m thick) tabular reefs (up to 6 km width and ≤ 10 m thick) with irregular tops (Plate 14b). The bioherms are capped by calcarenitic packstone of Fusulinacean Facies or Phylloid-Fusulinid Flank Facies and finally overlain by a thin wackestone unit of the Bryozoan Facies.

In some cases relatively thick cycles (see Appendix I: MBM, 0-50 m, 50-100 m, 210-300 m; ECR II, 0-17 m, 17-45 m, 45-90 m) show no boundstone development possibly related to high

terrigenous clastic influx in the basin present in these cycles. In other cases, phylloid boundstone is present within the regressive part or at the maximum regression of the cycle.

4.2.4 Wackestone Cycle

Wackestone cycles are present in more basinward sections such as McKinley Bay, East Cape River I and Mount Bridgman sections (see Appendix I: MKB, 613-631 m, ECR I, 0-23 m, 23-44, m 44-57 m; MBM, 100-115 m, 115-122 m, 122-127 m).

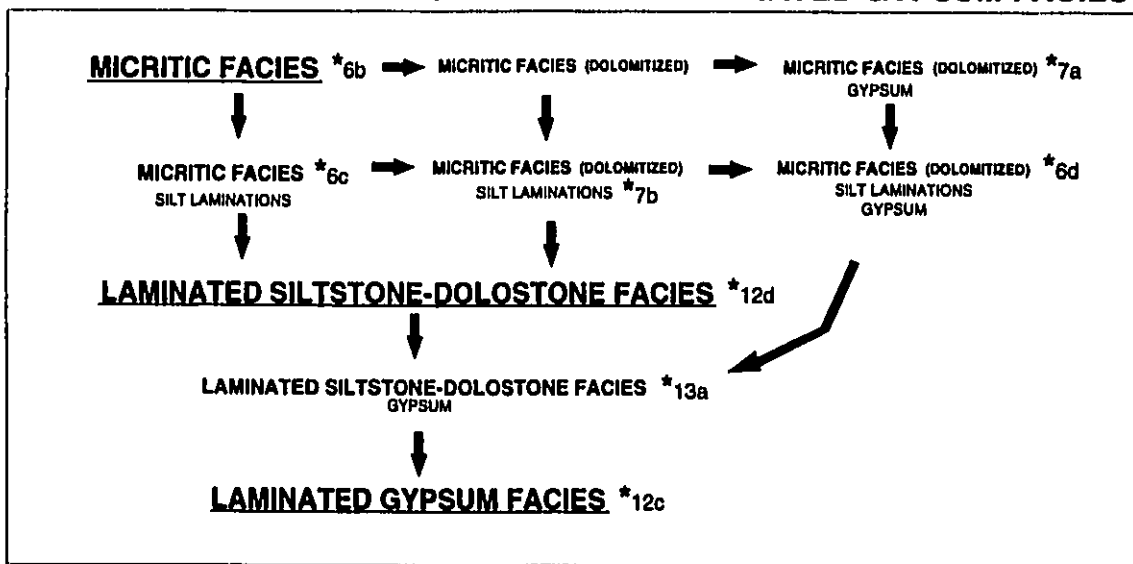
An **Idealized Wackestone Cycle** (Fig 4.1) is relatively thin (less than 10 m) and composed of dark grey calcareous mudstone at the base overlain by a dark massive to wavy bedded (Plate 14c) calcilutite mudstone to fine calcarenitic wackestone-packstone of the Micritic and Bryozoan Facies respectively. Cycles with thin layers of calcarenitic packstone of Fusulinacean Facies are rare. The packstone unit represents the maximum regression and is overlain by a layer of similar mudstone to wackestone-packstone of Micritic to Bryozoan Facies. In some cycles, the maximum regression coincides with silt-rich wackestone or calcareous siltstone (see Appendix I: MKB, 616-630 m; MBM, 100-130 m).

4.2.5 Anhydrite Cycle

Anhydrite cycles are present only within the Mount Bayley and the upper Antoinette formations in basinward sections such as North Greely Fiord, East Cape River I and II and Mount Bridgman. These cycles are composed of two major depositional facies: Laminated Siltstone-Dolostone Facies and Laminated Anhydrite Facies (Wallace and Beauchamp, 1990 and by Wallace, 1990).

Laminated Anhydrite Facies represent initial primary fabrics and is composed of millimetre to centimetre scale flat and parallel layers of anhydrite, commonly interbedded with the Siltstone-Dolostone Facies (Plate 12b and c). Rare individual halite hopper pseudomorphs are present. Laminated anhydrite is interpreted as being deposited in a deep water setting by Wallace and Beauchamp (1990) because of well preserved parallel laminations and a lack of bottom growth anhydrite, wave ripples or sabkha-like deposits. Parallel laminated anhydrite is usually indicative of evaporites accumulating in relatively deep water below the fair-weather wave base (Dean and Anderson, 1982). The Laminated Siltstone-Dolostone Facies is composed of finely laminated silty micritic dolomite. This facies is characterized by very fine laminae, as thin as 100 μm (Wallace, 1990) of peloid-rich micritic dolomite, alternating with silt-rich and organic-rich layers (Plate 12d). Angular, elongated to globular anhydrite crystals are commonly present between the fine laminae (Plate 13a). Detailed petrographic study of this facies shows a complete compositional spectrum from Micritic Facies to Laminated Siltstone-Dolostone to Laminated Anhydrite Facies (Fig. 4.2). In some cases, samples show several laminations of siltstone-dolostone between two layers of

TRANSITIONS FROM MICRITIC FACIES TO LAMINATED GYPSUM FACIES



* REFER TO PLATE NUMBER WHERE THESE TRANSITIONS ARE ILLUSTRATED

Figure 4.2: Flow chart showing transitions between Micritic Facies, Laminated Siltstone-Dolostone Facies and the Laminated Gypsum Facies. "Dolomitized" is for pervasively dolomitized microfacies, "silt laminations" is for the presence of thin parallel silt laminae, and "gypsum" is for the occurrence of "floating" gypsum crystals. These transitions depict temporal and spatial relationships between facies.

anhydrite. Depositional settings for the Laminated Siltstone-Dolostone Facies are similar in origin to the Laminated Anhydrite Facies, however, Laminated Siltstone-Dolostone Facies must have been deposited during a period and/or within an area of lower salinity. Wallace and Beauchamp (1990) proposed that these alternating silty and anhydrite laminae reflect varve-type sedimentation associated with short-term salinity turnovers in the subbasin.

An Idealized Anhydrite Cycle (Fig. 4.1) consists of dolomitized basal Micritic Facies, overlain by a thin unit (< 10 cm) of Laminated Siltstone-Dolostone Facies that grades upwards into a thick unit of Laminated Anhydrite Facies (Plate 12b). The laminated anhydrite is usually thicker at North Greely Fiord (more than 10 m) but thinner (less than 5 m) at East Cape River II and Mount Bridgman. The anhydrite is often recrystallized to nodular, crinkly laminated, bedded or massive mosaic textures (Wallace and Beauchamp, 1990). The transgressive part of the cycle is composed of a thin layer (5 to 50 cm thick) of green to dark grey shale. Relatively deep shelf carbonate facies (rarely dolomitized) such as the Bryozoan Facies, Fusulinacean Facies or even thin biostromes of Phylloid Boundstone Facies are present within a few anhydrite cycles (see Appendix I: MBM, 140 m, 164 m, 171 m; NGF, 457 m, 472 m).

The evaporite and related facies were probably deposited during sea-level lowstands related to high-frequency cyclic sedimentation. Anhydrite units coincide with maximum regressions, in some wackestone cycles (see Appendix I: ECR I, 457-475 m, 488-496 m, 515-522 m; NGF, 317-353 m). Laminated Siltstone-Dolostone Facies (laminae) are present, coinciding with the regression of several carbonate dominated cycles (see Appendix I: MBM, 115-122 m, 122-127 m; NGF, 67-100 m, 353-372 m). The same relationship is present with the dolomitized Micritic Facies (see Appendix I: NGF, 0-30 m, 30-62 m; ECR II, 60-76 m; MBM, 1-45 m) that is believed to be laterally equivalent to anhydrite facies (Fig 4.2).

4.3 CYCLE ANALYSIS

4.3.1 Theoretical considerations

Wide variations in the vertical and lateral distribution of idealized cycles are believed to be indicative of shifts in the tectonic evolution of the study area. In other words, the cyclic succession of each section can be used as a strip-chart that monitored its subsidence history. This hypothesis is based on the generally accepted idea that Late Paleozoic high-frequency cycles are of glacio-eustatic origin. The occurrence of major ice sheets in the southern hemisphere and the contemporary development of high-frequency cycles in all continent of the world from setting ranging from fluvial to strictly marine are well-documented (see Wilson, 1975; Heckel, 1984; Busch and Rollins, 1987). Furthermore, the amplitude inferred for Late Paleozoic glacio-eustatic

fluctuations appears to be of the same magnitude to that seen in the Pleistocene (Pitman and Golovchenko, 1983).

The strip-chart hypothesis is based on three fundamental premises: 1) glacio-eustatic fluctuations are of relatively constant periodicity; 2) glacio-eustatic fluctuations are of relatively constant amplitude; 3) sediment supply was sufficiently high to fill the available space (accommodation) in the basin. The strip-chart concept is depicted in Figure 4.3 which shows different tectonic regimes affecting the accumulation of high-frequency cycles. A passive subsidence regime (Fig. 4.3A) will theoretically result in the accumulation of cycles of relatively constant thickness and composition in any given section. Furthermore, such cycles will be correlatable across the depositional gradient. Conversely, a regime of rifting and fault-controlled subsidence would result in the accumulation of cycles of different thickness and composition. In addition, parts of the succession may be missing making individual cycles almost impossible to correlate on a regional scale because of coeval uplifts and erosion of fault blocks associated with the rifting (Fig. 4.3B).

In the study area, major differences in cycle thickness and composition were observed throughout the succession (Fig. 4.4). Cycles, however, can be grouped into three broad packages or assemblages, each characterized by an unique style of cyclicity. The lower and upper assemblages comprise cycles of relatively constant composition and thickness whereas the middle assemblage consists of cycles of variable thickness and composition.

Based on the above theoretical considerations; each assemblage is believed to correspond with an episode of sedimentation under an unique tectonic regime. These three approximately time-stratigraphic assemblages, are called Pre-, Syn- and Post-evaporite Assemblages (Fig 4.5).

4.3.2 Pre-evaporite Assemblage

Description

The Pre-evaporite Assemblage is present at East Cape River I, McKinley Bay and North Greely Fiord sections (Fig 4.5a, b) and comprises approximately 9 cycles. The Pre-evaporite Assemblage is made up of cycles of proximal character that are relatively constant in thickness and composition. This style of cyclicity is characterized by constant thickness of depositional cycles that can be easily depicted in well exposed cliffs (Plate 14d) and are well illustrated in Figure 4.4. The basal contact of this assemblage corresponds with the boundary between sequences 2 and 3 of Beauchamp *et al.* (1989a,b) whereas the upper contact is located at the change in cyclicity style with the Syn-evaporite Assemblage (Fig. 14d).

The basal contact with sequence 2 is present in two sections, one within the subbasin (East Cape River I) and the other one outside the subbasin (McKinley Bay). In both sections, the upper part of sequence 2 is characterized by cycles of very constant thickness and composition (Fig.4.4).

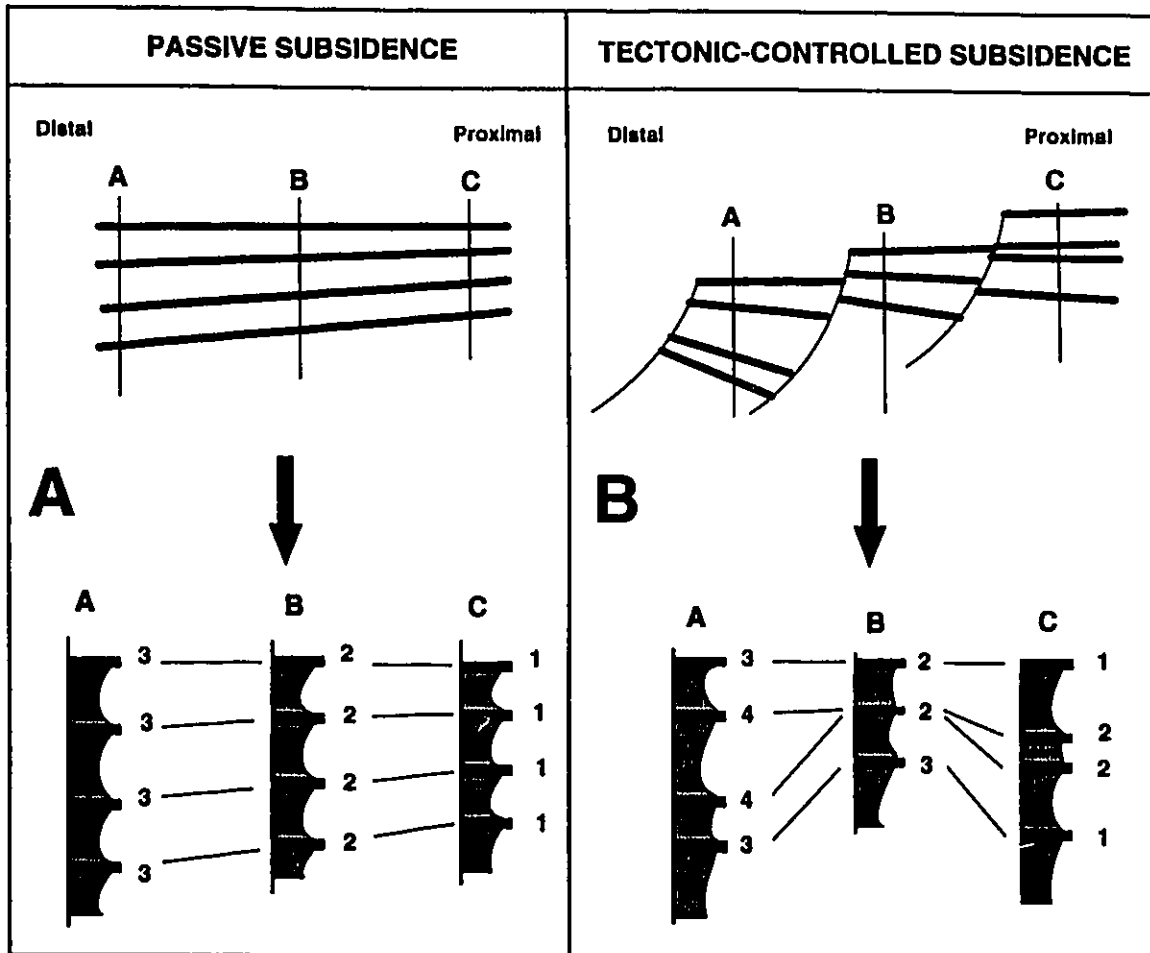


Figure 4.3: Figure showing the strip chart concept in different tectonic regimes. A passive subsidence regime results in the accumulation of cycles of relatively constant thickness and composition. A regime of rifting and fault-controlled subsidence results in accumulation of cycles of different thickness and composition. Numbers beside cycles refer to cycle composition; 1 is proximal and 4 is distal.

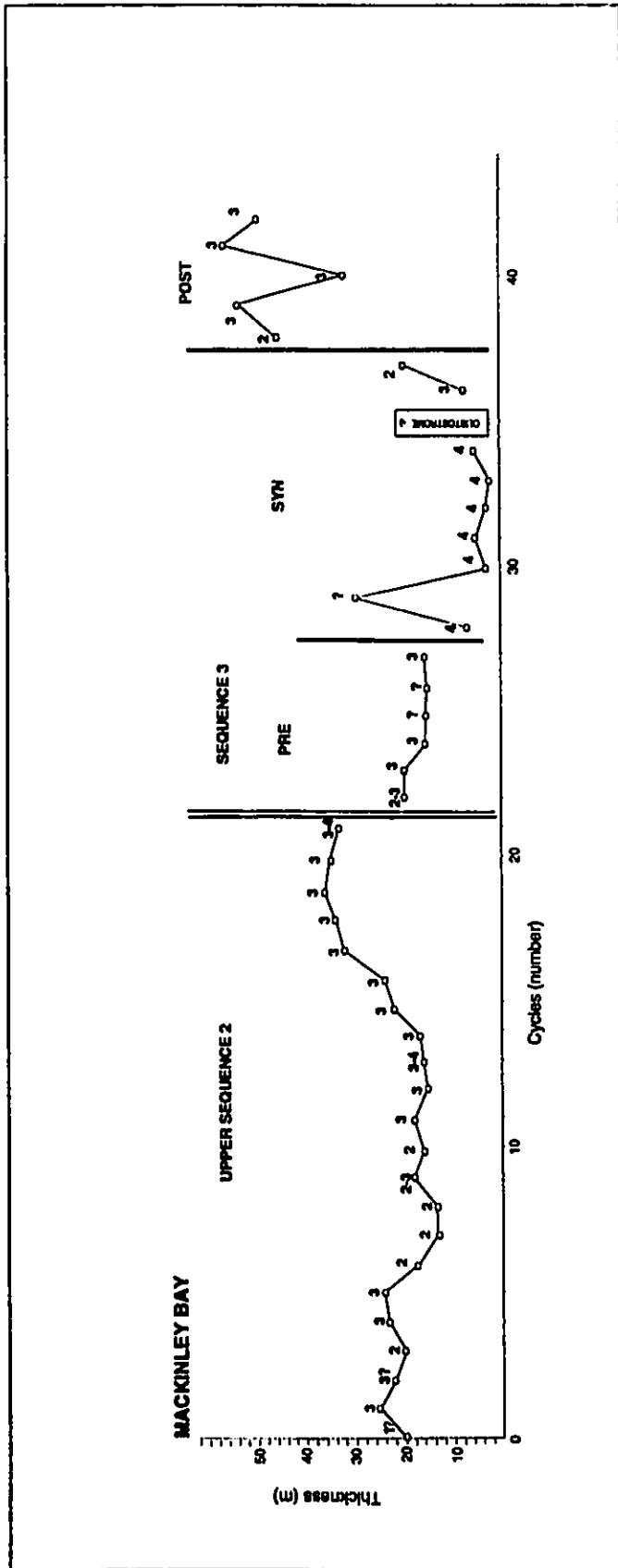
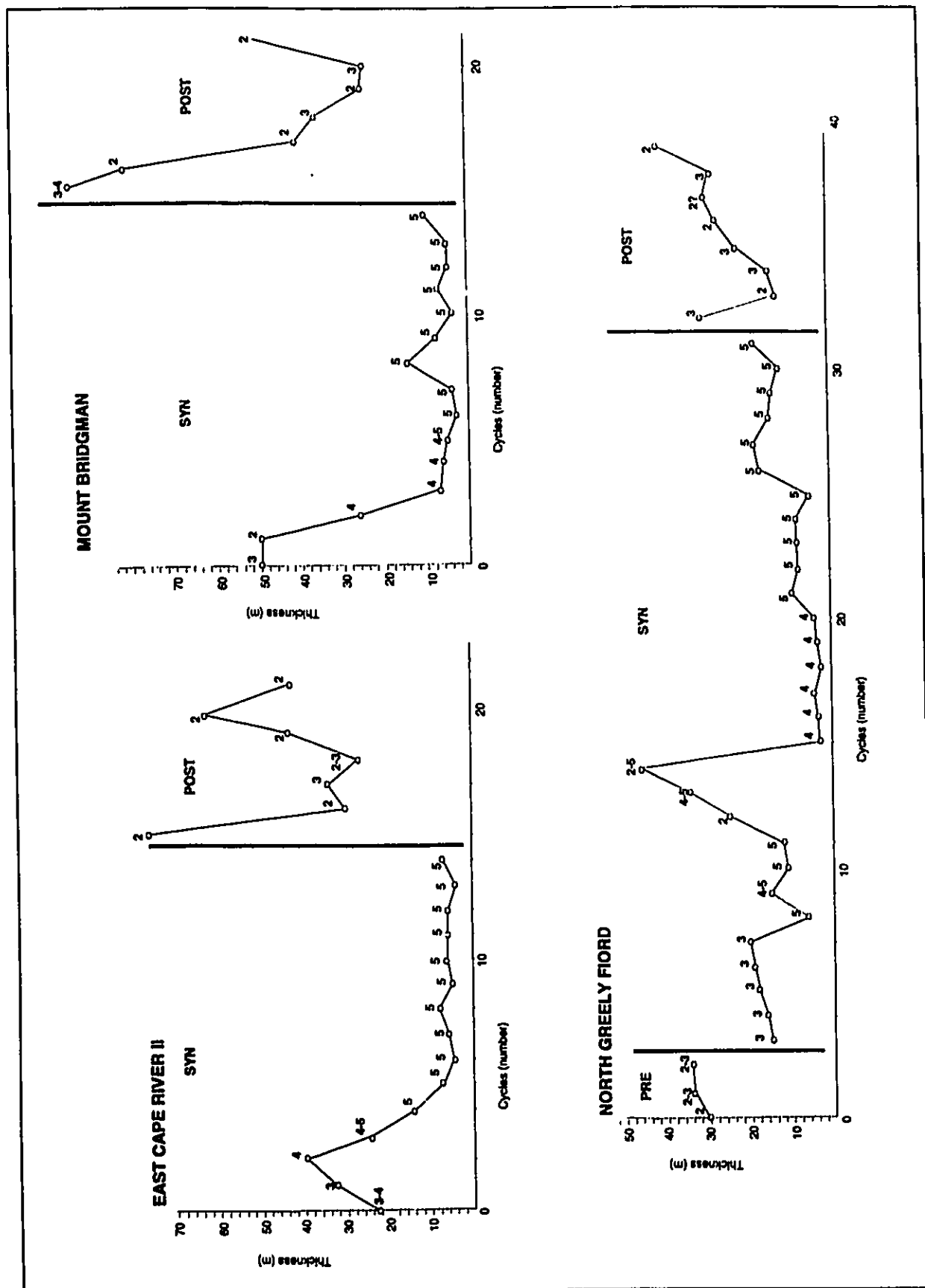
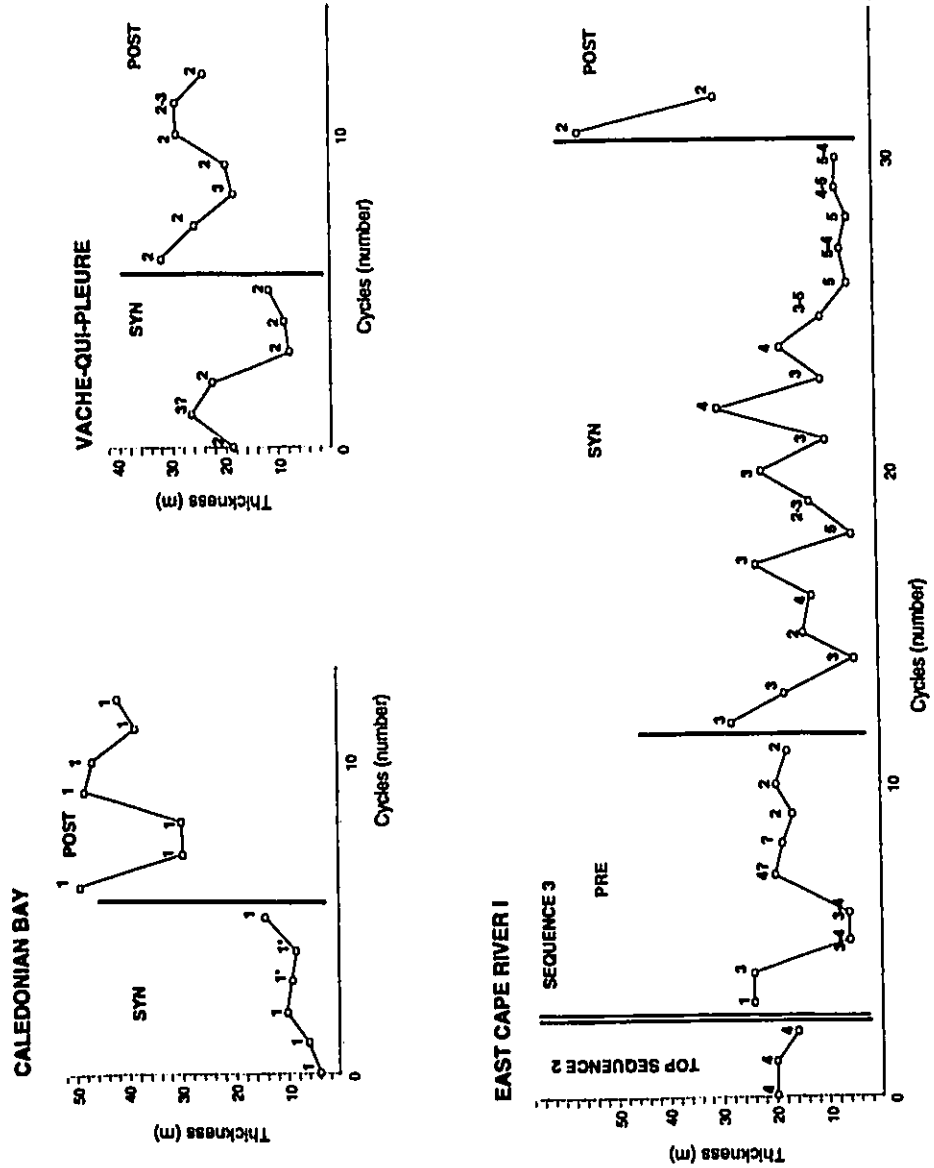


Figure 4.4: Diagram showing a modified histogram (bar chart) of cycles (horizontal axis) plotted against their thickness (vertical axis) for each measured section. Double vertical line is for sequence 2/3 boundary, single vertical line is for distinct boundary between assemblages, and horizontal line with question mark is for approximate limit between assemblages. The diagrams show: 1) that the top of sequence 2 is composed of distal cycles with relatively constant thickness and composition; 2) that the Pre-evaporite Assemblage (PRE) is composed of relatively proximal cycles of similar thickness and composition; 3) that the Syn-evaporite Assemblage (SYN) is composed of cycles of variable composition and thickness; and 4) that the Post-evaporite Assemblage (POST) is composed of cycles of relatively similar composition with a thick shale unit of varying thickness. Cycle compositions are defined by a number corresponding to the Idealized Cycles in Figure 4.1. Cycles with hybrid composition are also distinguished by the use of hyphen as 2-3 for hybrid cycles #2 and #3 and 1* is for Ideal Cycle #1 without carbonate. The diagram is based on cycle thickness, which was measured according to the vertical distance between two consecutive flooding surfaces extrapolated from the relative sea-level curvedata in Appendix I.





These cycles of distal character are overlain by relatively proximal cycles of the Pre-evaporite Assemblage. At McKinley Bay, the boundary is represented by an abrupt change in cycle composition, passing from thick packstone-wackestone-dominated cycles (Idealized Cycles 3-4) to relatively shallow water packstone-dominated cycles (Ideal Cycles 2-3) with significant amounts of siliciclastic material (see Appendix I; MKB, 480-500 m). A similar change in cycle composition is present at East Cape River I (Fig. 4.2) where the cycles change from distal cycles (Idealized Cycles 4) to proximal (Ideal Cycles 1 and 2; see Appendix I, ECR I, 50-70 m). In addition, the siliciclastic input at East Cape River I coincides with the presence of an intraformational orthoconglomerate (Plate 15a).

The upper contact with the Syn-evaporite Assemblage is present at East Cape River I, McKinley Bay and North Greely Fiord. It is characterized by a change from cycles with relatively similar composition and thickness (i.e. Pre-evaporite Assemblage) to cycles with extremely variable compositions and thicknesses (see Syn-evaporite below). The boundary is placed immediately above the last cycle of a relatively constant composition and thickness that is typical of the Pre-evaporite Assemblage. At East Cape River I, the boundary corresponds to a subaerial exposure surface evidenced by the presence of a caliche crust and a massive *Microcodium* bed (see Appendix I; NGF, 112 m). At North Greely Fiord, the contact is located at the first occurrence of thick sandstone bed (see Appendix I: MKB 575 m) which coincides with the disappearance of thick shallow water carbonate-dominated cycles. At McKinley Bay, the boundary is placed at the top of the last thick carbonate cycle that underlies the black to dark gray silty to shaly deep water cycle (see Appendix I; MKB, 575 m).

Two consecutive cycles at East Cape River I (Fig. 4.4), however, differ from typical cycles of the Pre-evaporite Assemblage. These two atypical cycles are relatively thin and distal in character (see Appendix I: ECR I, 110-120 m).

The Pre-evaporite Assemblage is time-stratigraphic. The base of the assemblage corresponds with the limit between sequences 2 and 3 and coincides with the Upper Carboniferous (Ghzelian)-Permian (Asselian) limit (Fig. 4.5a, b). This assemblage encompasses the entire Asselian and its upper boundary corresponds with the Asselian-Sakmarian limit (Fig. 4.5a, b).

4.3.3 Syn-evaporite Assemblage

Description

The Syn-evaporite Assemblage is present in all measured sections and contains approximately 19 cycles. The Syn-evaporite Assemblage is characterized by cycles with important variations in thickness and composition (Fig. 4.4) within and outside the Fosheim-Hamilton subbasin and by the occurrence of relatively deep shelf anhydrite cycles within the subbasin (Plate 15b). The vertical variations in cycle thickness and composition (i. e. referred also as their

stacking pattern) are inconsistent from section to section. In general, these cycles are relatively more distal than those of the Pre-evaporite Assemblage boundary (Fig. 4.4).

The lower boundary of the Syn-evaporite Assemblage (Fig. 4.5a, b) is located at the top of the last cycles of the Pre-evaporite Assemblage (see above Pre-evaporite Assemblage). The upper boundary of the Syn-evaporite Assemblage with the Post-evaporite Assemblage corresponds to the top of the Mount Bayley Formation that is believed to be synchronous throughout the Fosheim-Hamilton subbasin (Wallace and Beauchamp, 1990). In sections that are lacking anhydrites of the Mount Bayley Formation, the upper boundary is located by a sudden change in the style of cyclicity. This drastic change is characterized by the appearance of thick cycles with relatively constant thickness and composition and with common occurrence of green mudstone in their recessive part. The same drastic change in the cyclicity style is observed within the Post-evaporite Assemblage cycles when the Mount Bayley Formation is present. These cycles, forming the Tanquary Formation are composed of a resistant carbonate unit that is relatively constant in composition and thickness (the first cycle is always very thick, see Figure 4.4) and the recessive part is composed of variable thickness of green calcareous mudstone unit. The upper boundary at Caledonian Bay is positioned at the top of cycles with important amount of red shale (see Appendix I; CDB, 60 m) overlain by 1 m thick green shale unit and by relatively thick mixed carbonate-siliciclastic cycles. At McKinley Bay, the upper boundary is located at the base of the first very thick cycle (see Appendix I; MKB, 685 m).

In sections perpendicular to the facies belts (Fig. 4.5a), there is a general SE-NW trend over 50 km from relatively deep shelf carbonate to shallow shelf carbonate cycles from East Cape River II to Caledonian Bay, in association with a general increase of siliciclastic material and disappearance of subaqueous evaporite. These trends are also showing that the siliciclastic-dominated cycles are only present at the basin margin and the anhydrite cycles are restricted to the deep central subbasin. The anhydrite cycles are very thick at East Cape River II, thin and interdigitated with carbonates at East Cape River I and absent at Vache-qui-pleure. In sections parallel to the facies belts (Fig. 4.5b), the anhydrite units in these cycles appear to be thinner in a south-west direction away from North Greely Fiord. In addition, anhydrite and related facies beds are present in most cycles of the Syn-evaporite Assemblage at North Greely Fiord as opposed to the southwestern sections. The Syn-evaporite Assemblage at McKinley Bay is characterized by several thin cycles of relatively deep water carbonate cycles with black silt and shale and by a thick olistostrome unit. The occurrence of gypsum pseudomorphs within the Micritic Facies at the base of the assemblage at North Greely Fiord suggests that a Syn-evaporite Assemblage entirely composed of anhydrite could exist in subsurface in this part of the subbasin.

In addition to the occurrence of subaqueous anhydrite and large variations in cycle thickness and composition, the Syn-evaporite Assemblage contains peculiar features including

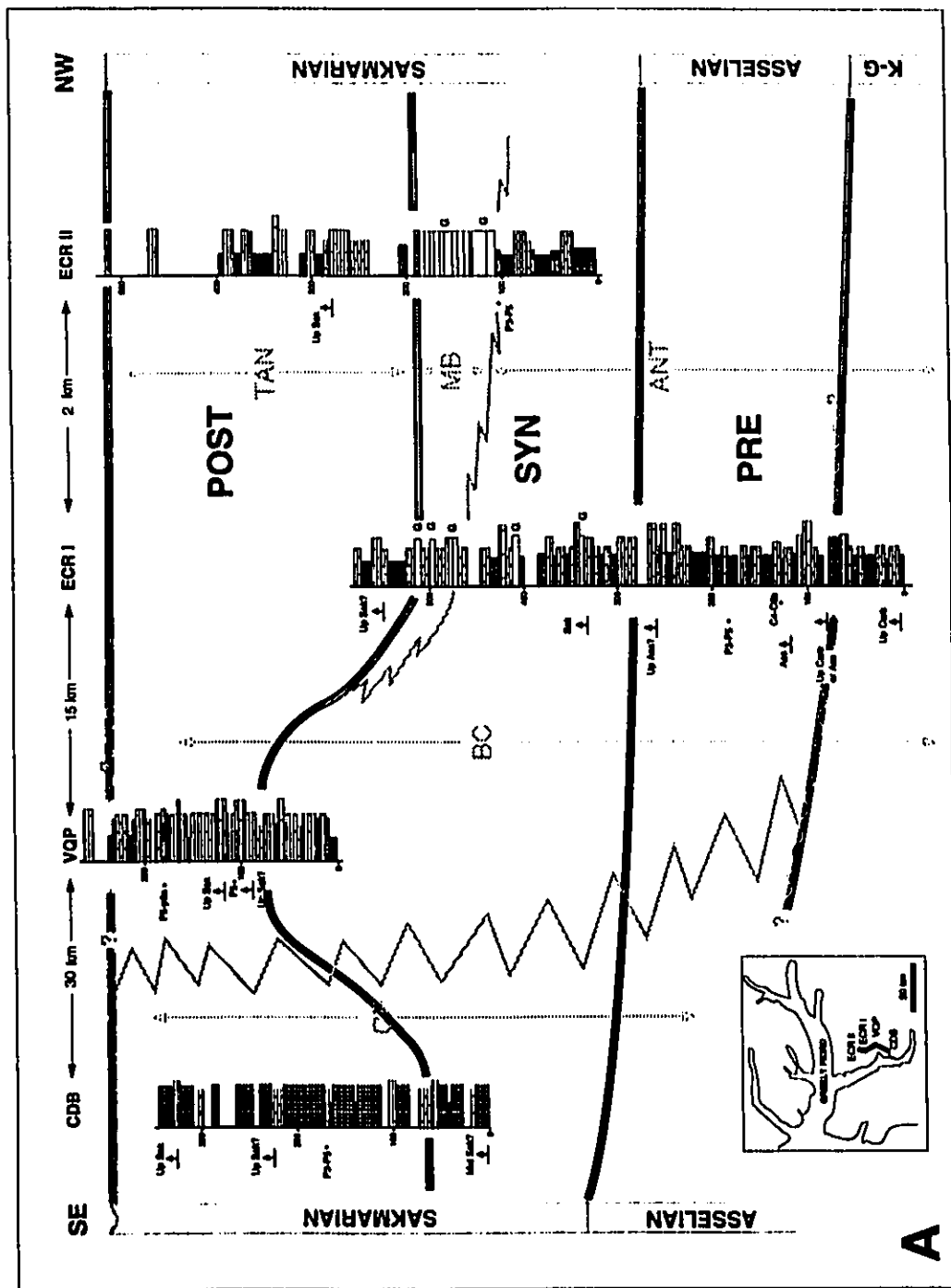
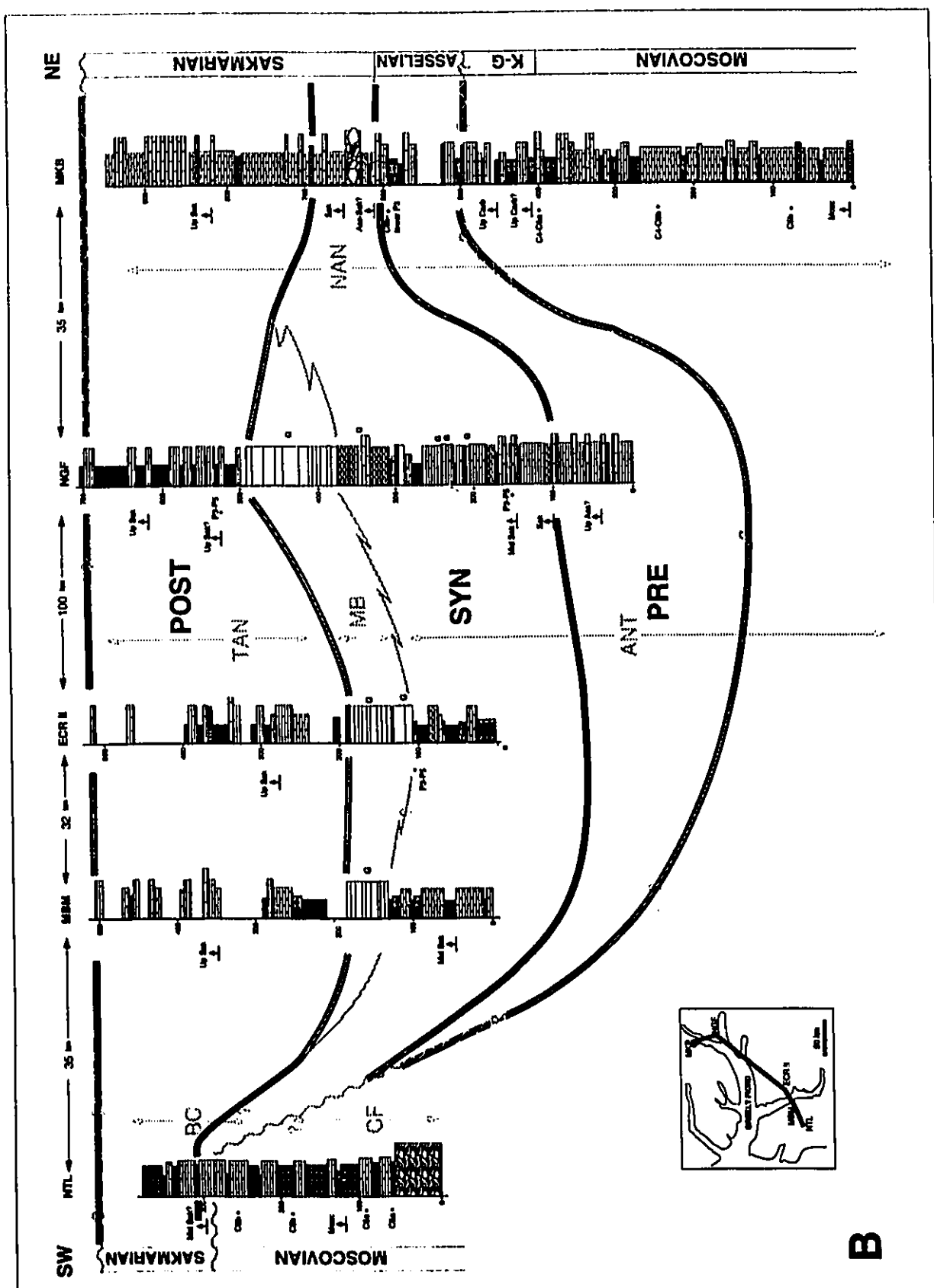


Figure 4.5: Diagram showing the subdivision of sequence 3 of Beauchamp (1989a,b) into three time-stratigraphic assemblages. Pre-, Syn-, and Post-evaporite Assemblages. Each of these assemblages are characterized by different styles of cyclicity and interpreted as having been deposited during different tectonic regimes. (See Figure 2.1 a, b for data on correlation surfaces). Diagram A shows sections oriented perpendicular to the general facies belt, whereas B shows sections parallel to the facies belt. The formation names are Canyon Fiord (CF), Belcher Channel (BC), Antoinette (ANT), Mount Bayley (MB), Tanquary (TAN), and Nansen (NAN). The section names are Caledonian Bay (CDB), Vache-qui-pleure (VQP), East Cape River (ECR I), East Cape River II (ECR II), Notch Lake (NTL), Mount Bridgman (MBM), North Greely Fiord (NGF) and McKinley Bay (MKB). G = gypsum occurrence (lithological symbols see legend in Appendix D).



subaerial exposure surfaces (*Microcodium*, caliches), syn-sedimentary faults, and a thick olistostrome.

Subaerial exposure is indicated by the occurrence of *Microcodium* and caliche coinciding with maximum regression level in some cycles. *Microcodium* consists of sub-millimetric polygonal plates of yellowish sparite, assembled in petal-like circles and forming undulating cylinders (Plate 15c and d). *Microcodium* are relatively scarce but locally massive comprising up to 80% of the host facies. *Microcodium* is interpreted as a calcified mycorrhizae (Klappa, 1978) but other origins have been proposed (Beauchamp, pers. comm.). Caliche are present in two sections (see Appendix I; ECR I, 234 m; CDB, 16 m) and represent prolong subaerial exposition (Esteban and Klappa, 1983). The localized occurrence of caliche and *Microcodium*, however, suggests a tectonic control for subaerial exposition in order to explain the patchy distribution of these features.

Syn-sedimentary faults are common in the Syn-evaporite Assemblage and present at Mount Bridgman, North Greely Fiord (Plate 16b) and McKinley Bay sections, as well as at an unmeasured Mount Bayley Formation section in the Fosheim Peninsula (Plate 16c).

The olistostrome at McKinley Bay section is a 30 meter thick unit with angular fragments in a quartz silt-dominated matrix. These fragments are mainly pebble to cobble size (Plate 16a) but range from sand-sized up to 5 m in diameter. The larger blocks show contorted bedding and matrix injection indicative of their unlithified nature at the time of deposition.

The Syn-evaporite Assemblage is a time-stratigraphic unit. The lower contact with the Pre-evaporite Assemblage coincides with the Asselian-Sakmarian boundary (Fig. 4.5). The upper contact with the Post-evaporite Assemblage corresponds with the limit between Mid and Late Sakmarian time.

Gypsum accumulation

Accepted models for deep water gypsum accumulation (Schmalz, 1969; Kendall, 1984) imply a semi-restricted basin separated from the main open ocean by a positive structure. This model implies that the gypsum crystals precipitated at the surface of the water, subsequently sank, and partially dissolved within the water column, and finally accumulated on the sea floor when the salt concentration (pycnocline) was very high. The density of the pycnocline (1.25 g/cm^3) keeps the undissolved gypsum crystals only within the subbasin deep areas. The gypsum crystals deposited above the pycnocline and reworked by waves and currents and possibly dissolved. This model suggests also that the accumulation of gypsum starts first and is greater in areas relatively far from the connection with the main open ocean.

The above model explains the major depositional features present in the Mount Bayley Formation. The gypsum (now anhydrite) within the Fosheim-Hamilton subbasin occurs in central sections and was deposited in a relatively deep water setting based on presence of parallel laminated anhydrite beds and associated deep shelf carbonate facies (i.e. Micritic Facies). The

thickness variation and the thinning of the anhydrite deposits from north-east to south-west also suggest that the connection of the subbasin with the main open ocean (Sverdrup sea) was located in its southwestern part of the subbasin. This model explains also the occurrence of common anhydrite crystals in deep water carbonate facies (e.g. Micritic Facies). The Elmerson High was possibly this positive topographic high restricting water circulation during deposition of the Syn-evaporite Assemblage. Areas with extensional tectonic regime are commonly characterized by large local uplift, 10-20 km wide, extending over many tens of kilometers (King and Ellis, 1990). These uplifts are an isostatic response to half-graben collapse. Similar basin collapse has been recognized in sequences of the same age in Raanes Peninsula (Beauchamp, 1987).

The nature of the carbonate and evaporite depositional systems are usually different and mutually exclusive but this common association of mixed carbonate-evaporite in cyclic sequences is best explained by reciprocal sedimentation regime (Wilson, 1975). Reciprocal sedimentation implies the existence of a relatively shallow connection of an isolated subbasin with the open ocean separated by a positive structure. Carbonates are deposited during a period of sea-level highstand while the evaporite precipitation occurs when the sea-level is low enough to allow water restriction in the subbasin. This model is directly applicable to the evaporite sequence in the Fosheim-Hamilton Subbasin where anhydrite and related facies are interbedded with relatively thick carbonate units. The vadose effect on exposed carbonate sediment is minimum because of the arid to semi-arid climate and because of the short exposure time implied for each very high-frequency cycles (see interpretation of gypsum cycles below).

As proposed above, the evaporite precipitation is function of relative sea-level oscillations. The number of cycles present in the Syn-evaporite Assemblage is different from section to section. The North Greely Fiord and East Cape River I sections are characterized by 29 and 19 cycles respectively. This difference is largely explained by the number of anhydrite cycles (Ideal Cycle #5) and laterally equivalent cycles (Ideal Cycle #4 with abundant Laminated Siltstone-Dolostone Facies) at North Greely Fiord section (Fig 4.2), given that the East Cape River I section is dominated by carbonate and minor anhydrite situated within carbonate cycles. The large number of anhydrite cycles (Ideal Cycle #5) is explained by the high accumulation rate up to 3-4 m/ 1000 years: about 10 times faster than shallow subtidal shelf carbonates (Schreiber, 1978). This rapid accumulation rate was in operation when the salinity was high enough, therefore, evaporite system was extremely sensitive to relative sea-level variations controlled by higher frequency sea-level fluctuations.

4.3.4 Post-evaporite Assemblage

Description

The Post-evaporite Assemblage is present in all measured sections (Fig. 4.5) and comprises 7 or 8 cycles. The Post-evaporite Assemblage is characterized by relatively thick cycles with basal shale units of varying thickness and with thin middle units of shallow shelf carbonate with constant thickness (Plate 16d). The basal contact of the Post-evaporite Assemblage with the Syn-evaporite Assemblage is characterized by a change in cyclicity style coeval with the end of evaporite accumulation in the subbasin (see upper contact of Syn-evaporite Assemblage). The upper limit of the Post-evaporite corresponds with the boundary between sequences 3 and 4 (Fig. 4.5).

Depositional cycles of the Post-evaporite Assemblage are characterized and easily recognized by a cyclicity style with thin ledge-forming resistant carbonate units alternating with recessive shale-dominated units of various thickness. The resistant carbonate unit is composed either of Grainstone-Palaeoplysiniid cycles (#2) or Packstone-Phylloid cycles (#3) characterized by a relatively important amount of siliciclastic material. Variations in cycle thickness are important in the Post-evaporite Assemblage (Fig. 4.4), however, these differences are mostly related to shale thickness. Shale units are thicker (up to 50 m) immediately above the anhydrite cycles of the Syn-evaporite Assemblage in central sections at Mount Bridgman, East Cape River II, East Cape River I and North Greely Fiord (Fig. 4.2), but thinner or even absent in marginal sections at Vache-quipleure, Caledonian Bay and Notch Lake (see Appendix I). Cycles in subbasin central sections at Mount Bridgman and East Cape River II are composed of thick shale unit changing gradually upward into siltstone to fine sandstone capped by carbonate unit. The Mount Bridgman section shows some evidence of slump scars of more than 300 m large and 80 m deep within the recessive shaly unit (Plate 16d). Subbasin marginal sections at Caledonian Bay and Notch Lake are characterized by the occurrence of thick basal sandstone unit overlain by thin shallow shelf carbonate unit. At McKinley Bay, the shale is relatively rare but the carbonate-dominated portion of these cycles are thicker.

The Post-evaporite Assemblage is also time-stratigraphic. The lower contact corresponds with the limit between Mid and Late Sakmarian time (Fig. 4.5). This assemblage encompasses the Upper Sakmarian and its upper contact coincides with the boundary between sequences 3 and 4 which separates Sakmarian from Artinskian strata in the study area.

4.4 TECTONIC REGIMES

UPPER SEQUENCE 2

The upper part of sequence 2, within and outside the subbasin, is composed of distal cycles that show constant thickness and composition. This regularity in the stacking pattern of cycles suggests a passive subsidence regime. The mechanisms responsible for high-frequency relative sea-level changes were probably dominated by glacio-eustatic variations.

PRE-EVAPORITE

The pre-evaporite is characterized by proximal cycles of relatively constant thickness and composition. The base of this assemblage is rich in siliciclastic and unconformably overlying sequence 2 within the subbasin at East Cape River I and outside of the subbasin at McKinley Bay. The nature of the boundary with sequence 2 and the sudden cycles change (i.e. from proximal to distal) within and outside the subbasin are indicative of an abrupt and important relative sea-level drop during the early stage of the Pre-evaporite Assemblage. A tectonic origin for this abrupt sea-level drop (i.e. tectonic uplift) is favoured because this drop was certainly greater than 100 m*. In addition, the tectonic origin of this relative sea-level drop is evidenced by the occurrence of 29 cycles within the Asselian strata of Raanes Peninsula (Beauchamp, 1987) whereas in the study area only 9 similar cycles are present. This suggests that the Fosheim and Hamilton peninsulas area stayed "uplifted" during a large portion of the Asselian time. The late stage of the Pre-evaporite Assemblage shows a cyclicity style characterized by relatively regular cycles (composition and thickness) suggesting that the relative sea-level changes were controlled by glacio-eustatic variations. Using the strip-chart approach, the tectonic regime is one of passive subsidence with localized tectonic activity. The local fault-controlled tectonic is evidenced at East Cape River I by the isolated occurrence of two thin distal cycles (Fig. 4.4) indicative of a rapid local relative sea-level rise. At McKinley Bay, the cycles are constant throughout the Pre-evaporite Assemblage indicating a more stable setting.

SYN-EVAPORITE

Depositional cycles of the Syn-evaporite Assemblage are characterized by both variable thickness and composition (Fig. 4.5). The Syn-evaporite displays evidence of relatively important tectonic activity. Fault-controlled subsidence is indicated by the variations in the cycle stacking pattern, by the occurrence of a deep subbasin, local subaerial exposure surfaces, syn-sedimentary

* The minimum amount of relative sea-level drop is interpreted from East Cape River I section, where the cycles pass from very distal wackestone (Bryozoan Facies)-dominated cycles (ideal cycle 4) accumulating below the limit of photic zone, to very shallow sandstone and grainstone (Bioclastic Facies)-dominated cycles (ideal cycle 1) accumulating in shallow nearshore.

faults and an olistostrome at McKinley Bay section. The stacking pattern of cycles varies within each section and from section to section. The development of the subbasin is evidenced by the occurrence of deep water anhydrite associated with distal cycles; this subbasin must have been restricted by a topographic high in order to accumulate a thick gypsum succession. The occurrence of localized subaerial exposure surfaces suggests that the subbasin was subdivided into several fault blocks with differential subsidence. The occurrence of different fault blocks are also evidenced by the presence of syn-sedimentary faults. The presence of a thick olistostrome indicates that tectonic activity was also important outside of the subbasin. The syn-evaporite is interpreted as an active rifting period during which the mechanisms responsible for the relative high-frequency sea-level changes were dominated by fault-controlled subsidence superimposed on a background of glacio-eustatic variations.

POST-EVAPORITE

The Post-evaporite Assemblage is characterized by a constant number of relatively thick cycles made up of thick shale units of variable thickness alternating with thin shallow shelf carbonate units of constant thickness (Fig. 4.5). The constant number of cycles and the relatively similar composition and thickness (at least for carbonate units) suggest a regime of passive subsidence.

There is an substantial increase in siliciclastic influx within the Post-evaporite Assemblage with respect to the other assemblages, as shown by thick recessive shaly units and by the relatively important siliciclastic material within carbonate units. The occurrence of a deltaic complex is suggested: 1) by the composition of basal recessive units passing from shale to siltstone and finally to fine sandstone toward the top of each cycle; 2) by the thick subbasin central mud deposits and thinning laterally equivalent sandstones in basin margin section, and 3) by the presence of large slump scars. Slump scars are very common in uncompacted unstable prodeltaic muds (Elliott, 1978). A deltaic complex located in the Caledonian Bay area is proposed for younger strata of sequence 4 (Scott, 1991) as well as for Triassic strata (J. Devaney, pers. comm.). In addition, Scott (1991) suggested that another delta was probably present in the northeastern part. The increase in siliciclastics is explained by a change in tectonic regime or by a climatic change. There is no direct evidence for active tectonic activity during the Post-evaporite Assemblage and the only evidence for climatic change is at the top of the Tanquary Formation with the occurrence of rare vadose silts indicative of more humid climate (Beauchamp, 1987). A climatic change in the source area in the southern part of the continent, however, cannot be ruled out.

The thickness variations in the recessive shale units from cycle to cycle within this assemblage is probably related to the occurrence of delta lobes on which were developed the

relatively shallow water carbonate units. The mechanisms behind relative high-frequency sea-level changes during the Post-evaporite Assemblage were controlled by glacio-eustatic fluctuations with the local but important influence of siliciclastic influx.

4.5 PALEOGEOGRAPHIC AND TECTONIC EVOLUTION

UPPER SEQUENCE 2

The upper part of sequence 2 represents a period of passive subsidence which records the development of a stable carbonate platform over the study area (Fig. 4.6A). This platform was similar to the idealized carbonate shelf of Figure 3.2 but with siliciclastics deposits at the basin margin. On this shelf relative sea-level changes of glacio-eustatic origin controlled the development of distal depositional cycles. There is no evidence for the existence of the Elmerson High and therefore for the existence of the Fosheim-Hamilton subbasin.

PRE-EVAPORITE

The early stage of the Pre-evaporite Assemblage was characterized by a major regional uplift of the previously stable platform (Fig. 4.6B). The later stage of this assemblage was one of passive subsidence regime with some evidence of local block movements (Fig. 4.6C). The depositional cycles deposited during this stage were generally proximal in character and rich in siliciclastics at the base. There was still no evidence for the existence of the Elmerson high and for the Fosheim-Hamilton subbasin at that time.

SYN-EVAPORITE

The Syn-evaporite Assemblage represents the differential collapse of the previously uplifted platform. As mentioned earlier this collapse in the Fosheim-Hamilton subbasin is evidenced by the occurrence of important thickness variations in cycles, by syn-sedimentary faults, by the presence of deep water anhydrite facies, and by localized subaerial exposure surfaces. The area north of the subbasin was also affected by the same collapse, where distal carbonate cycles and associated thick olistostrome unit were deposited. The Fosheim-Hamilton subbasin was probably isolated at that time by the active Elmerson tectonic High concomitant with subbasin collapse. Except for periods of extreme sea-level lowstand (highstand mode of Fig. 4.6D) the subbasin was characterized by deposition of a complex pattern of carbonate-dominated facies. During periods of extreme sea-level lowstand the Elmerson High acted as a barrier and restricted water circulation allowing the evaporite deposition in deepest part of the subbasin. In other parts of the shelf sediments were briefly subaerially exposed or were located over the pycnoline (gypsum preservation). The water exchange area was probably located in the northwestern part of the subbasin as suggested by the location of the anhydrite depocentre in the opposite northeastern area.

Figure 4.6: Paleogeographic and tectonic evolution of the Fosheim-Hamilton subbasin from the upper sequence 2 to lower sequence 4. Cross-sections are roughly in south-north orientation from the south margin the Fosheim-Hamilton subbasin through the Elmerson High area and further north toward the main Sverdrup Basin.

A) Cross-section represents the upper part of the sequence 2 that is characterized by distal cycles (Idealized Cycles 3 and 4) with relatively constant thickness and composition associated with a passive thermal subsidence regime. There is no evidence for the existence of the Elmerson High at that time.

B) Cross-section represents the early stage of the Pre-evaporite Assemblage of sequence 3 that started with an abrupt platform uplift. The tectonic uplift is evidenced by the major unconformity at the base of the sequence 3 and by the relatively small number of cycles present within the Asslian strata in the study area.

C) Cross-section represents the late stage of the Pre-evaporite Assemblage of sequence 3 that is characterized by a passive subsidence with evidence of local tectonic activity. This assemblage is mainly characterized by proximal cycles of relatively constant thickness.

D) Cross-section represents the Syn-evaporite Assemblage of sequence 3 interpreted as the differential collapse of the previously uplifted platform. Uplifting of the Elmerson High was probably concomitant with the Fosheim-Hamilton subbasin collapse. This assemblage is characterized by cycles with important lateral and vertical variations in thickness and composition suggesting that local fault-controlled tectonic subsidence. The presence of thick subaqueous gypsum units shows that the Fosheim-Hamilton subbasin was periodically isolated from the open ocean.

Periods of sea-level high stand in the Fosheim-Hamilton subbasin was characterized by the deposition of a complex pattern of cycles ranging from proximal to distal. During periods of sea-level lowstand the Elmerson High was restricting the water circulation and gypsum was deposited in deepest parts of the subbasin (grey area). The water exchange area was probably located in the northwestern part of the subbasin as suggested by the occurrence of gypsum mainly in opposite northeastern portion.

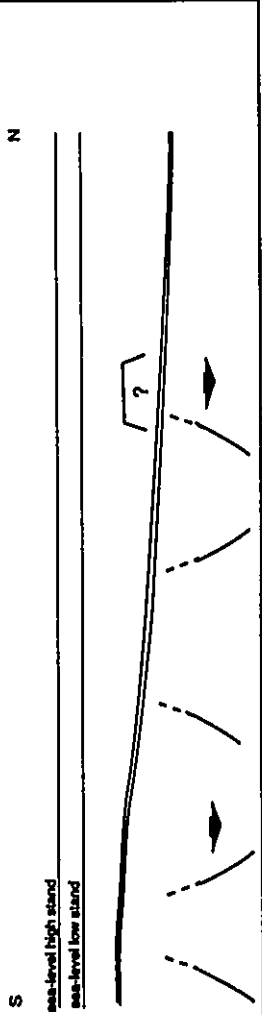
E) Cross-section represents the Post-evaporite Assemblage of sequence 3 interpreted as a change from localized platform collapse to regional passive thermal regime. This assemblage is characterized by a marked increase in siliciclastic influx mainly from the southwestern part of the subbasin. The depositional cycles are composed of thick shale units (thick in central sections but thinner in marginal sections) of deltaic origin and deposited during sea-level high-stand. During periods of sea-level lowstand a carbonate unit (black area) was deposited throughout the subbasin.

F) Cross-section represents the lower part of sequence 4. The lower part of sequence 4 is interpreted as tectonically active by Scott (1991) but best described as a rapid platform tilt (Fig. 4.6E).

A UPPER SEQUENCE 2

UPPER CARBONIFEROUS (KASIMOVIAN AND GZELIAN)

PASSIVE SUBSIDENCE



B SEQUENCE 3 PRE-EVAPORITE ASSEMBLAGE

EARLY ASSELIAN TO LATE ? ASSELIAN

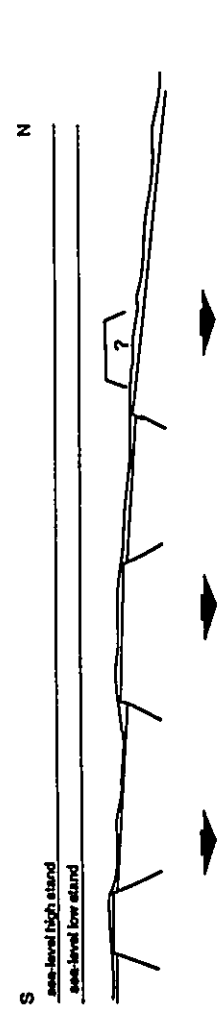
EARLY STAGE- UPLIFT



C SEQUENCE 3 PRE-EVAPORITE ASSEMBLAGE

LATE ? ASSELIAN

LATE STAGE- PASSIVE SUBSIDENCE

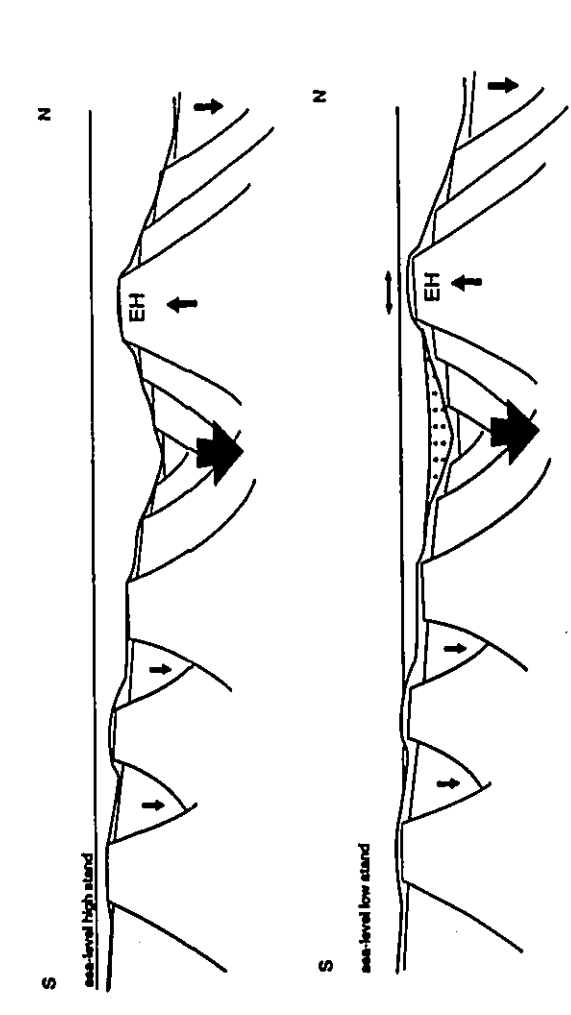


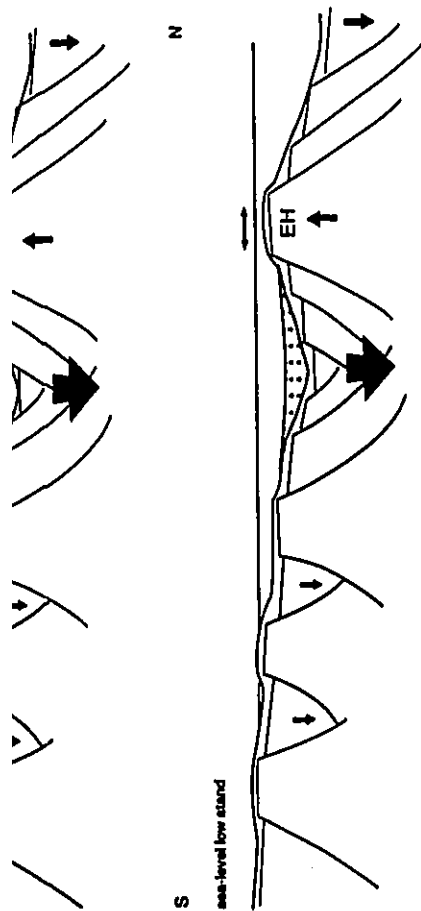
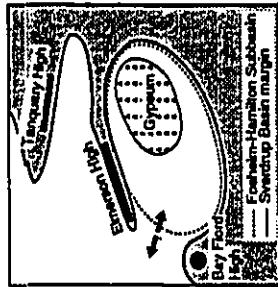
PASSIVE REGIONAL SUBSIDENCE WITH LOCAL BLOCK MOVEMENTS

D SEQUENCE 3 SYN-EVAPORITE ASSEMBLAGE

EARLY TO MIDDLE SAKMARIAN

RIFTING REGIONAL COLLAPSE WIDESPREAD BLOCK MOVEMENTS

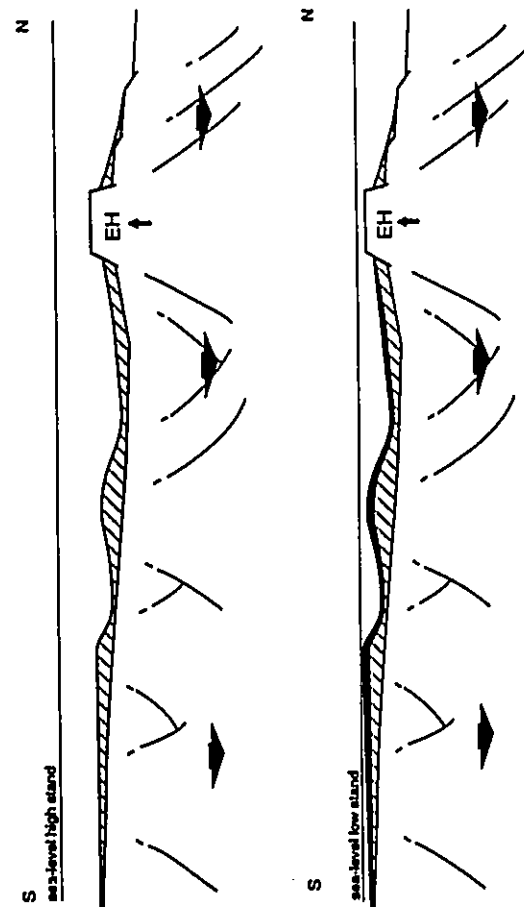
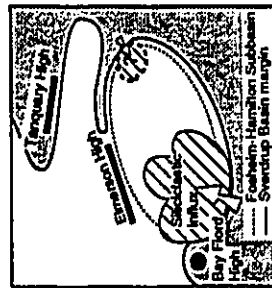




E SEQUENCE 3 POST-EVAPORITE ASSEMBLAGE

LATE SAKMARIAN

PASSIVE SUBSIDENCE



F LOWER SEQUENCE 4

EARLY ARTINSKIAN

UPLIFT PLATFORM TILT



POST-EVAPORITE

The Post-evaporite Assemblage was a period of passive subsidence regime following the platform collapse. The Post-evaporite Assemblage is characterized by large amounts of siliciclastic deposits. This siliciclastic material was deltaic in origin with a depocentre most likely located in the southwestern part of the subbasin (Fig. 4.6E). A second, localized delta was possibly situated in the northeast as suggested by the occurrence of common relatively coarse siliciclastic material in North Greely Fiord. Outside the subbasin, between Tanquary and Elmerson highs, the sedimentation was dominated by carbonate deposition with relatively rare siliciclastics.

During sea-level highstand, the subbasin was partially filled with siliciclastic mud prior to carbonate sedimentation. The variation in shale thickness is probably related to delta lobe location. This is evidenced by the large amount of shale and siltstone in subbasin central sections and by the occurrence of sandstone at the basin margin sections (NTL and CDB sections). During sea-level lowstand, carbonate sedimentation took over with widespread deposition of relatively shallow shelf facies throughout the entire subbasin.

LOWER SEQUENCE 4

The lower part of the Artinskian sequence 4 unconformably overlies sequence 3. The nature of this boundary differs from place to place ranging from angular unconformity, to disconformity missing complete fossils zones to conformable contact. The lower part of sequence 4 is interpreted as tectonically active by Scott (1991) but best described as a rapid tilt (Fig. 4.6F) of the platform (B. Beauchamp pers. comm.)

4.6 TECTONIC MODEL OF THIRD-ORDER SEQUENCE

The Pre-, Syn- and Post-evaporite assemblages represent three successive tectonic regimes corresponding to uplift, collapse and passive subsidence, respectively. This succession is most likely reflecting the behavior of a rifting event starting with an abrupt uplift of the rifting area, followed by a passive subsidence, its collapse and eventually by a passive thermal subsidence, that all encompass a third-order depositional sequence (*sensu* Beauchamp *et al*, 1989 a,b).

The relationship between third-order sequence and initial rift pulse of the sequence 3 is also present in sequence 2. The two sequences are quite similar in terms of occurrence of subaqueous evaporites at the base of each sequence and of similar stacking pattern of high-frequency cycles; especially at McKinley Bay and Notch Lake sections where measured Carboniferous strata can be interpreted following the present strip-chart approach. The Notch Lake section has a stratigraphic range from Upper Bashkirian to Early Moscovian and the McKinley Bay section from Early Moscovian to Sakmarian. These two sections if joined encompass most of sequence 2 (Fig. 4.7). The base of Notch Lake section is composed of a thick cobble to pebble red conglomerate similar

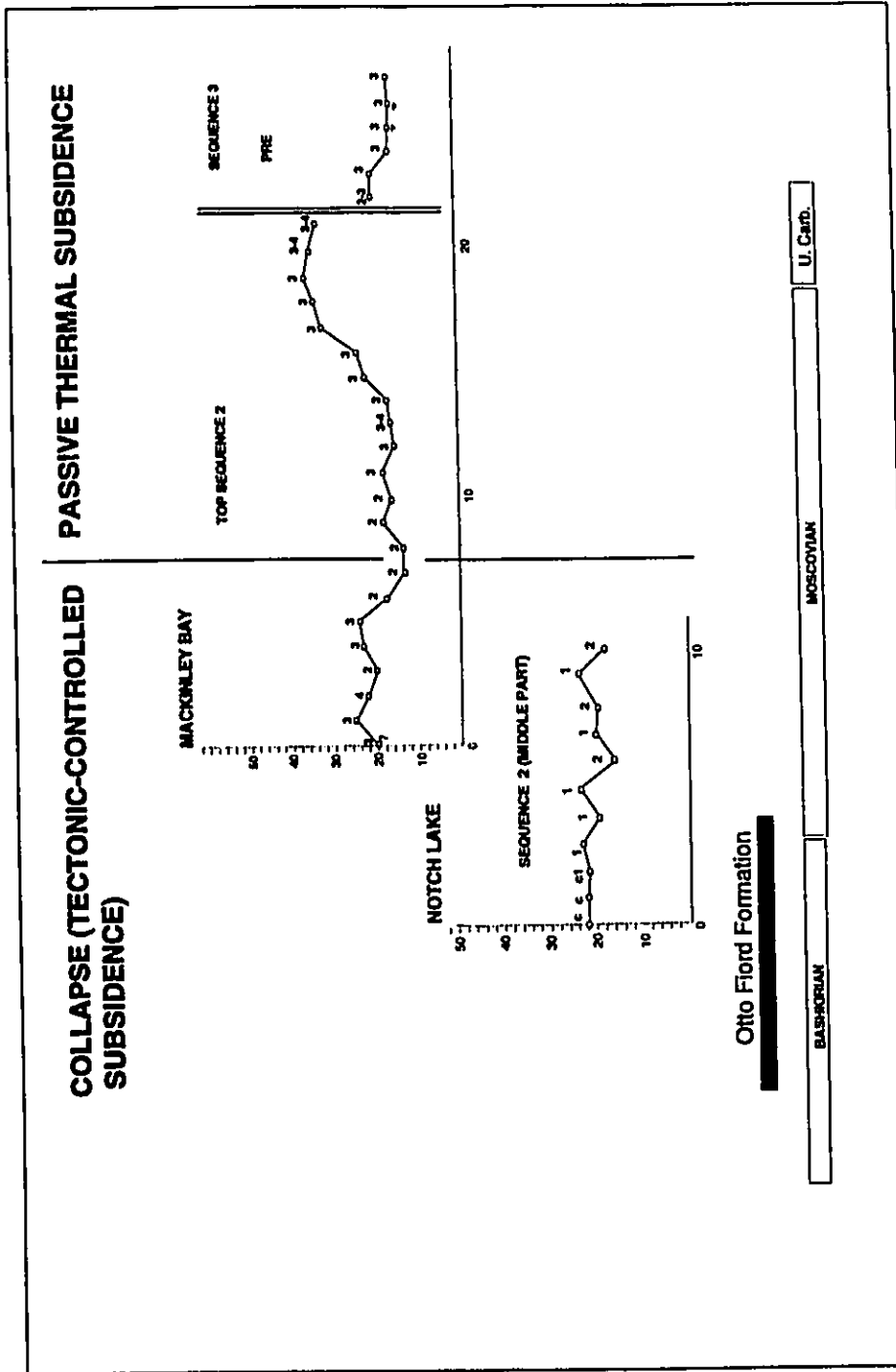


Figure 4.7: Temporal relationship between modified cycle histogram and main sedimentologic features of sequence 2. The diagram shows temporal similarities between collapse and passive thermal subsidence interpreted from cycle histogram of measured sections (McKinley Bay and Notch Lake sections) and stratigraphic position of Otto Fiord Formation. The base of the Notch Lake section is composed of thick continental conglomerate (C in diagram) of syn-tectonic origin. The variations in thickness and composition of the upper part of the Notch Lake section suggests a fault controlled subsidence. The base of McKinley Bay section is characterized by cycles of variable composition and thickness with a relatively large amount of siliclastic material, under tectonic controlled subsidence. The upper part of the McKinley Bay section is characterized by cycles with regular thickness and composition with minor amounts of siliclastics. The occurrence of subaqueous gypsum in the Otto Fiord Formation suggests a localized collapse area in order to restrict sea water circulation.

to that of the continental assemblage CF1 of Thériault and Beauchamp (1991) associated with syn-faulting episode. The overlying cycles are characterized by relatively important variations in thickness and composition (Fig. 4.7) indicative of a probable tectonic-controlled subsidence. The base of McKinley Bay section is also characterized by similar cycles and contains substantial amounts of siliciclastic material (see Appendix I: MKB section) suggesting tectonic control on subsidence. The upper part of McKinley Bay section (Fig. 4.7) shows cycles characterized by the gradual change in composition and thickness characteristic of passive thermal subsidence. In addition the evaporites of the Otto Fiord Formation are coeval (Fig. 4.7) with the probable active tectonic period interpreted from Notch Lake and McKinley Bay sections. These evaporites were deposited in isolated subbasins, controlled by local tectonic subsidence (see Nassichuk and Davies, 1980). In summary, this preliminary evaluation shows that sequence 2 follows the same pattern of rift pulse with an active tectonic collapse followed by a regime of passive subsidence. The initial uplift period is not yet recognized, because the base of the sequence is missing from these sections.

The fact that the two sequences (i.e. sequences 2 and 3) displays the same cycle stacking pattern suggests that for the rifting phase of the Sverdrup Basin (see Fig. 1.3) a rift pulse corresponds to a 3rd order sequence (rift pulse=third order sequence) and therefore that the 3rd order sequences are primarily of tectonic origin and not of eustatic origin.

CHAPTER 5: CONCLUSIONS

The Asselian-Sakmarian sequence 3 of Beauchamp *et al.* (1989 a,b) in the Fosheim and Hamilton peninsulas area comprises six formations that are all characterized by high-frequency (mainly 4th order) depositional cycles. The Canyon Fiord Formation is mainly composed of marginal to continental siliciclastic, the Belcher Channel, Antoinette, Tanquary and Nansen formations are composed of platformal carbonate that are surrounding the subaqueous evaporite of the Mount Bayley Formation deposited in the Fosheim-Hamilton subbasin. The base Mount Bayley is possibly diachronic from the northeast to the southwest and therefore overlies and passes laterally into the Antoinette Formation. The top of the Mount Bayley, however, is synchrone and overlain by the Tanquary Formation.

The carbonate strata are subdivided into 19 depositional facies and grouped into four categories named after the interpreted depositional setting; as lagoonal, barrier and shoal, and on-reefal and reefal mid-shelf facies. Lagoonal facies comprises two facies deposited in relatively restricted shallow water. Barrier and shoals facies are composed of four facies representing sediments deposited within the wave action zone. Non-reefal facies of the mid shelf comprises three open marine facies deposited from below the wave zone to below the photic zone. Reefal facies of the mid-shelf include ten facies composed of various boundstones and related flank facies deposited on the shelf from below the wave action zone to below the photic zone.

Depositional environments of these carbonate facies are used to interpret a relative sea-level curve for each measured section. High-frequency depositional cycles are identified from these relative sea level curves for all formations and grouped into five idealized cycles including from proximal to distal order: Sandstone-Carbonate (#1); Grainstone-Palaeoplysiniid (#2); Packstone-Phylloid (#3); Wackestone (#4) and Anhydrite Cycles (#5). Using a strip-chart approach, the sequence 3 is subdivided into three successive time-stratigraphic cycles assemblages characterized by depositional cycles with an unique stacking pattern of cyclicity representing distinct episodes of tectonically-controlled sedimentation and include: a Pre-, a Syn- and a Post-evaporite Assemblages

The Pre-evaporite Assemblage (Asselian to Early Sakmarian) is composed of proximal cycles of relatively constant composition and thickness that are unconformably overlying distal cycles of upper sequence 2. Pre-evaporite assemblage formed during a passive subsidence phase following a major uplifting of the shelf and at a time when the relative high-frequency sea-level changes in the basin were controlled by glacio-eustatic variations but with evidence of localized tectonic subsidence.

The Syn-evaporite Assemblage (Early to Middle Sakmarian) is composed of depositional cycles with important variations in composition and thickness and by the occurrence of subaqueous

anhydrite deposited by reciprocal sedimentation with carbonate in a restricted deeper depression of the Fosheim-Hamilton subbasin. Syn-evaporite Assemblage developed during the collapse of the previously uplifted shelf when the relative sea-level changes were controlled by tectonic fault-controlled subsidence with a glacio-eustatic background.

The Post-evaporite Assemblage (Late Sakmarian) is characterized by a constant number of relatively thick cycles with basal and upper shale units of various thickness in between a thin shallow shelf carbonate unit of constant thickness. The important increase of siliciclastic material during the Post-evaporite is probably related to a climatic change influencing the source area, located in the south of the study area. Post-evaporite Assemblage recorded a change from tectonic fault subsidence to a more passive thermal subsidence, in the subbasin when the relative sea-level changes were partially of glacio-eustatic origin but also partially influenced by local but important siliciclastic influx.

The sequence 3 accumulated under four successive tectonic regimes: i.e. uplift passive subsidence-collapse-passive subsidences which correspond to a rifting pulse. Preliminary investigations suggest that the sequence 2 is also affected by a similar succession of tectonic regime. Thus the rifting phase of the Sverdrup Basin are punctuated by rift pulses which probably define individual 3rd order sequences (sequence=rift pulse).

This study suggests that the sequences deposited in rift tectonic environment are related to extensional pulse and therefore related to tectonism more than to global eustatic variations. One of the major implication of this study is that the thermal history of sedimentary rift basin does not follow a linear trend but is characterized by several extensional pulses separated by periods of passive subsidence and uplift. This study has also shown: 1) that detailed analysis of high-frequency cycles can be used to decipher different episodes of subsidence history; 2) that it is possible to discriminate the influence of tectonic, glacio-eustasy and sediment supply within an assemblage of high-frequency depositional cycles; and 3) that the cyclic stacking pattern characteristic of individual assemblages can be easily used as a correlation tool applicable in the field.

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PLATES

PLATE 1**Peloidal and Foraminiferal Facies**

- a. Photomicrograph of Peloidal Facies in packstone (microsparite). Peloids, globivalvulinids (G), *Earlandia* (E) are the most common elements. Note common quartz silt grains. Scale bar is 0.5 mm.
- b. Photomicrograph of Peloidal Facies in packstone showing a detailed illustration of *Earlandia* (E) and Globuvalvulinid (G). Scale bar is 0.2 mm.
- c. Photomicrograph of Foraminiferal Facies in wackestone/packstone. Globuvalvulinids (G) and Ostracods are common. Apterrinellids (A) are also present. Scale bar is 0.5 mm.
- d. Photomicrograph of Foraminiferal Facies in packstone-grainstone showing globuvalvulinids (G), Ostracods (O), fasciellids algae (F) and globular to digitate apterrinellids (A). Rare fenestellids bryozoans (FB) are present. Scale bar is 0.5 mm.

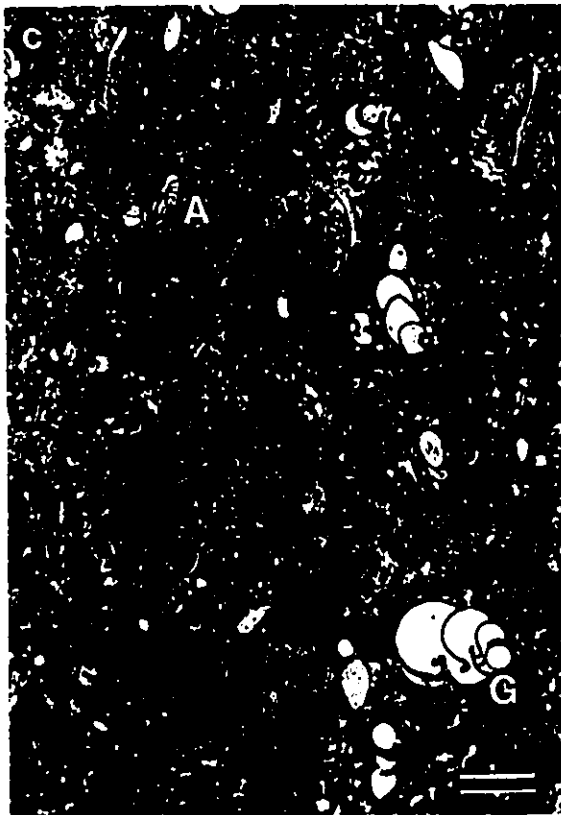
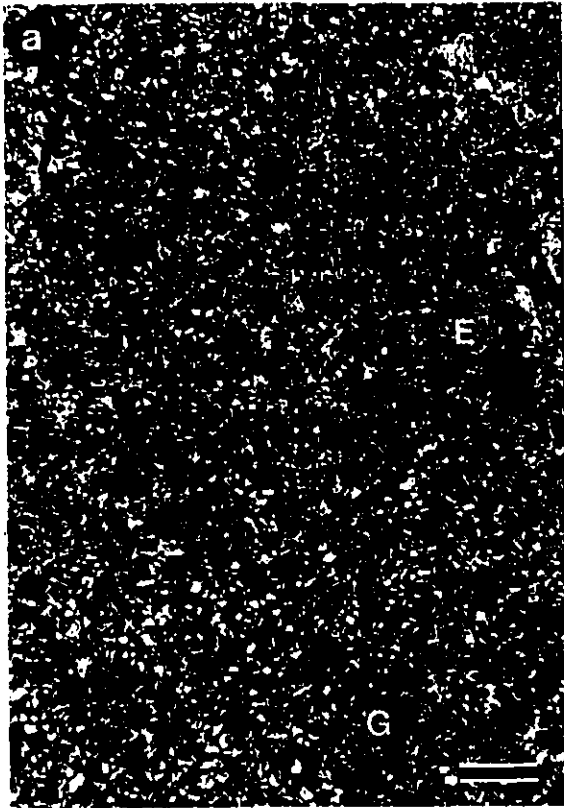


PLATE 2**Foraminiferal and Oolitic Facies**

- a. Photomicrograph of Foraminiferal Facies in packstone. Globivalvulinids (G), globular apterrinellids (GA), epibiont apterrinellids (EA), ostracods (O) and encrusting fasciellids algae are common. Scale bar is 0.5 mm.
- b. Field photograph showing a bed surface composed of clusters of colonial rugosan within the Foraminiferal Facies. Hemispherical rugosan coral heads are forming an irregular "hummocky-like" surface. Antoinette Formation at East Cape River I section.
- c. Photomicrograph of Oolitic Facies in grainstone showing silt-sized quartz and peloid nuclei ooids. Scale bar is 0.2 mm.
- d. Photomicrograph of Oolitic Facies in grainstone illustrating completely dissolved or spar filled ooids. Nuclei are made of peloids, quartz silt grains, echinoderms and micritized grains. Some ooids are "decentered" (D) because of pervasive cortex dissolution. Scale bar is 0.5 mm.

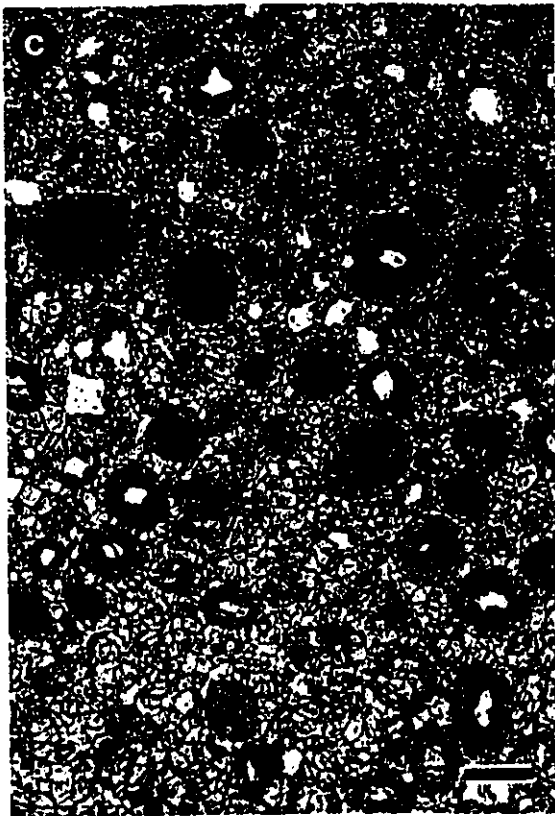


PLATE 3**Bioclastic Facies**

- a. Photomicrograph of Bioclastic Facies in grainstone showing abundant peloids, intraclasts (I) and common fusulinids (F). Scale bar is 0.5 mm.
- b. Photomicrograph of Bioclastic Facies in grainstone showing common dissolved dasycladacean algae (*Epinastopora* sp.) (D), and rare dasycladacean with preserved internal pores (Dp). Fenestellid bryozoan (B), echinoderms (E) and fusulinacean (F) are common. Scale bar is 0.2 mm.
- c. Photomicrograph of a Oolitic Facies in grainstone, in which nuclei have a composition similar to the Bioclastic Facies showing common sand sized quartz grains, fusulinids (F), fenestellid bryozoans (f), brachiopods (B) and echinoderms (E). Scale bar is 0.5 mm.
- d. Photomicrograph of Bioclastic Facies in grainstone showing a transitional microfacies from Bioclastic Facies to Oolitic Facies. Most of bioclastic grains (e.g. echinoderms (E), oncoids (O), fusulinids (F), intraclasts (I)) and sand-sized quartz grains are coated by an oolitic cortex. Matrix is dominated by quartz silt fragments. Scale bar is 0.2 mm.

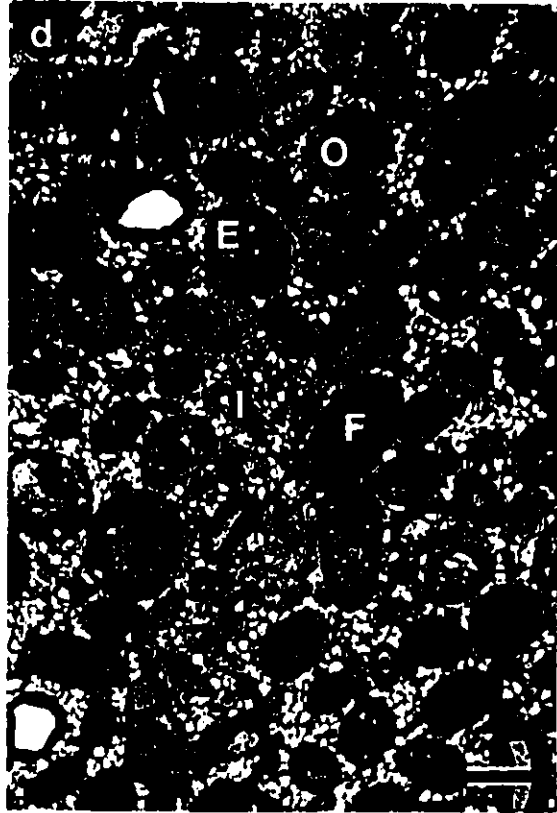
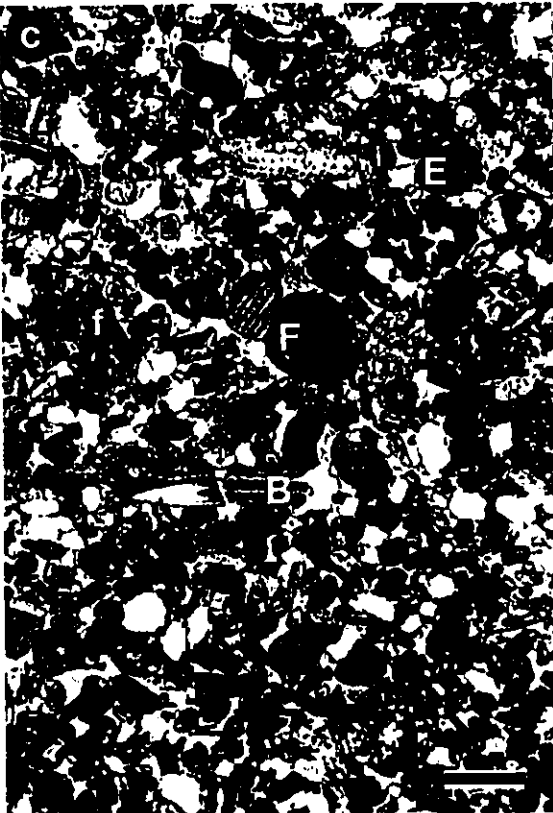


PLATE 4**Dasycladacean and Oncoidal Facies**

- a. Photomicrograph of Dasycladacean Facies in grainstone showing abraded dasycladacean fragments with preserved internal pores and micritic envelopes. Other grains are echinoderms (E), fusulinids (f) and gastropods (G). Scale bar is 0.5 mm.
- b. Photomicrograph of Dasycladacean Facies in grainstone showing abundant dissolved lightly rounded dasyclad fragments with globular apterrinellids (g) and fusulinids (f). Scale bar is 0.5 mm.
- c. Photomicrograph of Oncoidal Facies ("restricted subfacies") in a packstone matrix. Oncoid nucleus are composed of phylloid algae fragments. The packstone matrix consists of common ostracods, and silt-sized quartz grains. Scale bar is 2.5 mm.
- d. Photomicrograph of Oncoidal Facies "open subfacies" in a grainstone/packstone. The matrix is made up of common fusulinids, peloids, globular apterrinellids and echinoderms. Scale bar is 2.5 mm.

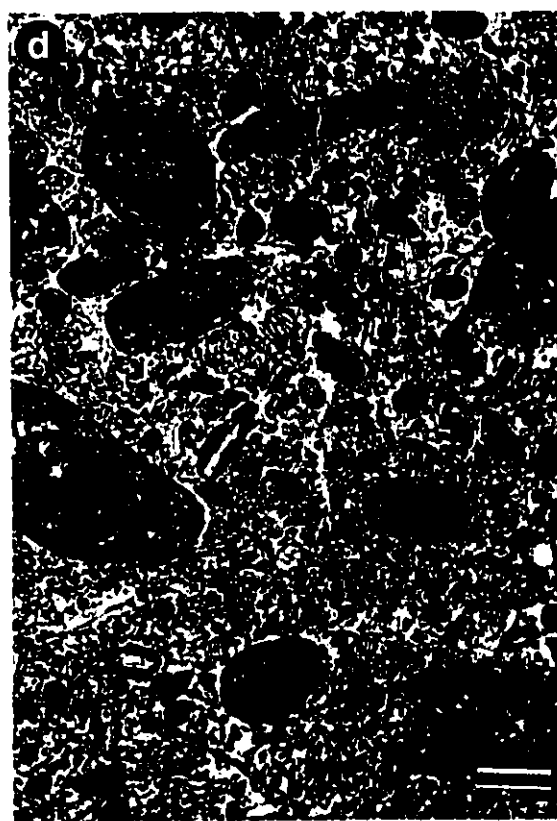
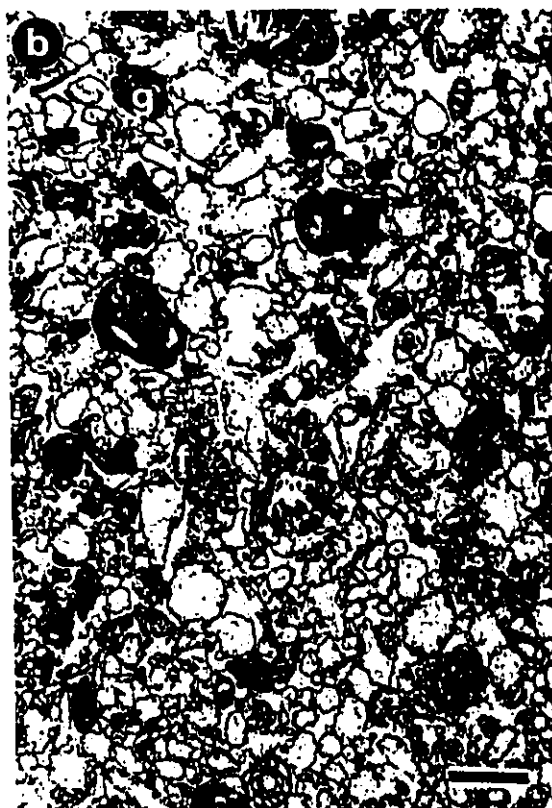


PLATE 5**Fusulinacean Facies**

a. Photomicrograph of Fusulinacean Facies in packstone/grainstone showing fusulinids, echinoderms, fasciellid algae, fenestellid bryozoan, apterrinellids and *Tubiphytes*. Scale bar is 1.5 mm.

b. Photomicrograph of Fusulinacean Facies in wackestone showing fusulinids (F), fenestellid bryozoan (B), *Tetrataxis* (t) and fasciellid algae. Scale bar is 1.5 mm.

c. Photomicrograph of Fusulinacean Facies in poorly sorted packstone showing fusulinids, ramose bryozoans, rugosan, fenestellids bryozoan and paleotextularid (P). Scale bar is 0.5 mm.

d. Photomicrograph of Fusulinacean Facies in "fusulinite" packstone composed largely of abundant fusulinids. Scale bar is 2.5 mm.



PLATE 6**Bryozoan and Micritic Facies**

- a. Photomicrograph of Bryozoan Facies in wackestone showing fenestellid bryozoan, echinoderms , brachiopods and peloids. Scale bar is 0.5 mm.
- b. Photomicrograph of Micritic Facies in mudstone-wackestone showing sponge spicules, peloids and silt-sized quartz. Scale bar is 0.2 mm.
- c. Photomicrograph of Micritic Facies showing quartz-rich silty laminations in micritic matrix. Scale bar is 0.2 mm.
- d. Photomicrograph of Micritic Facies showing gypsum crystals (partly dissolved) floating in a micritic matrix with silty quartz-rich laminations. Scale bar is 1 mm.

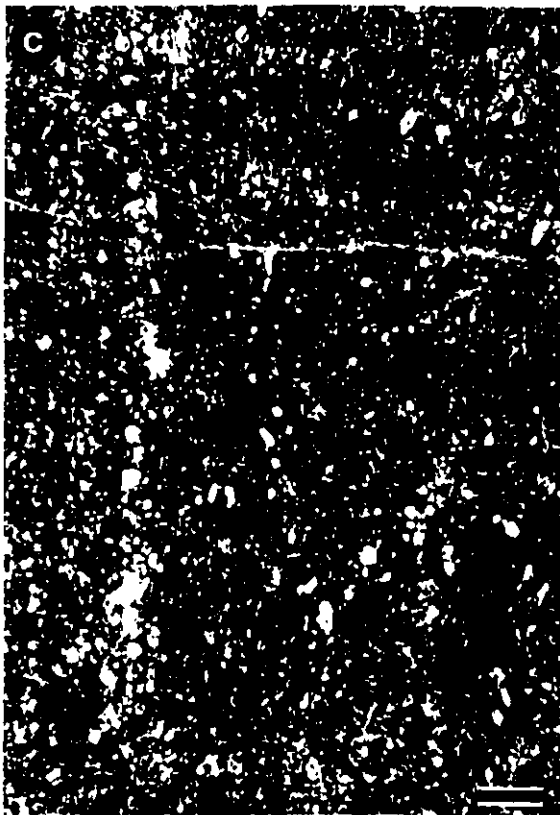
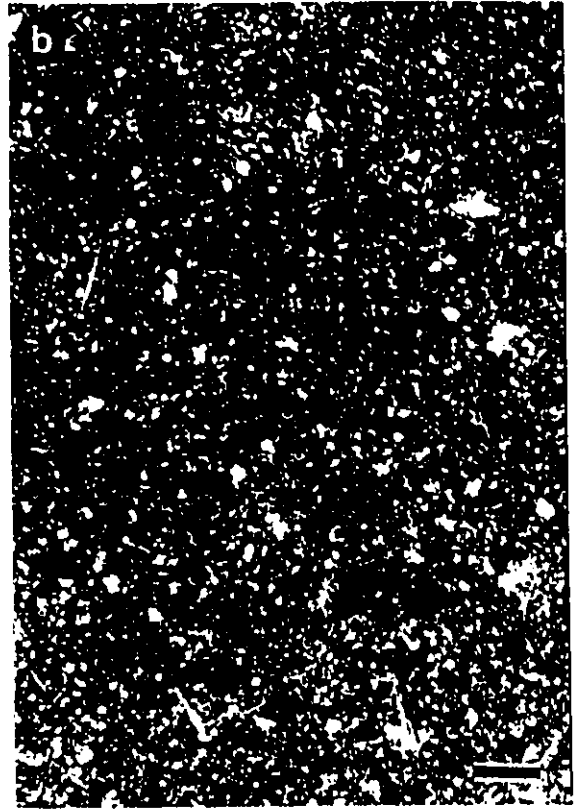


PLATE 7

Micritic and Palaeoaplysiniid Boundstone Facies

- a. Photomicrograph of dolomitized Micritic Facies showing pervasively dolomitized micritic matrix. Relict peloids and dissolved (voids) gypsum crystals are present. Scale bar is 0.5 mm.
- b. Photomicrograph of dolomitized Micritic Facies showing dolomitized micrite with laminations of silt-sized quartz. Scale bar is 0.5 mm.
- c. Photomicrograph of Palaeoaplysiniid Boundstone Facies showing a detailed view of preserved internal structures of *Palaeoaplysina*. Scale bar is 0.2 mm.
- d. Photomicrograph of Palaeoaplysiniid Boundstone Facies. *Palaeoaplysina* plates are replaced by sparry calcite, but internal canal are locally filled by micrite. Top is left. Scale bar is 3 mm.

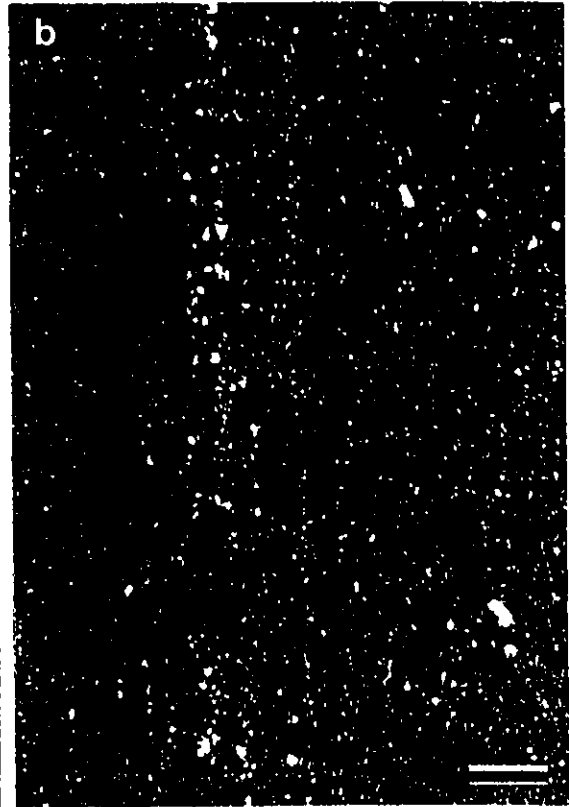


PLATE 8**Palaeoaplysiniid Boundstone, Palaeoaplysiniid-Dasyclad and
Phylloid Boundstone Facies**

- a. Photomicrograph of Palaeoaplysiniid Boundstone Facies showing dissolved *Palaeoaplysina* plates. Partially dolomitized wackestone matrix between plates contains fusulinids, fenestellid bryozoan and solitary rugosa. Scale bar is 5 mm.
- b. Photomicrograph of Palaeoaplysiniid-Dasyclad Facies showing mud-free grainstone with abraded *Palaeoaplysina* fragments (P), poorly preserved dasyclad fragments (D) and *Tubiphytes* (T). Scale bar is 0.5 mm.
- c. Photomicrograph of Phylloid Boundstone Facies showing poorly preserved phylloid algae. The sediment infill is made up of packstone with peloids, silt-sized quartz, fusulinids, echinoids and fenestellids. Phylloid algae is encrusted by an multi-layered irregular apterrinellids (I). Scale bar is 0.5 mm
- d. Photomicrograph of Phylloid Boundstone Facies showing dissolved phylloid algae. Sediment matrix is packstone. Note spar filled shelter cavity. Scale bar is 5 mm.



PLATE 9**Phylloid-Fusulinid, Palaeoaplysiniid-Phylloid Boundstone and
Bryozoan-*Tubiphytes* Boundstone Facies**

- a. Photomicrograph of Phylloid-Fusulinid Facies showing packstone with abundant phylloid platy fragments. Common fusulinids, echinoderms, brachiopods and bryozoans are present. Scale bar is 2.5 mm.
- b. Photomicrograph of Palaeoaplysiniid-Phylloid Boundstone Facies showing phylloid algae against *Palaeoaplysina* plate. Scale bar is 1 mm.
- c. Photomicrograph of Bryozoan-*Tubiphytes* Boundstone Facies showing ramose and fenestellid bryozoans partially encrusted by *Tubiphytes*. Scale bar is 0.25 mm.
- d. Photomicrograph of Bryozoan-*Tubiphytes* Boundstone Facies showing ramose and fenestellid bryozoans partially encrusted by *Tubiphytes*. Sediment infill is made up of abundant peloids. Scale bar is 0.2 mm.

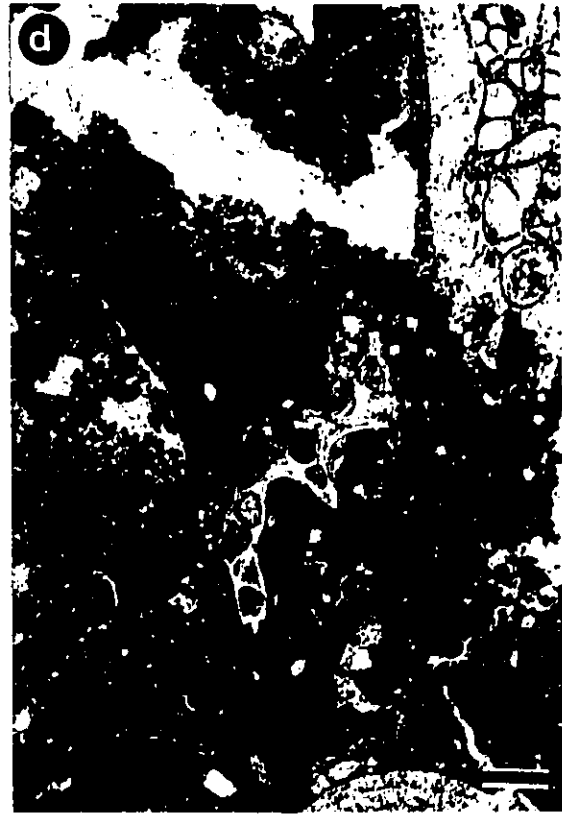


PLATE 10**Bryozoan-*Tubiphytes*, Syringoporid Boundstone and Spongiostromid Facies**

- a. Photomicrograph of Bryozoan-*Tubiphytes* Facies in packstone showing ramose bryozoan fragments encrusted by *Tubiphytes* (R). Fusulinids, *Tubiphytes* (T) and echinoderm fragments are present. Note progressive replacement of micrite by microspar. Scale bar is 2 mm.
- b. Photomicrograph of Syringoporid Boundstone Facies showing syringoporid coral encrusting ramose bryozoan. Top is left. Scale bar is 2 mm.
- c. Photomicrograph of Syringoporid Boundstone Facies showing syringoporid coral encrusting solitary rugosan. Scale bar is 2.5 mm.
- d. Photomicrograph of Spongiostromid Boundstone Facies. Note the stromatactis-like cavity partially filled by micritic sediment in Spongiostromid (S). Top is left. Scale bar is 0.5 mm.



PLATE 11**Beresellid Boundstone and apterrinellids growth shape**

- a. Photomicrograph of Beresellid Boundstone Facies showing abundant beresellid algae. Scale bar is 0.5 mm.
- b. Photomicrograph of irregular nodular apterrinellids (A) in packstone (Foraminiferal Facies). Associated grains are ostracods and peloids. Scale bar is 0.5 mm.
- c. Photomicrograph of globular apterrinellids in grainstone (Foraminiferal Facies). Scale bar is 0.5 mm.
- d. Photomicrograph of single-layered (epibiont) apterrinellids (Foraminiferal Facies) showing internal transversal (P) and section (S) view. Note the sharp edges and base in longitudinal section. Scale bar is 0.2 mm.

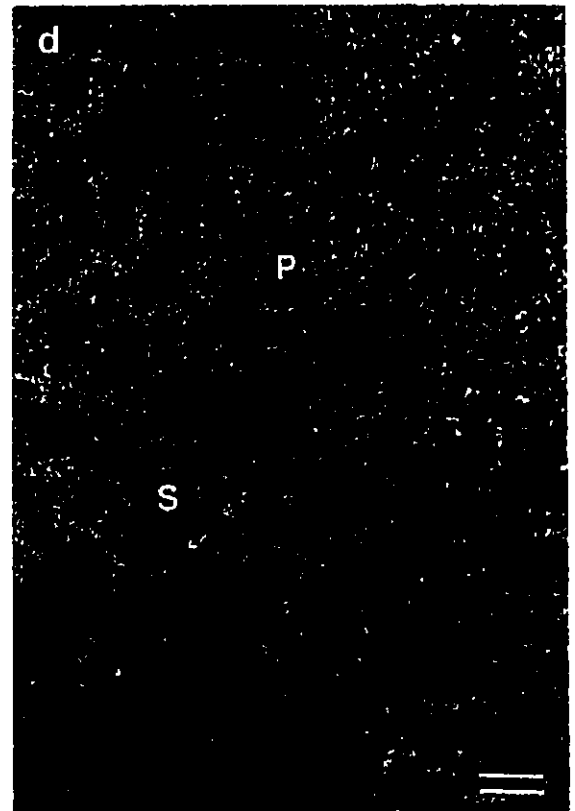
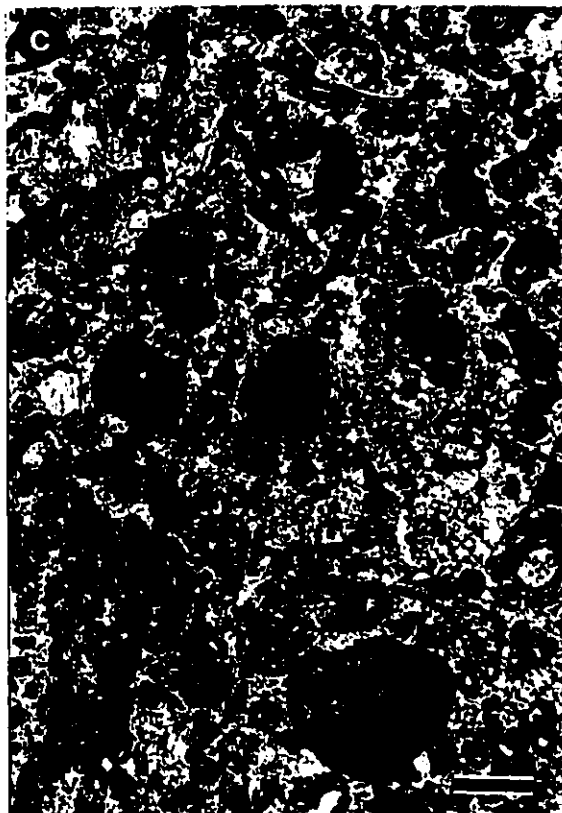
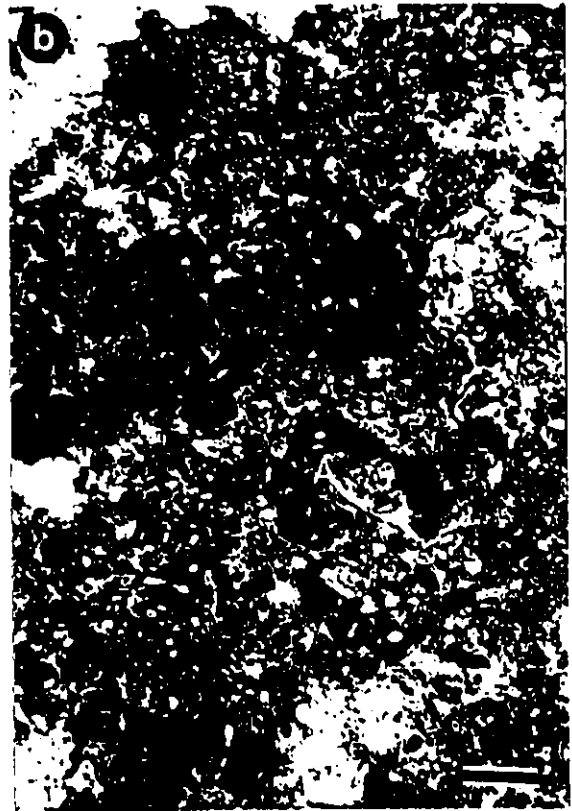
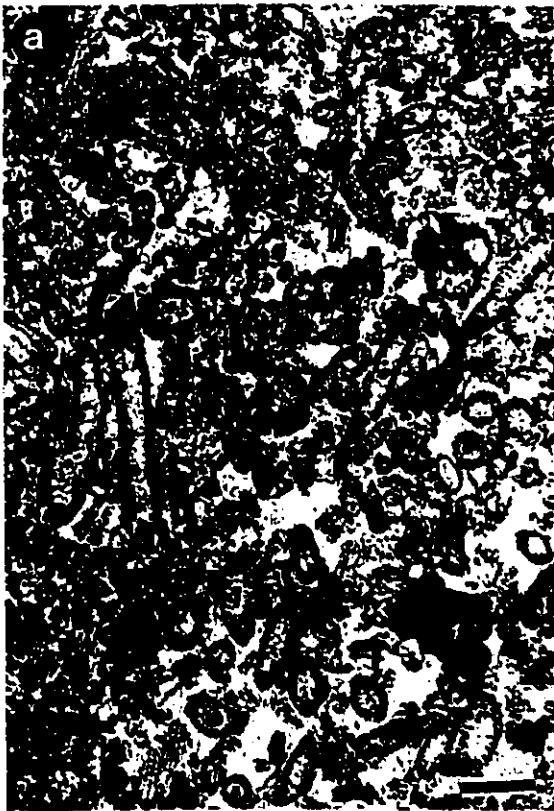


PLATE 12**Apterrinellids and Evaporite Facies**

- a. Photomicrograph of Foraminiferal Facies showing abundant single-layered (epibiont) apterrinellids in packstone. Associated allochems are peloids, ostracods and fasciellid algae. Scale bar is 0.5 mm.
- b. Field photograph showing Laminated Gypsum Facies (Ideal Cycle #5) in small cliff exposure. Mount Bayley Formation at North Greely Fiord Section.
- c. Photomicrograph of Laminated Gypsum Facies showing several siltstone-dolostone laminae between gypsum layers. Note the slight diagenetic transformation of the laminated gypsum. Scale bar is 4 mm.
- d. Photomicrograph of Laminated Siltstone-Dolostone Facies showing laminations rich in silt-sized quartz and fine dolomite. Scale bar is 0.5 mm.

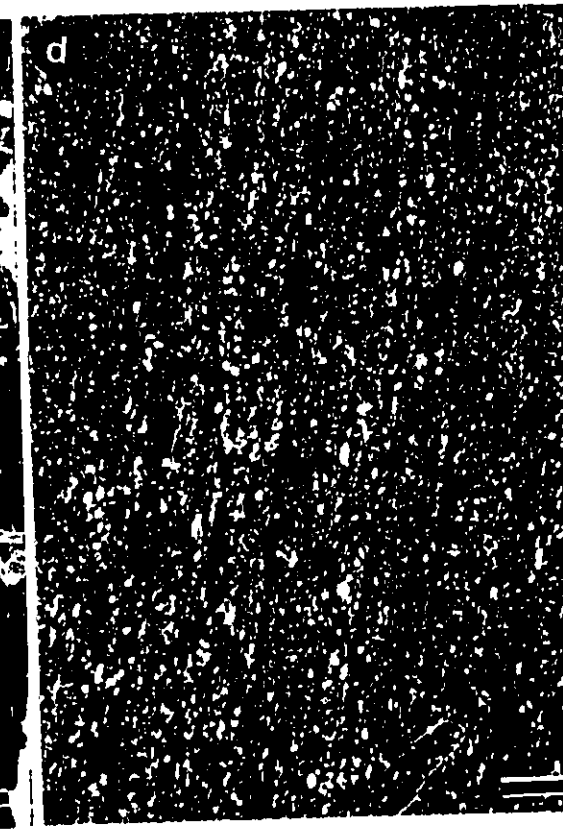


PLATE 13**Non-carbonate Facies and high-frequency cycles**

a. Photomicrograph of Laminated Siltstone-Dolomite Facies. Gypsum crystals (partially dissolved) are present between laminae. Top is left. Scale bar is 3 mm.

a. Photomicrograph of siltstone showing sub-angular silt-sized quartz grains (crossed nicols). Scale bar is 0.5 mm.

c. Photomicrograph of mixed siltstone:Fusulinacean Facies showing echinoderms, fusulinids and fenestellids in silt-sized quartz matrix. Scale bar is 2 mm.

d. Field photograph showing in cliff exposure a Sandstone-Grainstone cycle with massive thick bedded medium sandstone overlain by medium bedded medium sandstone with large scale, low angle cross-beds. Canyon Fiord Formation at Caledonian Bay section.

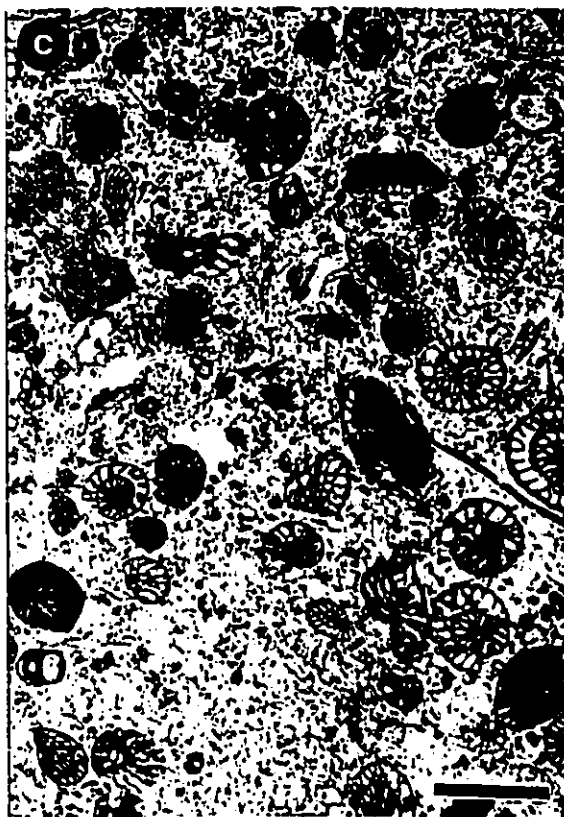
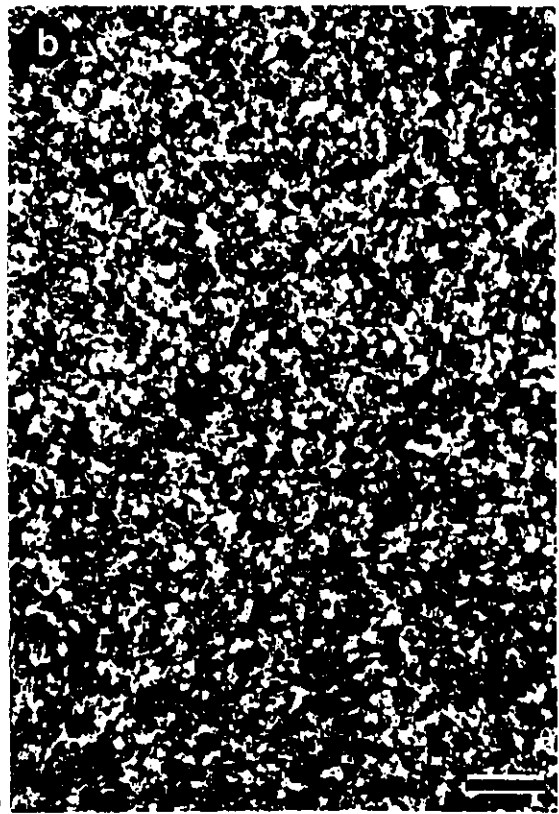


PLATE 14**High-frequency cycles and Pre-evaporite Assemblage**

- a. Field photograph showing thick Grainstone-Palaeoaplysiniid cycle with basal recessive clastic-rich packstone-wackestone, overlain by thick resistant grainstone unit followed by recessive siltstone and packstone. The cycle is capped by thick ledge-forming palaeoaplysiniid tabular reef. Belcher Channel Formation at Vache-qui-pleure section.
- b. Field photograph of a Packstone-Phylloid cycle showing in maximum regression cycle position medium bedded packstone (base of the outcrop) overlain by a large phylloid patch reef (6 m thick). Antoinette Formation at East Cape River I section.
- c. Field photograph showing cliff exposure with two Wackestone cycles overlying a Packstone-Phylloid cycle (note the irregular top of the large tabular phylloid patch reef). Field assistant for scale. Antoinette Formation at East Cape River I section.
- d. Field photograph of the Antoinette Formation in cliff exposure at south Greely Fiord showing cycles with constant thickness of the Pre-evaporite Assemblage (PRE) overlain by cycles with variable thickness of the Syn-evaporite Assemblage (SYN). White lines are showing the cycle boundaries.

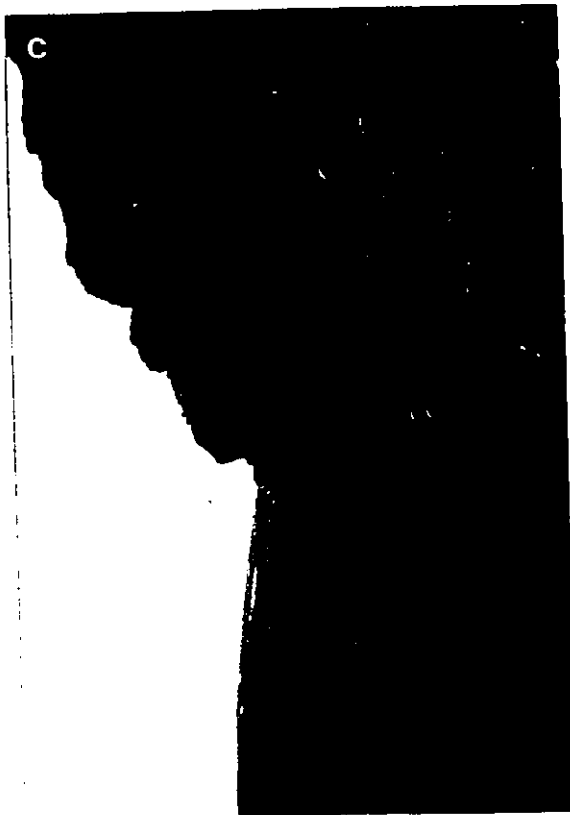


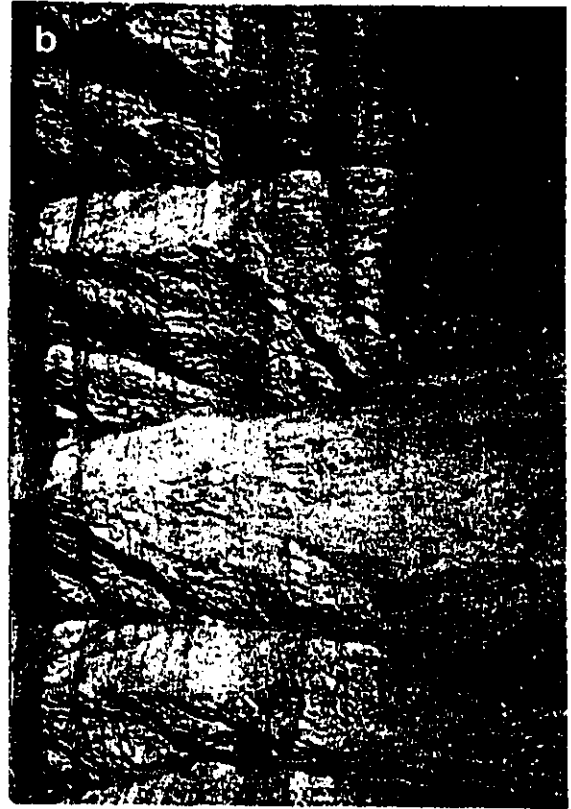
PLATE 15**Pre- and Syn-evaporite Assemblage and *Microcodium***

- a. Close up view of the unconformable contact between Beauchamp's sequences 2 and 3, showing intraformational conglomerate with sandy orthoquartzite matrix. Cobbles and pebbles in the conglomerate as well as the underlying carbonate are composed of relatively deep shelf carbonate facies (Micritic Facies). Antoinette Formation at East Cape river I.
- b. Field photograph showing cliff exposure at Mount Bridgman with Antoinette (basal carbonate-dominated cycles) and Mount Bayley Formation (gypsum cycles). The overlying Post-evaporite Assemblage is defined by recessive shale-based cycles of the Tanquary Formation. Light-coloured gypsum unit is 55 m thick.
- c. Photomicrograph of *Microcodium* showing a longitudinal section of partially silicified *Microcodium* in a silty packstone. Note the concentration of quartz grains around *Microcodium*. Scale bar is 0.5 mm.
- d. Photomicrograph of *Microcodium* showing a transversal section of partially silicified *Microcodium* in a silty packstone. Scale bar is 0.5 mm.



PLATE 16**Syn-evaporite and Post-evaporite Assemblages**

- a. Field photograph of Mackinley Bay olistostrome showing angular to sub-angular fragments. Nansen Formation. Jacob's staff for scale.
- b. Field photograph of the north side of Greely Fiord showing syn-sedimentary fault within the Syn-evaporite Assemblage. Mount Bayley Formation. The gypsum thickness is 125 m over the uplifted block. Top is left.
- c. Field photograph of Mount Bayley Formation outcrop in the Hamilton Peninsula showing evidence of syn-sedimentary faulting. The outcrop consists of approximately 100 m of gypsum.
- d. Field photograph of the Post-evaporite Assemblage (Tanquary Fm) overlying the Syn-evaporite Assemblage (Mount Bayley Fm) at Mount Bridgman section showing an impressive thickness of recessive shale units between ledge-forming resistant carbonate units. A peculiar feature is the occurrence of possible slump scar, cutting (indicated by white lines) through the first cycle of the Tanquary Formation. Note that the "lower green unit" of Beauchamp's sequence 4 is the thick recessive unit (L) overlying the last resistant thin carbonate layer. Gypsum thickness is 55 m.

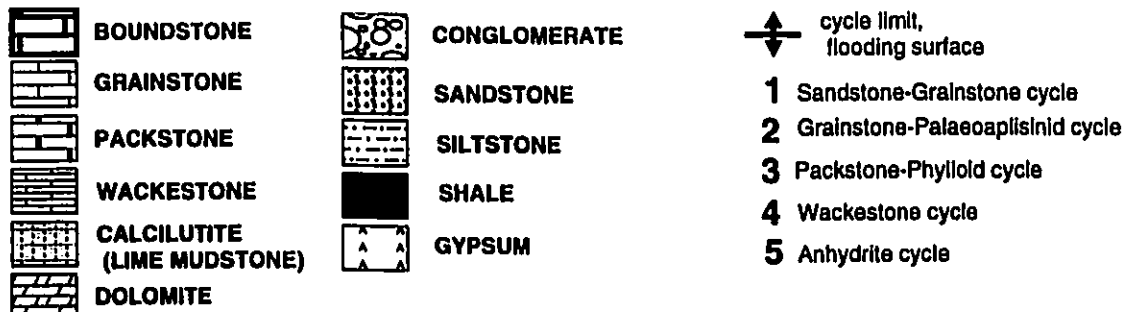
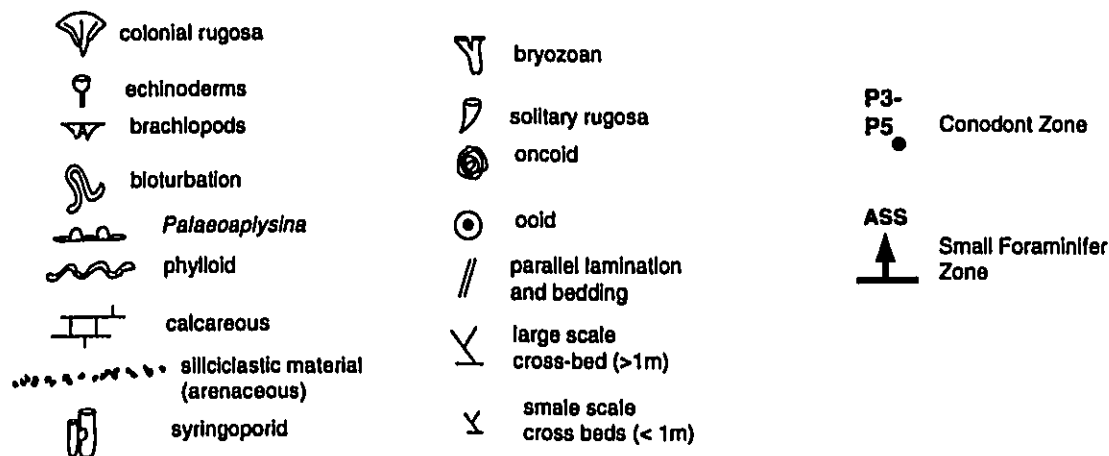


APPENDIX I: STRATIGRAPHIC SECTIONS

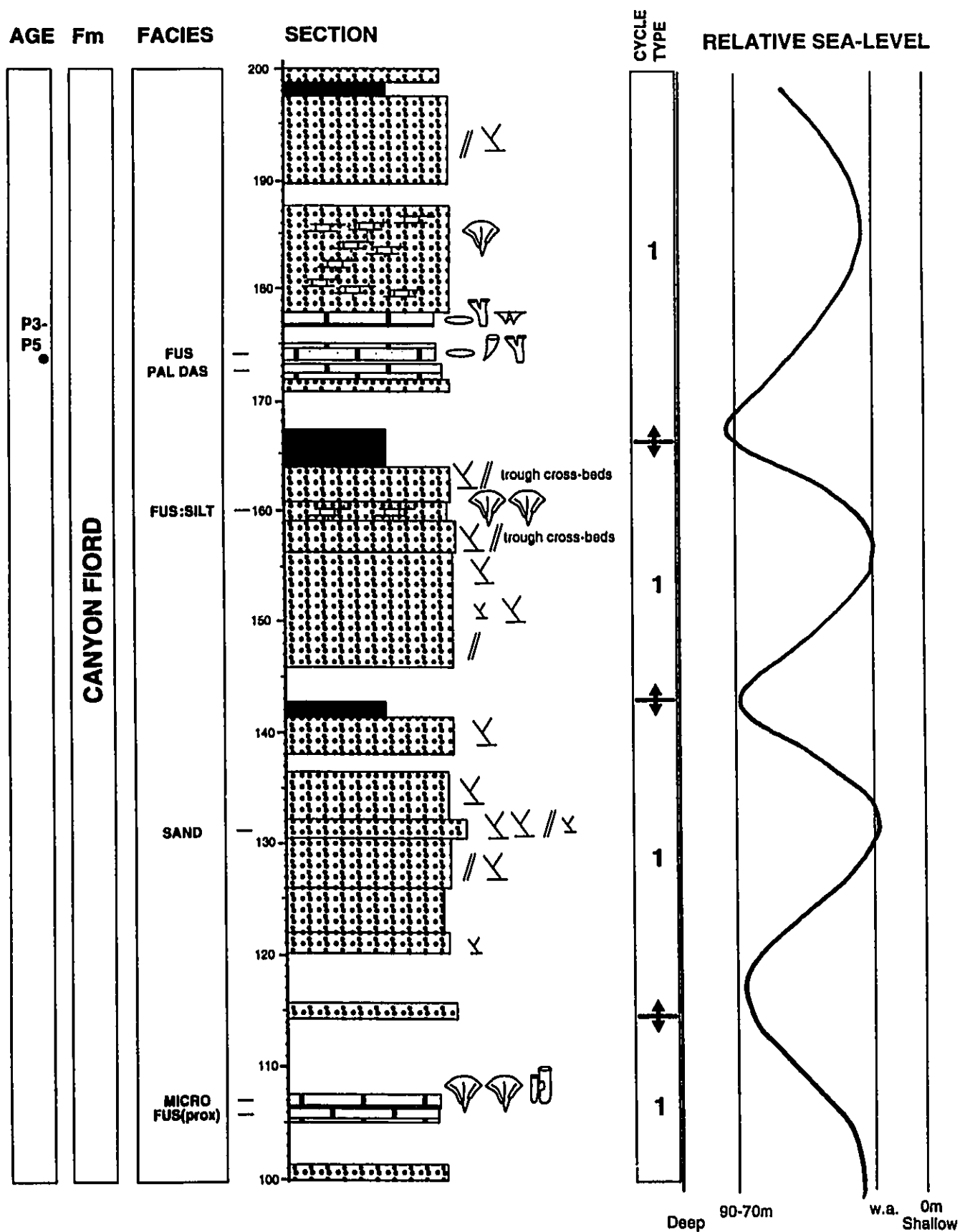
Simplified stratigraphic columns of all measured sections. The age is based on "small" foraminifera zones of Pinard (1990) and on conodont zones of Henderson (1988). Sections are presented in alphabetical order. Symbols used are listed below:

PEL Peloidal Facies
 MICRO Foraminiferal Facies
 OOID Oolitic Facies
 BIO Bioclastic Facies
 DAS Dasycladacean Facies
 ONC (M) "restricted" Oncoid Facies
 ONC (F) "open" Oncoid Facies
 FUS(prox) "proximal" Fusulinacean Facies
 FUS "distal" Fusulinacean Facies
 BRY Bryozoan Facies
 MICRI Micritic Facies
 MICRI(gypsum) Micritic (gypsum crystal) Facies
 LAM DOL-SILT Laminated Siltstone-Dolostone Facies
 LAM DOL-SILT (gypsum) Laminated Siltstone-Dolostone Facies with gypsum crystals
 DOL (MICRI) Micritic (dolomitized) Facies
 DOL(gypsum) Micritic (dolomitized+gypsum crystals) Facies

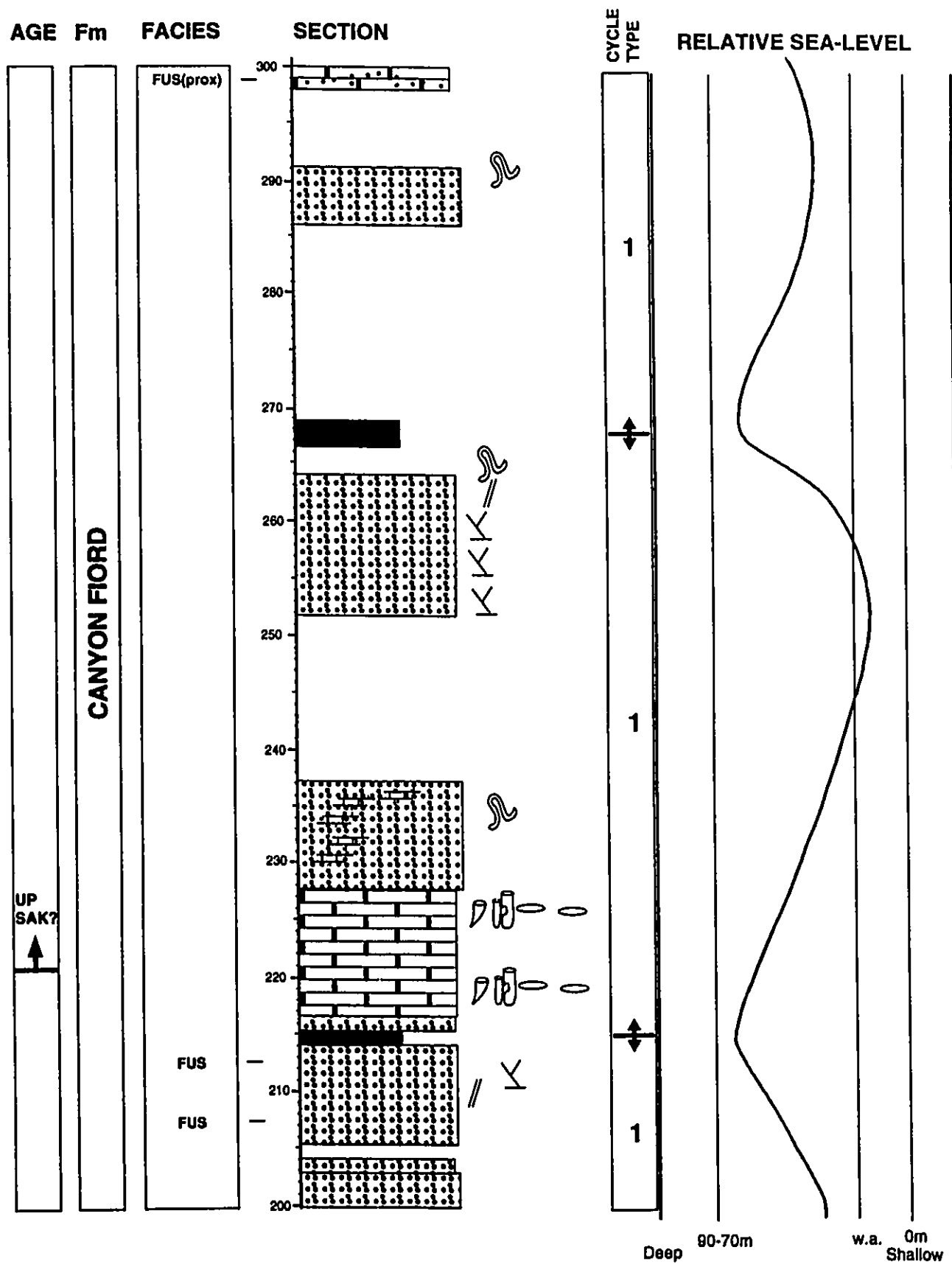
BER Beresellid Boundstone Facies
 PAL Palaeoaplysiniid Boundstone Facies
 PAL DAS Palaeoaplysiniid-Dasyclad Facies
 PHY Phylloid Boundstone Facies
 PHY FUS Phylloid-Fusulinid Facies
 PAL PHY Palaeoaplysiniid-Phylloid Boundstone Facies
 BRY TUB Bryozoan-Tubiphytes Boundstone Facies
 BRY TUB Bryozoan-Tubiphytes Facies
 DET
 SYR Syringoporiid Boundstone Facies
 SPON Spongiostromiid Boundstone Facies
 SAND Sandstone
 SILT Siltstone
 FUS:SILT Mixt Fusulinacean: Siltstone
 FUS :SAND Mixt Fusulinacean-Sandstone



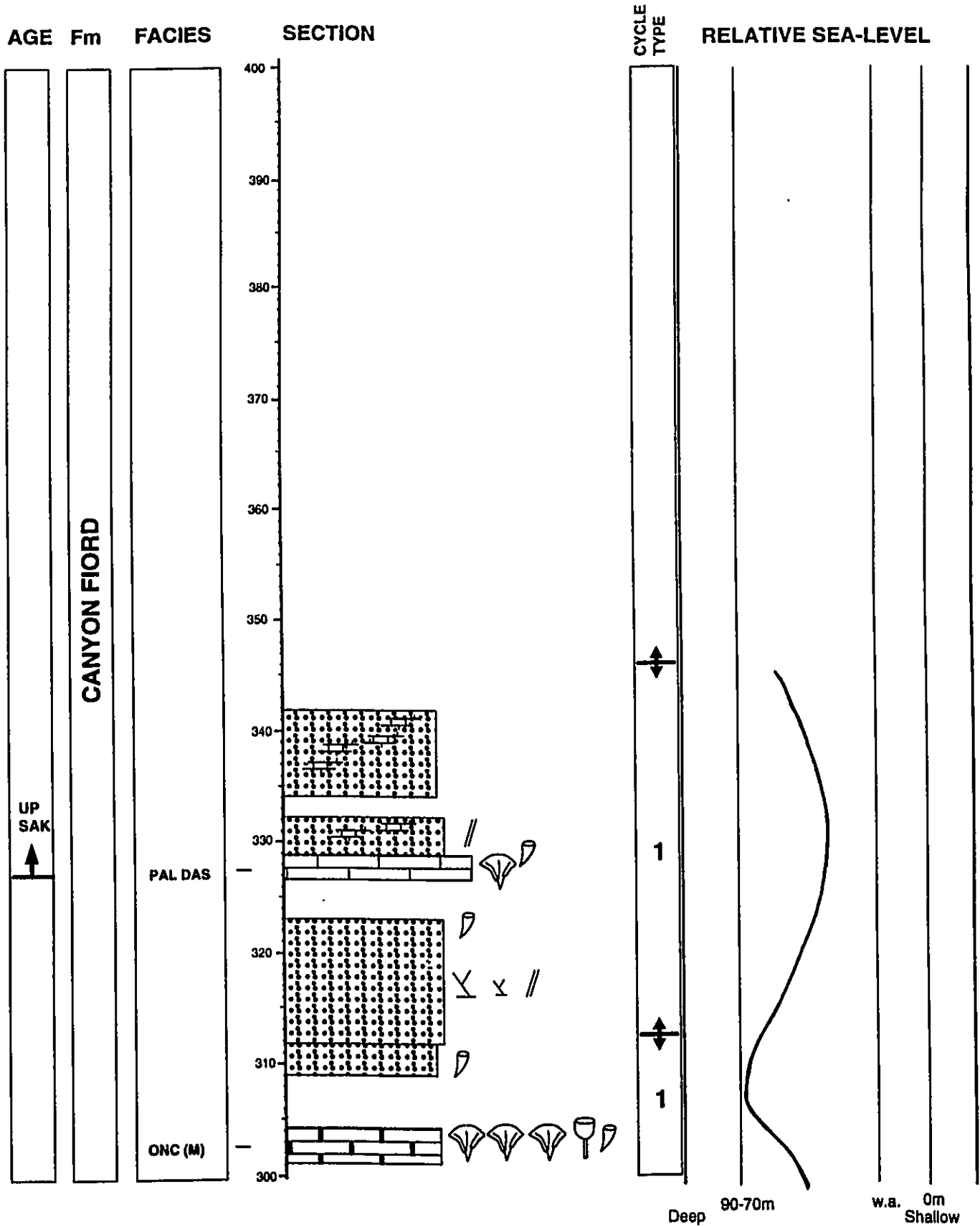
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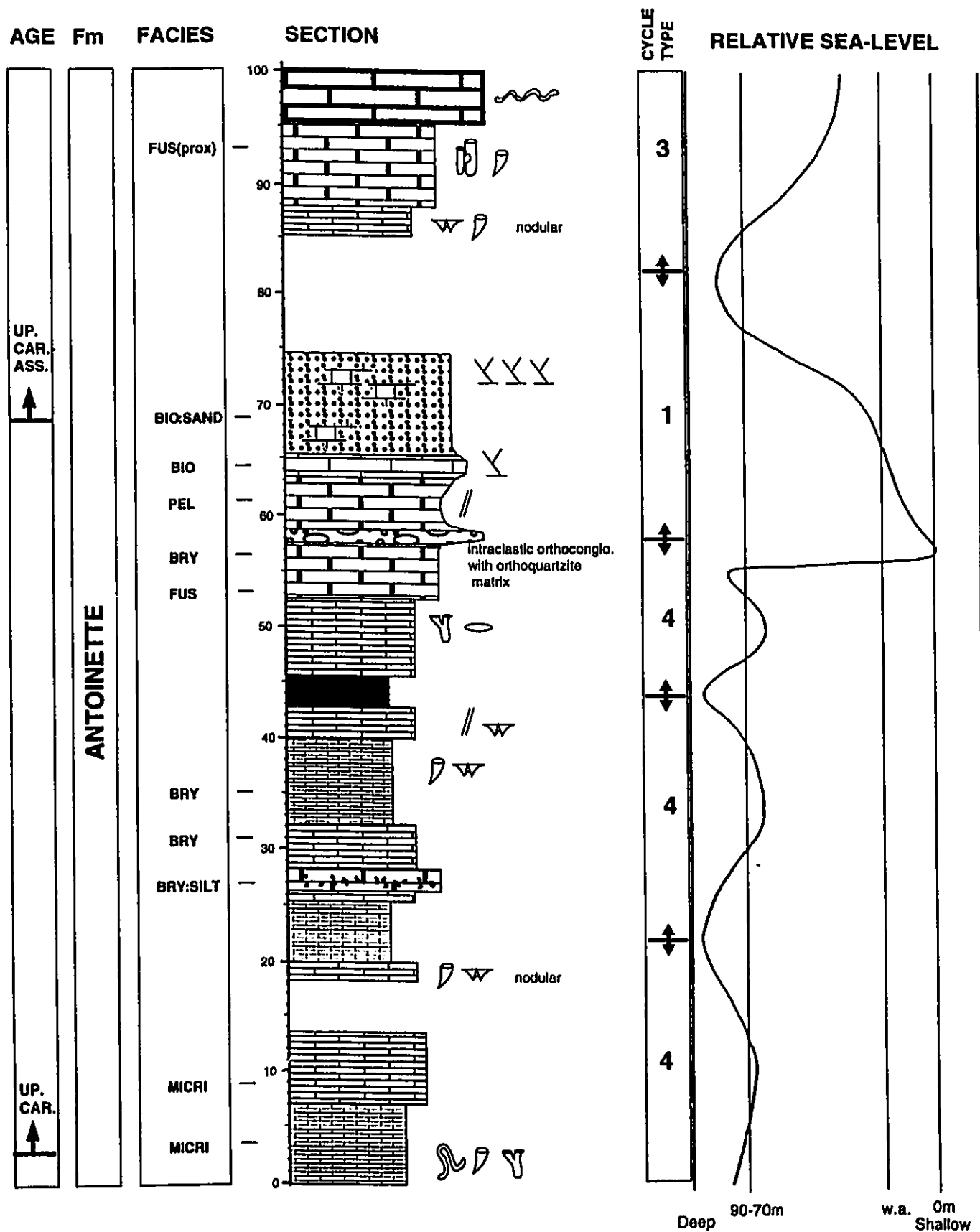
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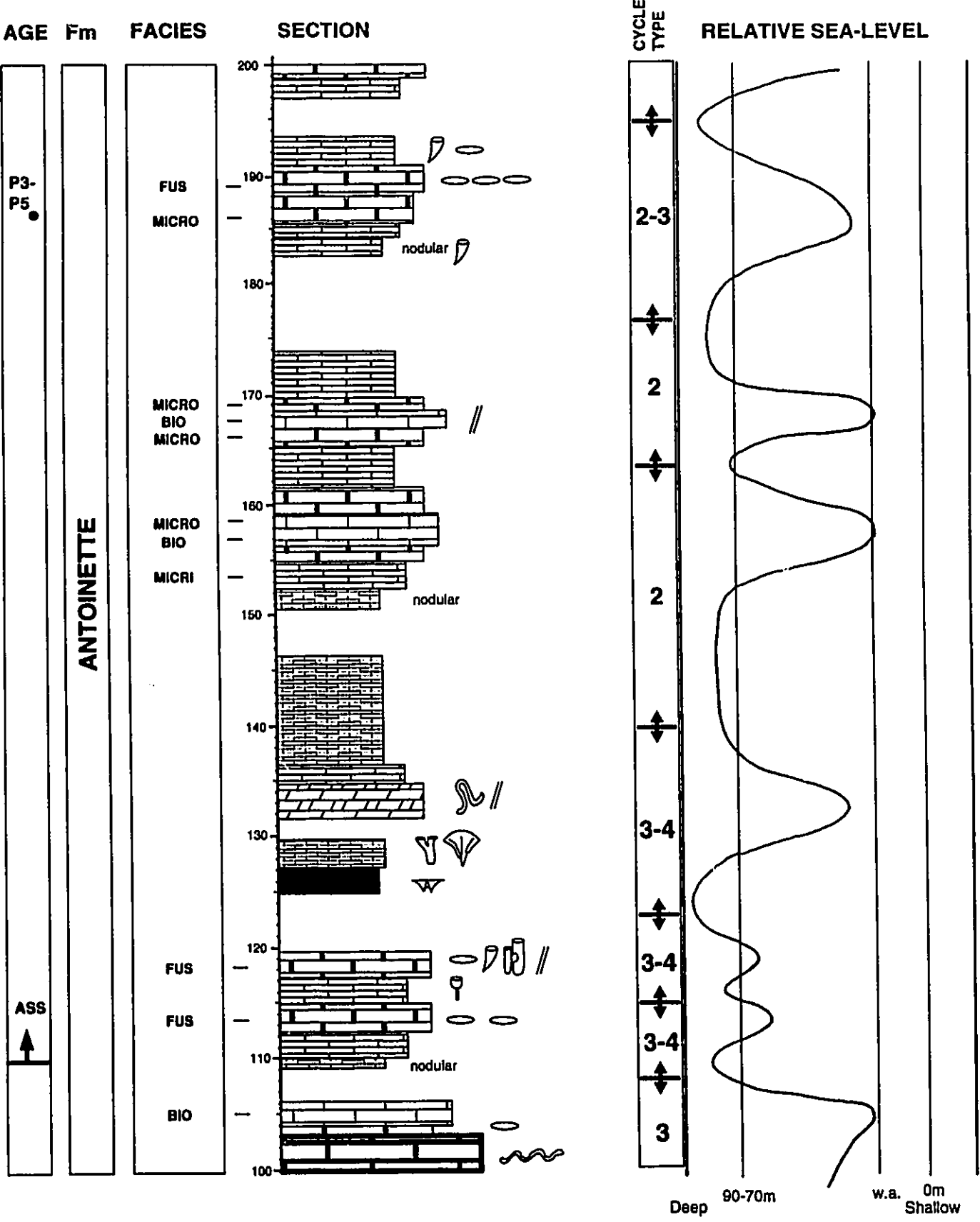
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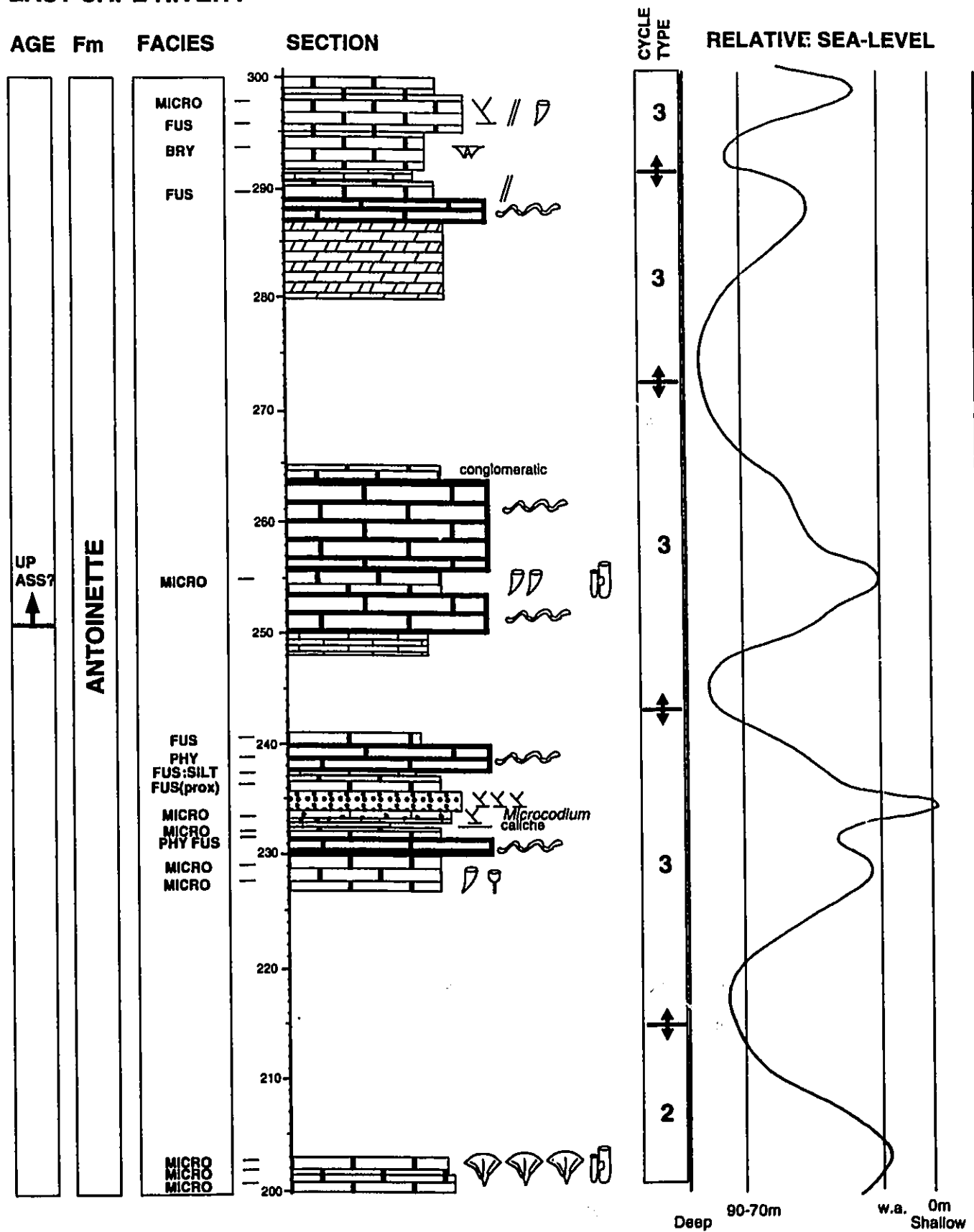
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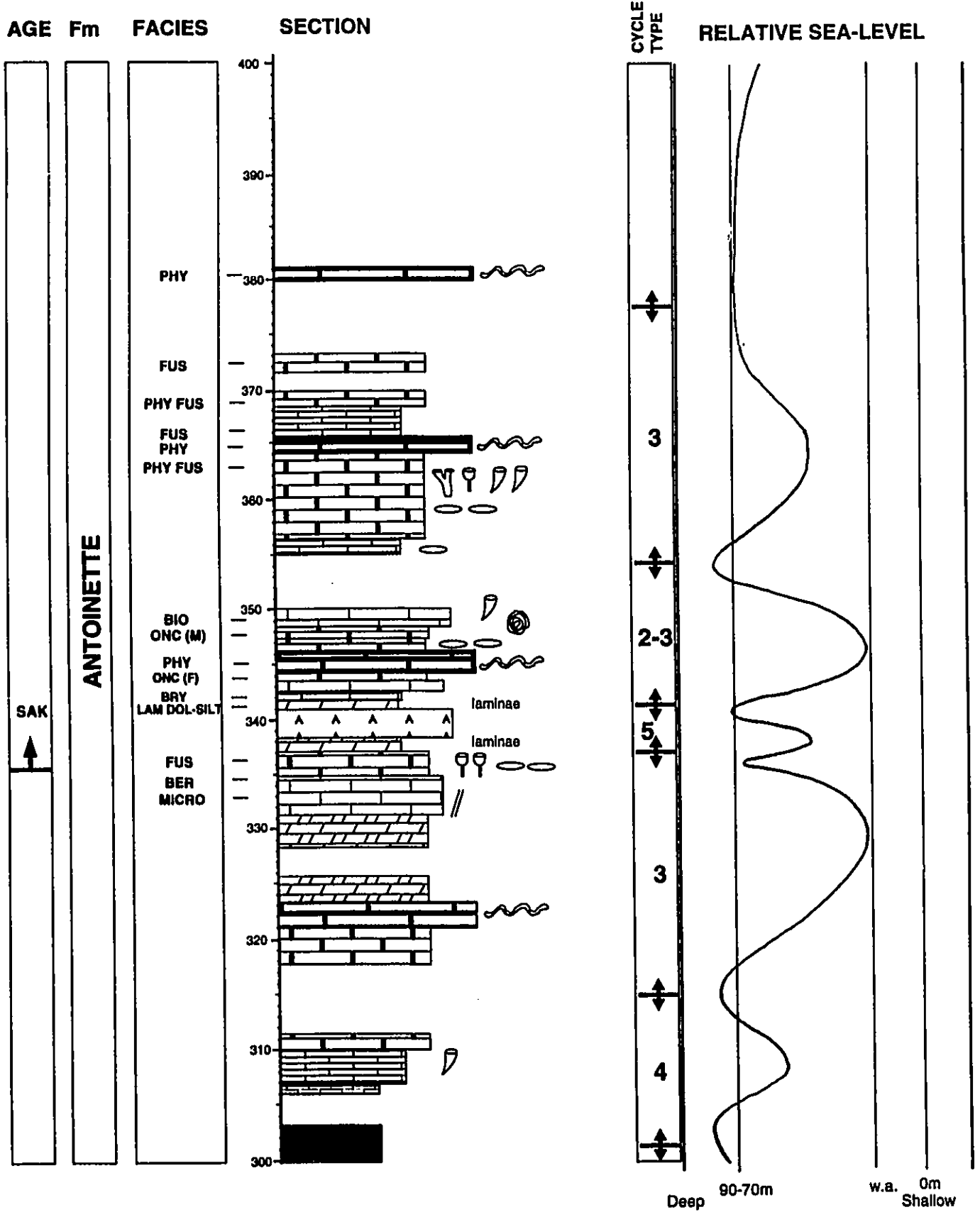
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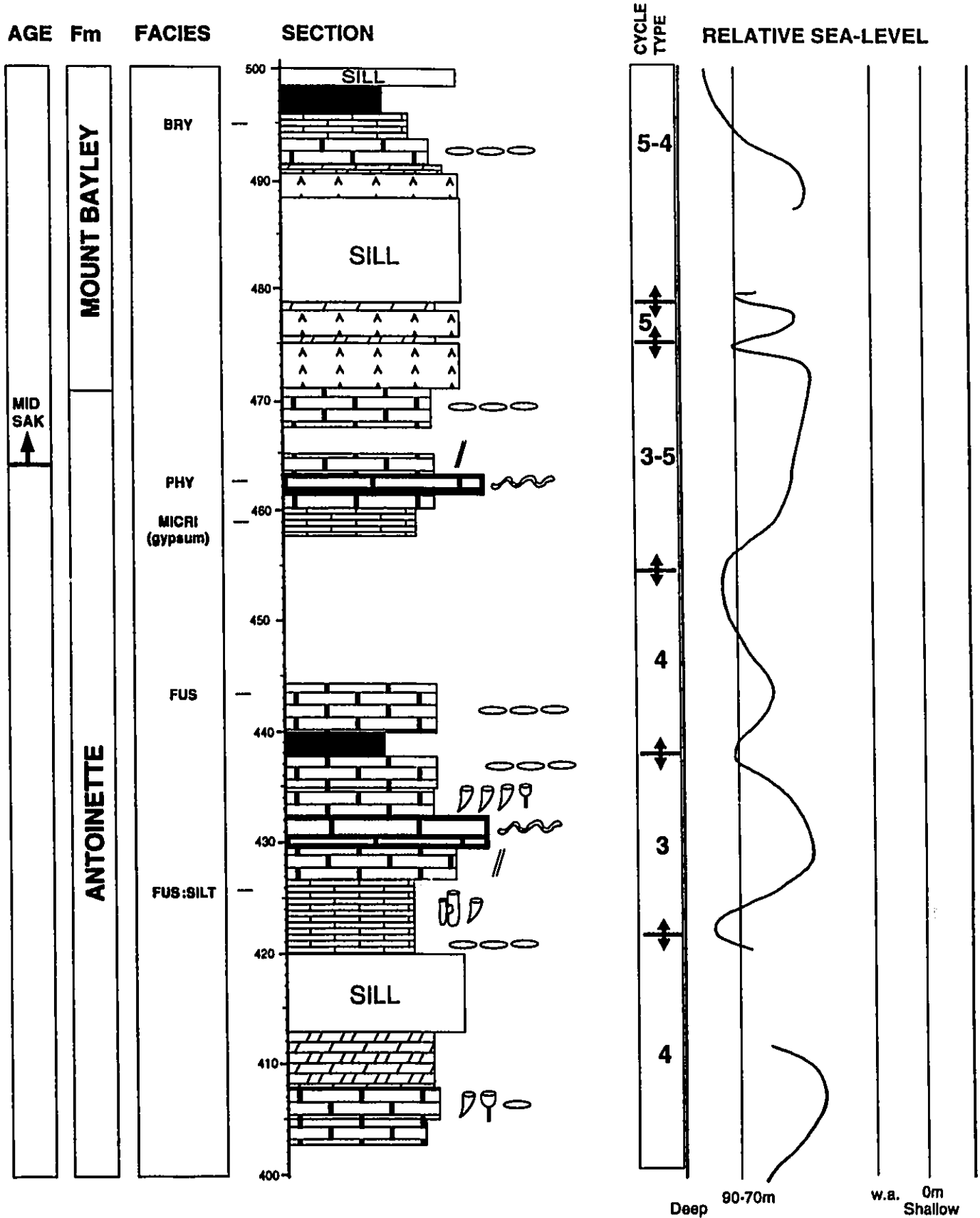
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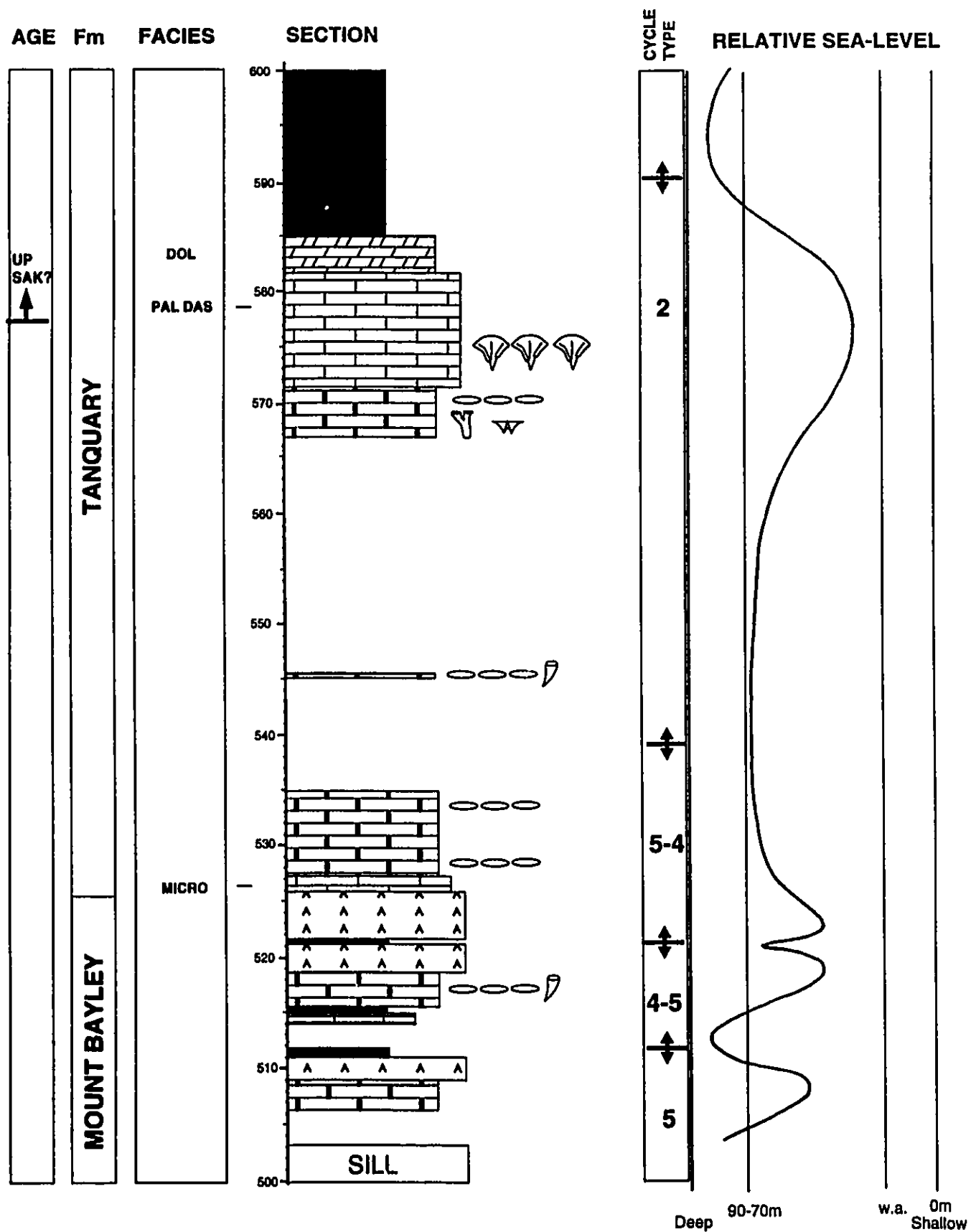
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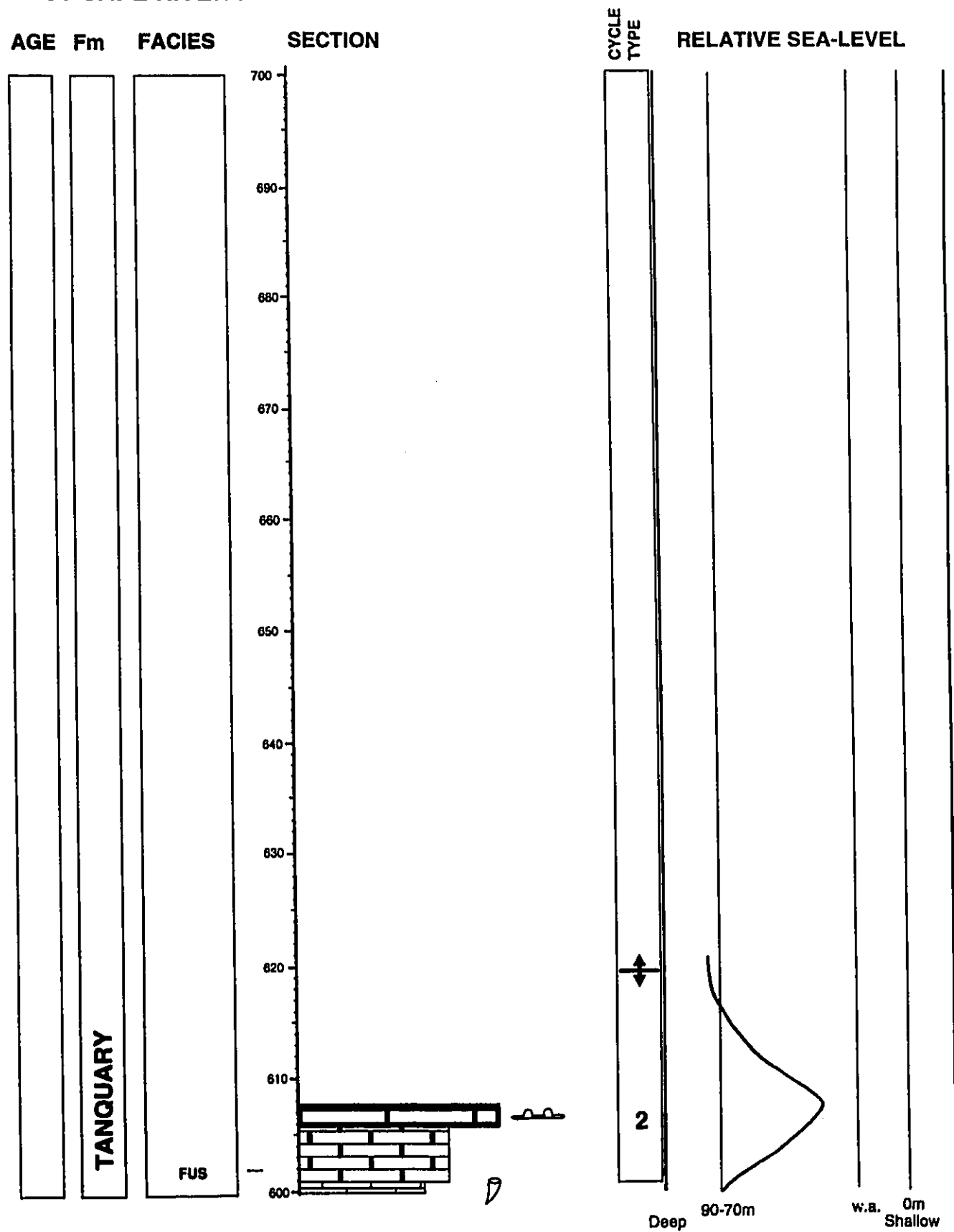
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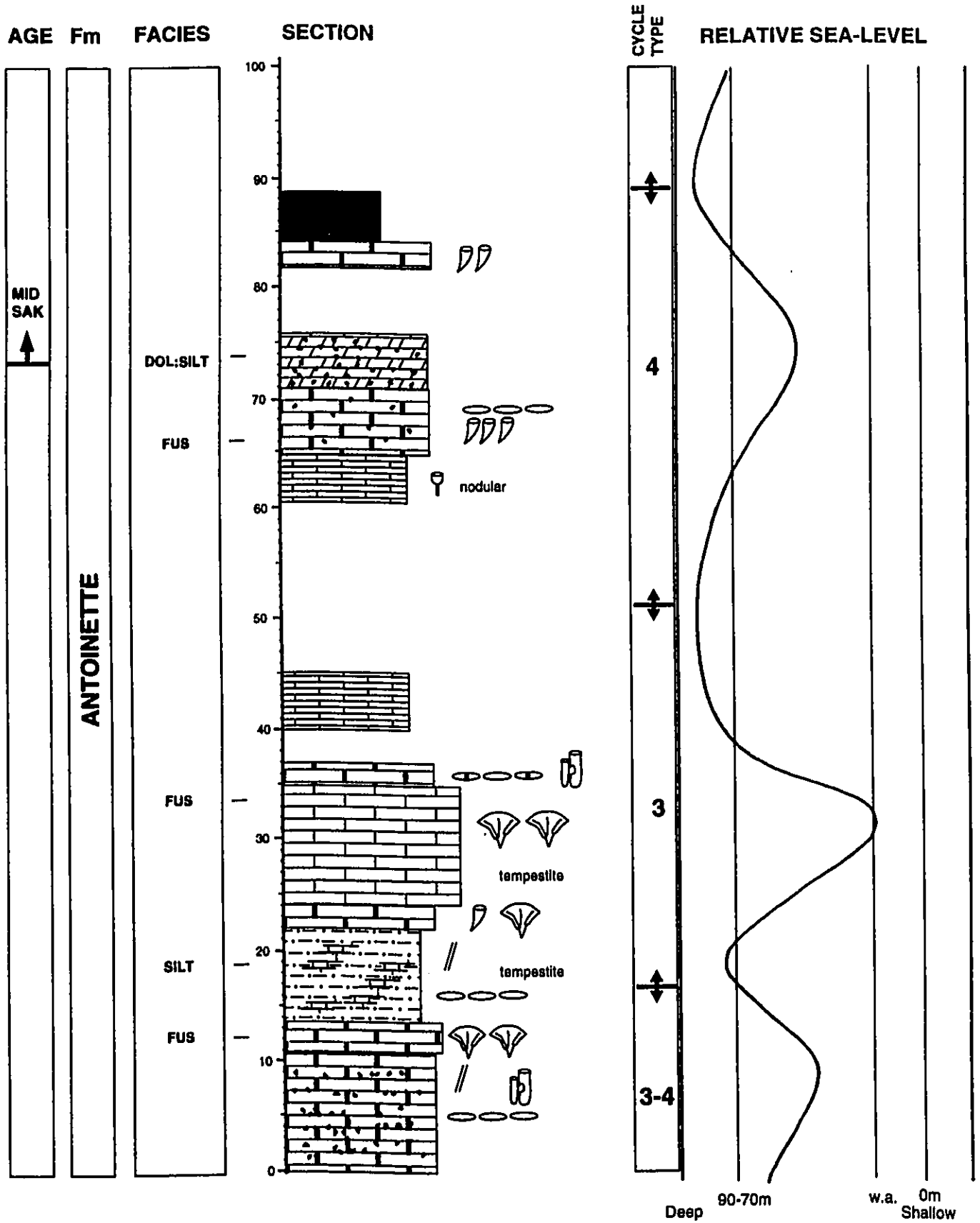
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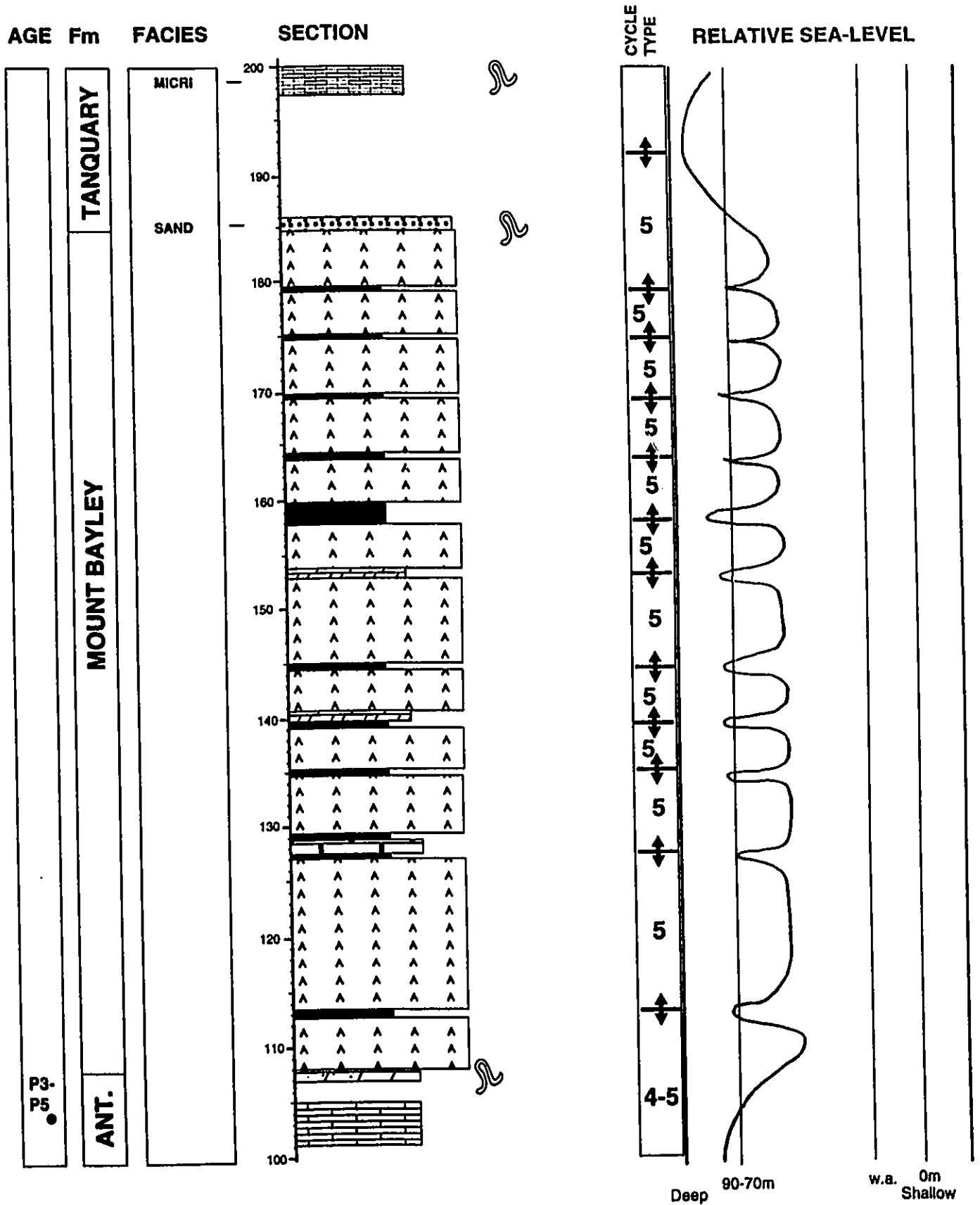
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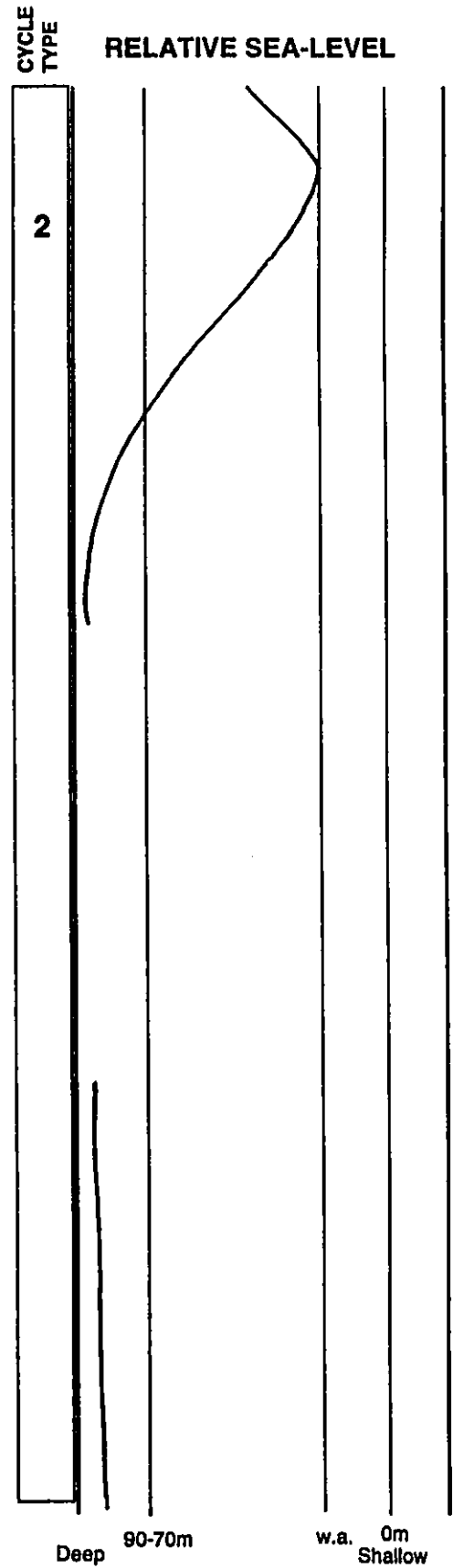
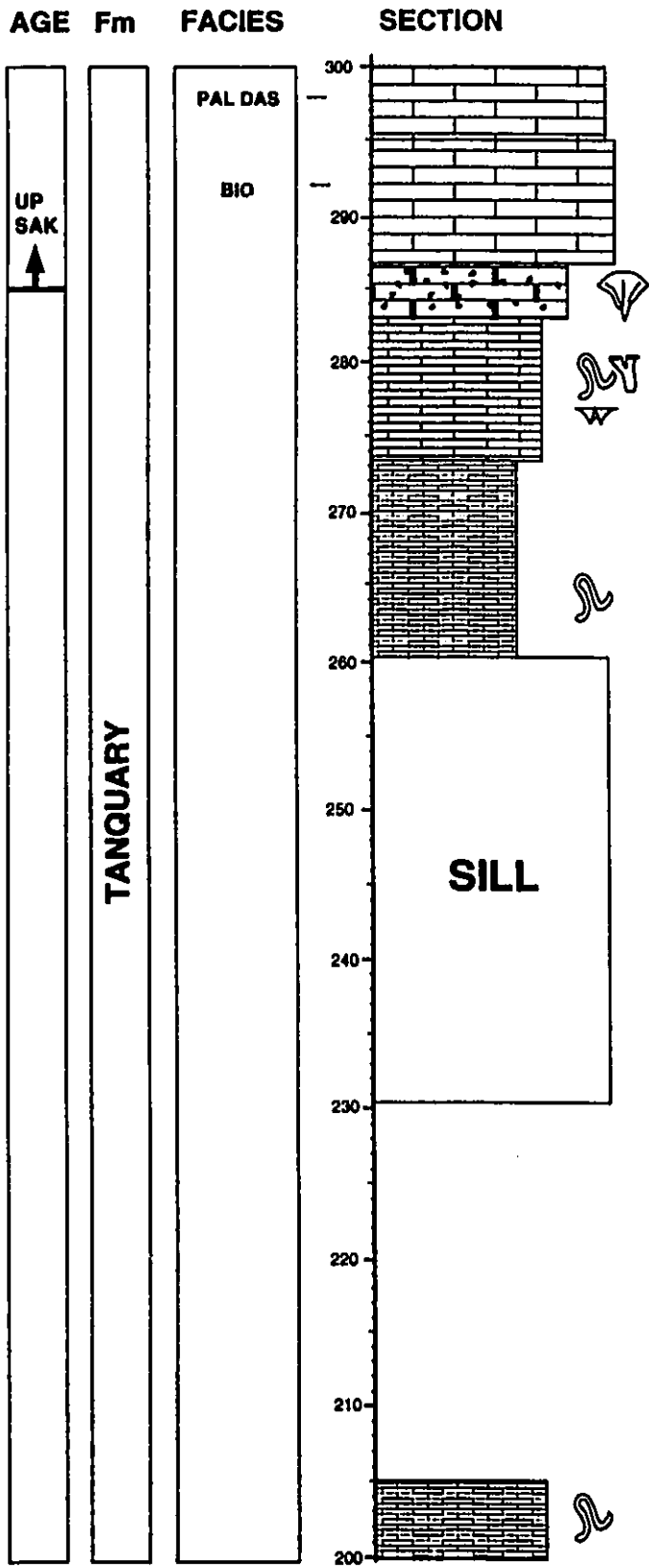
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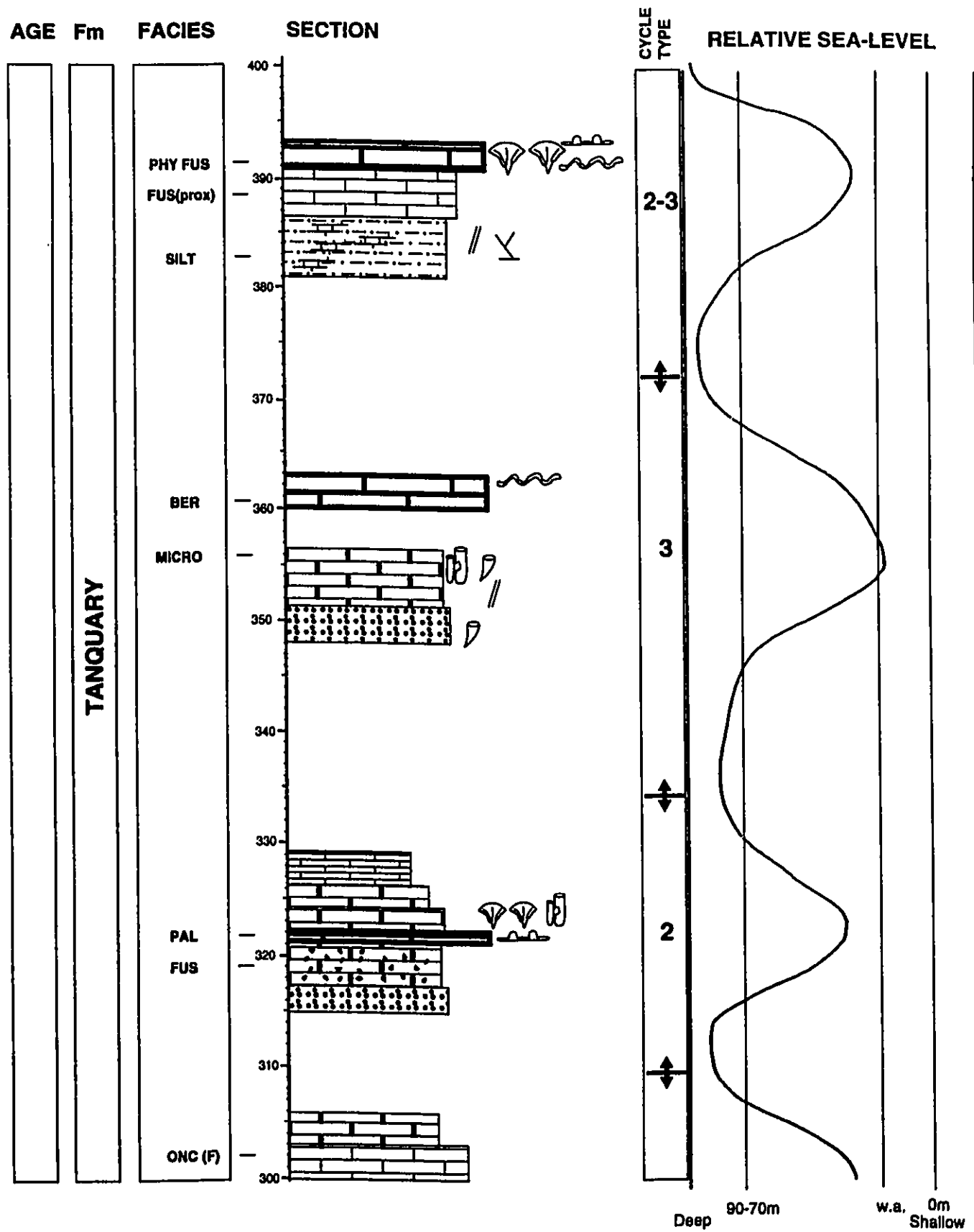
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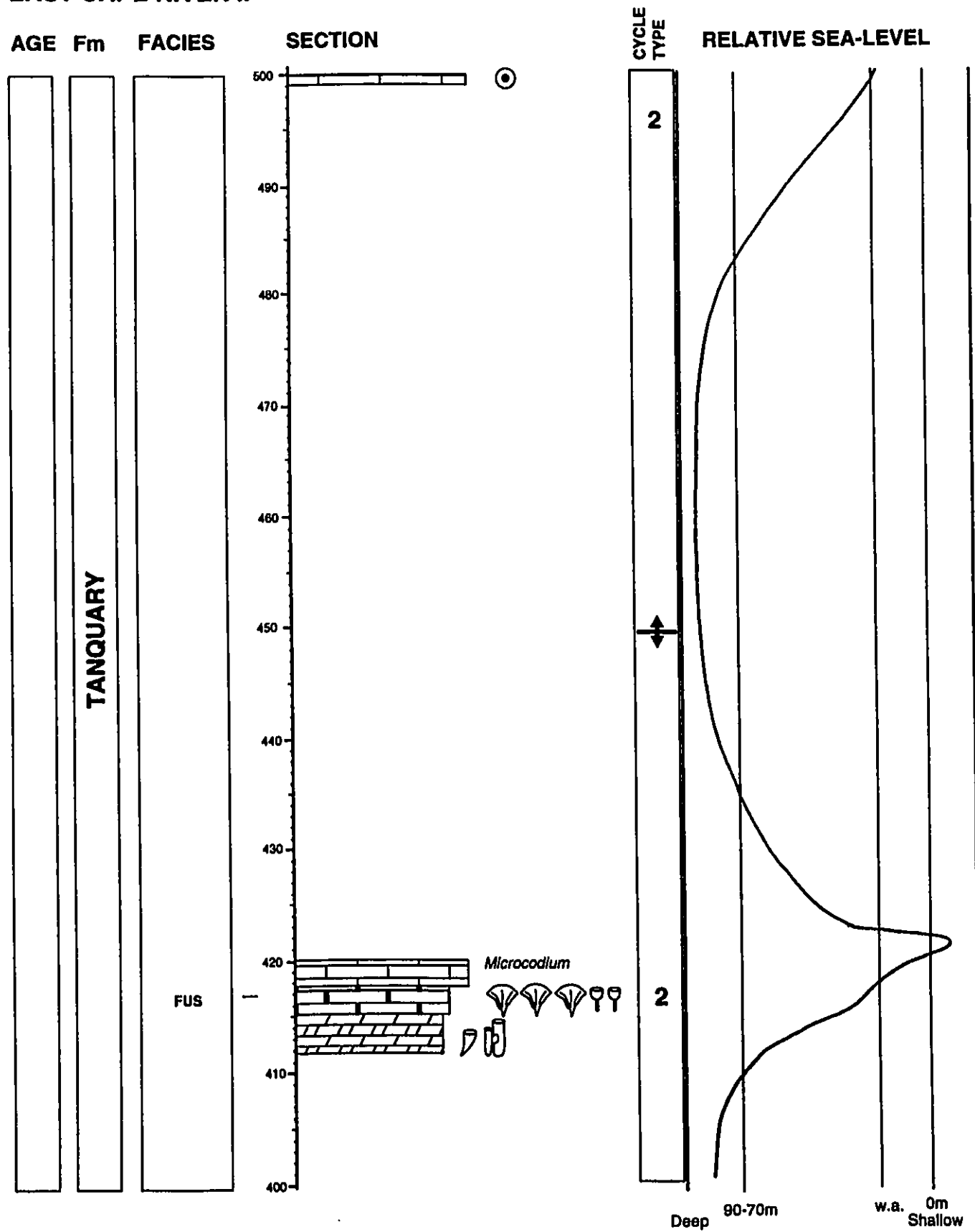
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EAST CAPE RIVER II

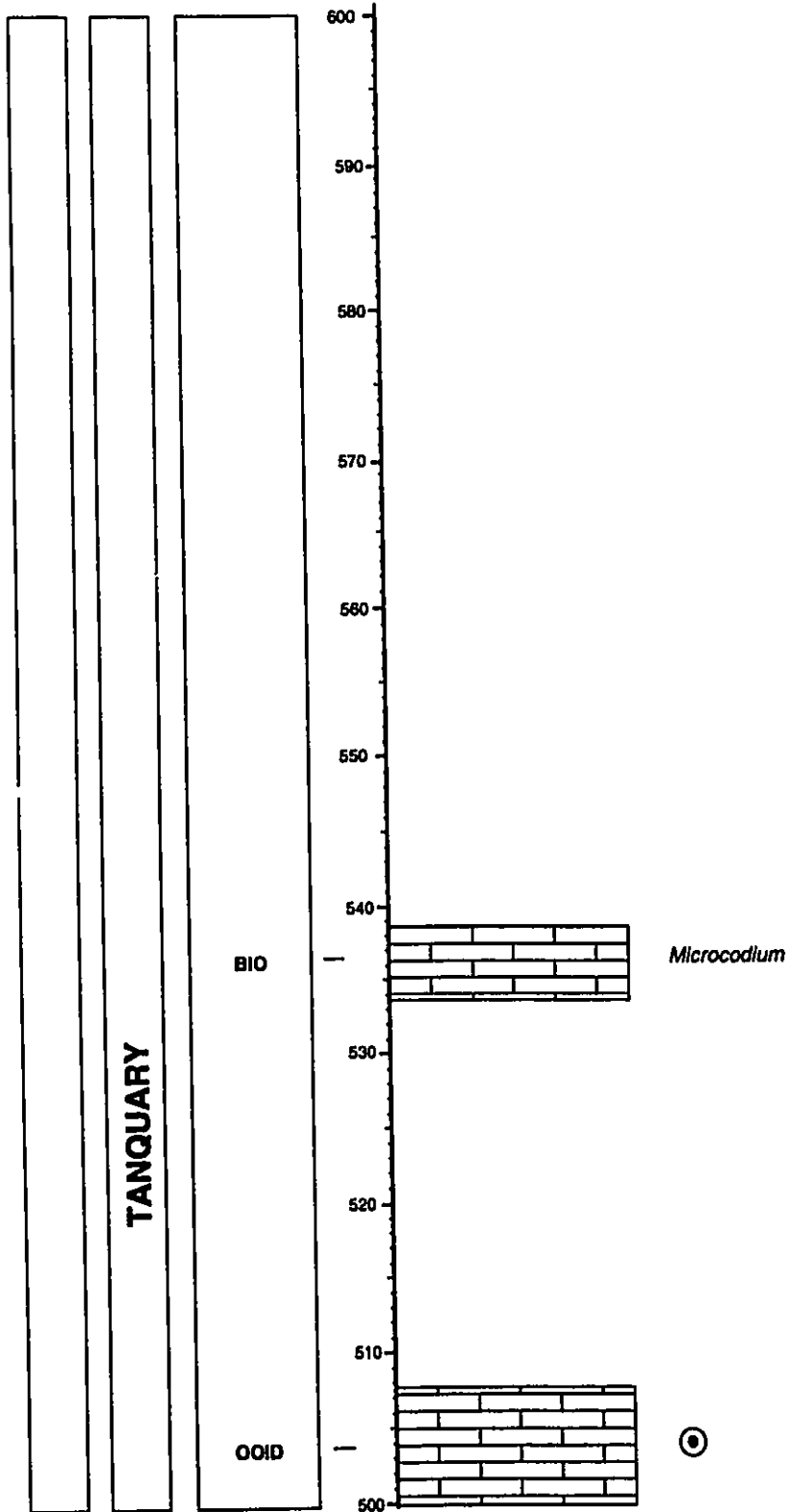


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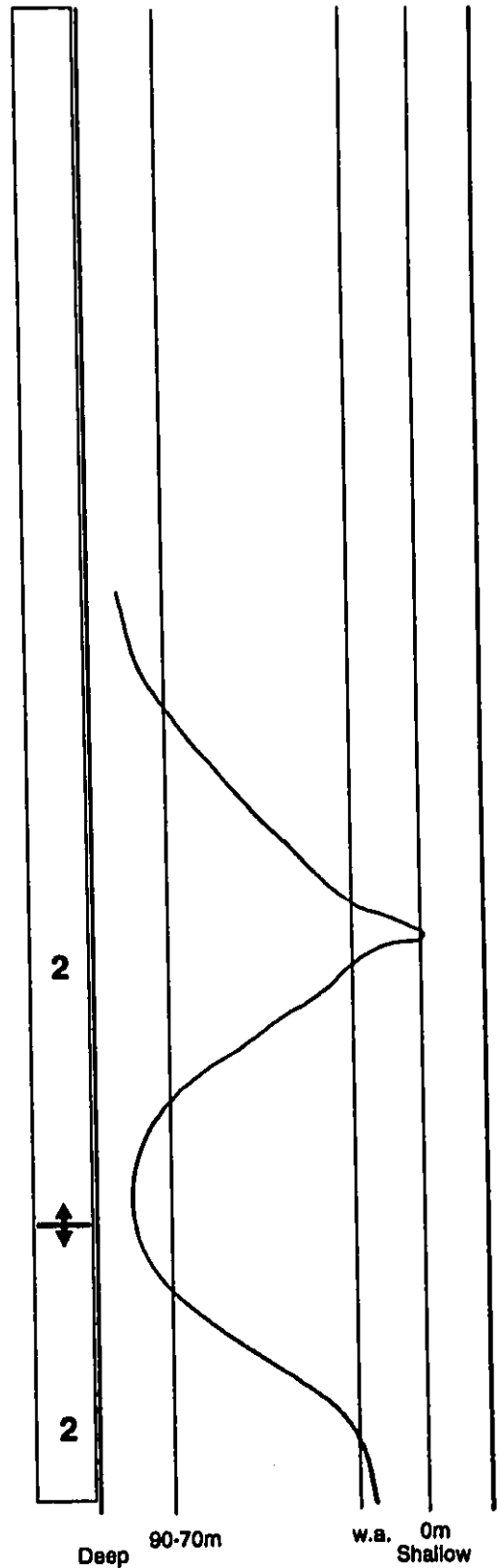


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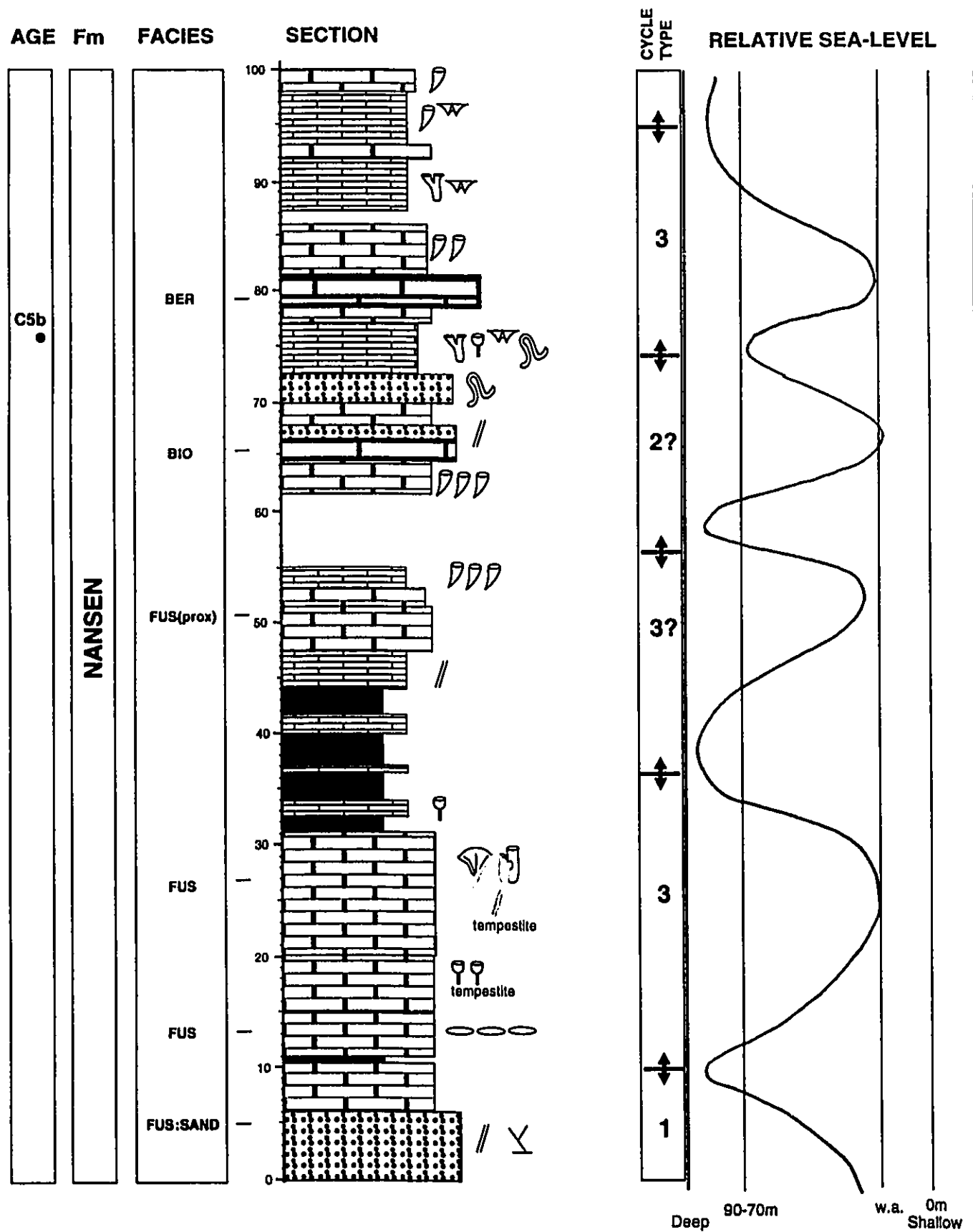
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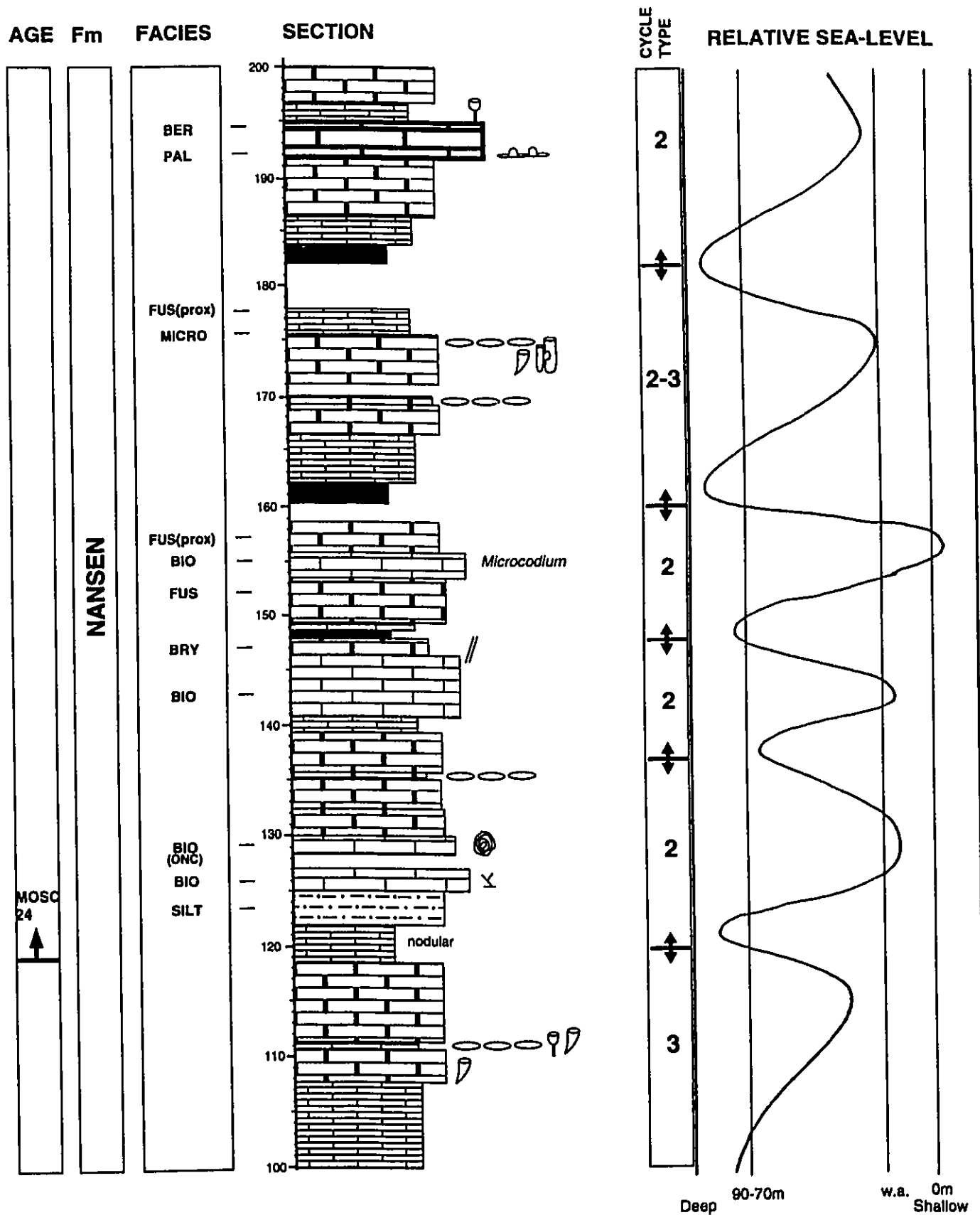
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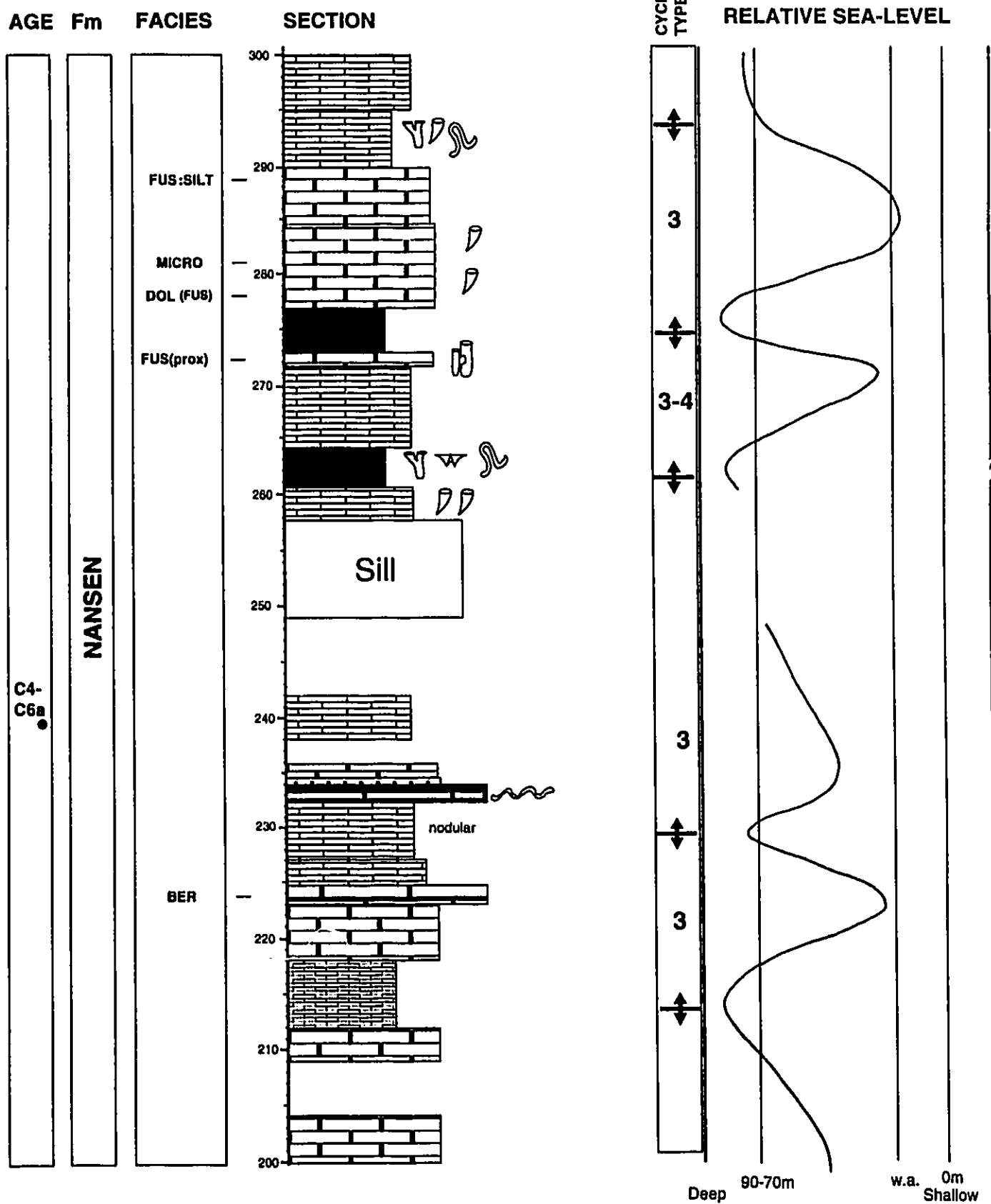
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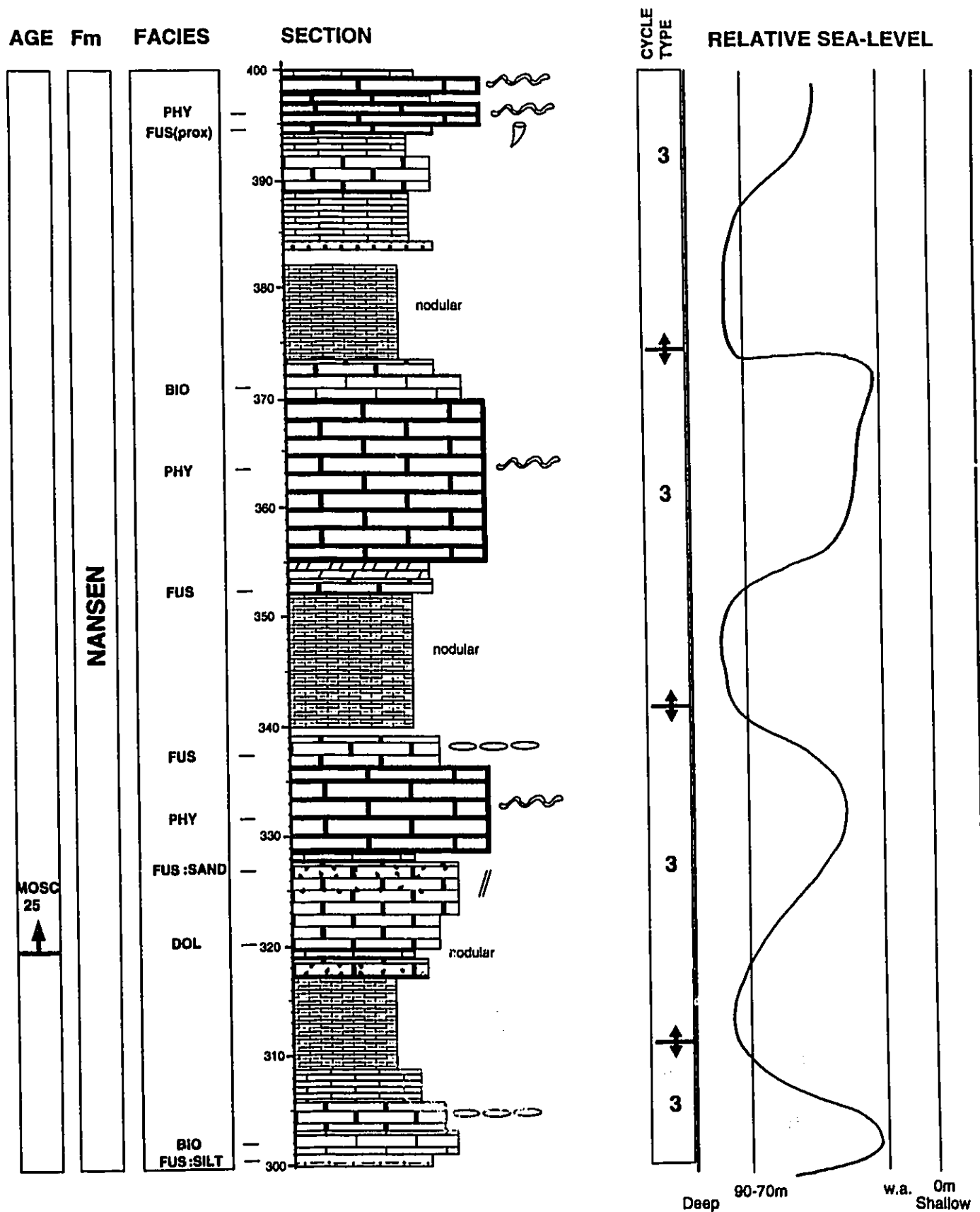
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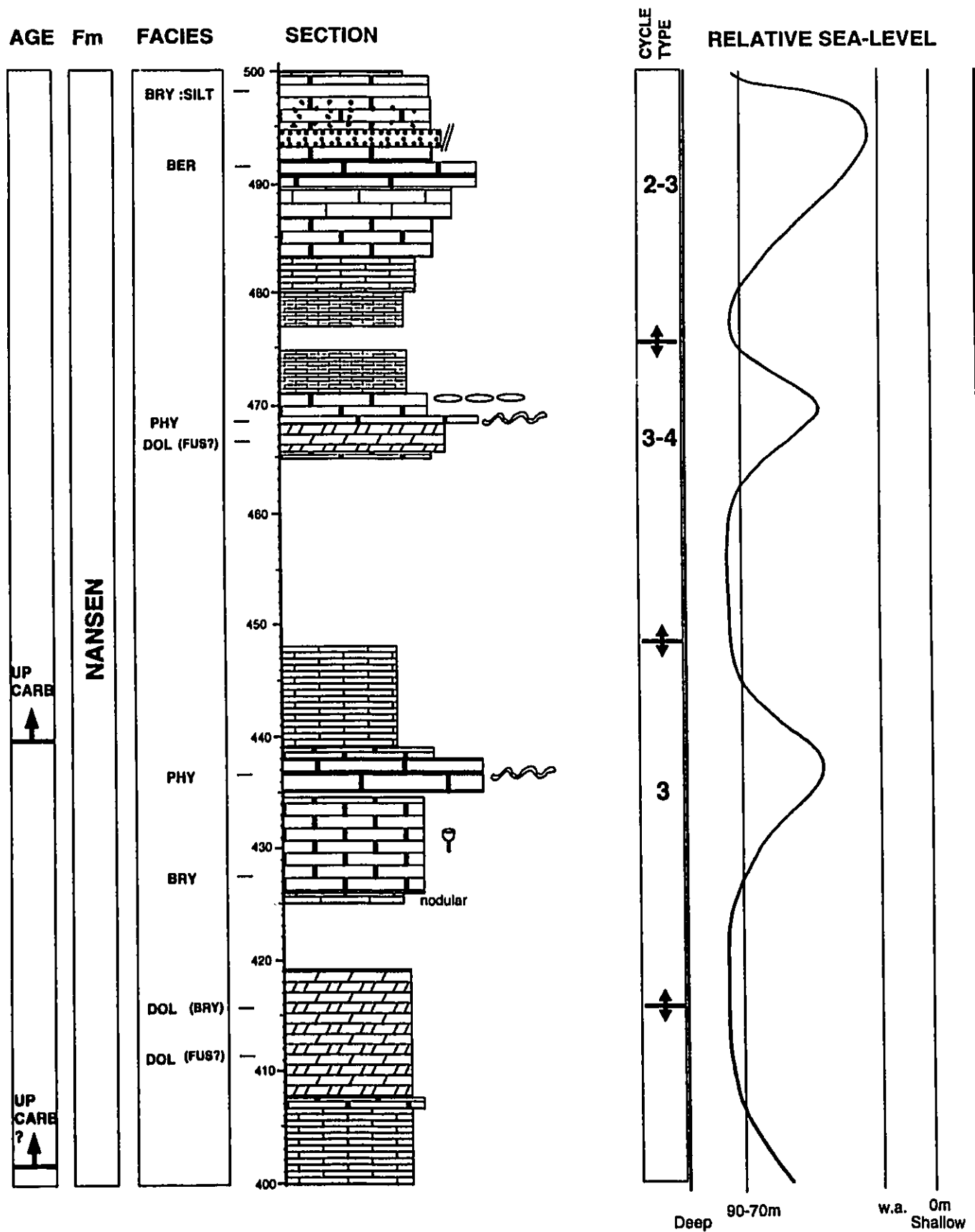
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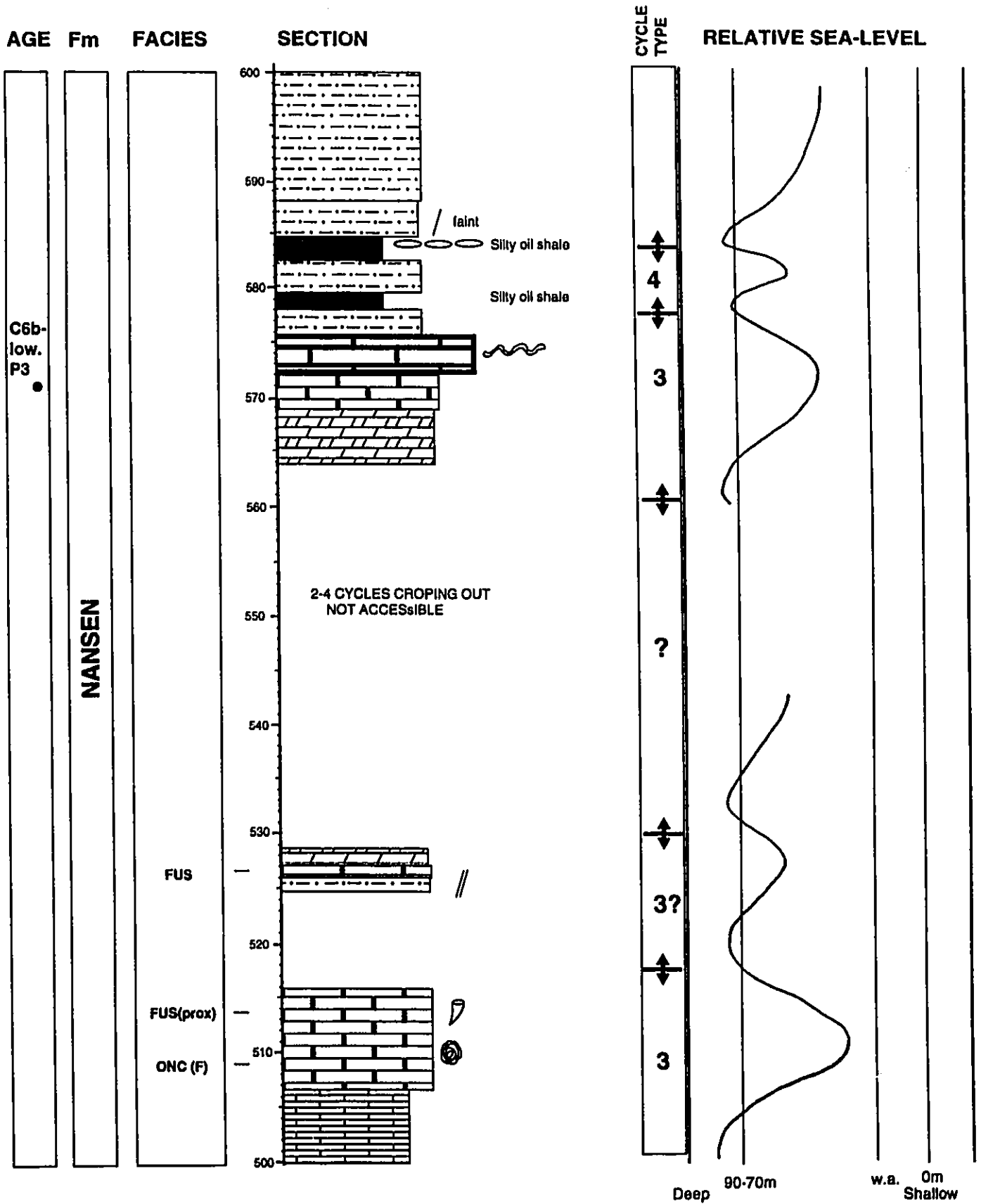
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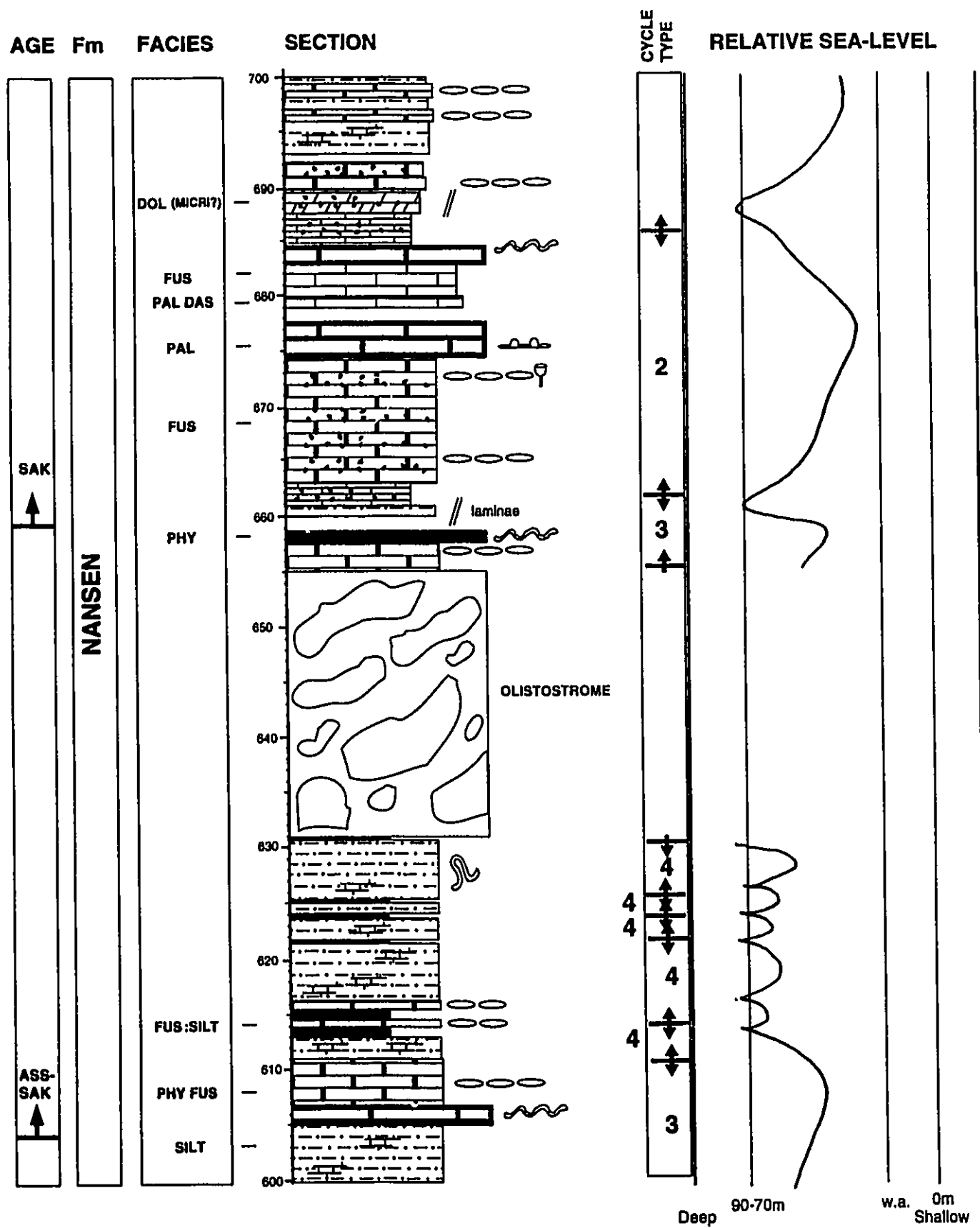
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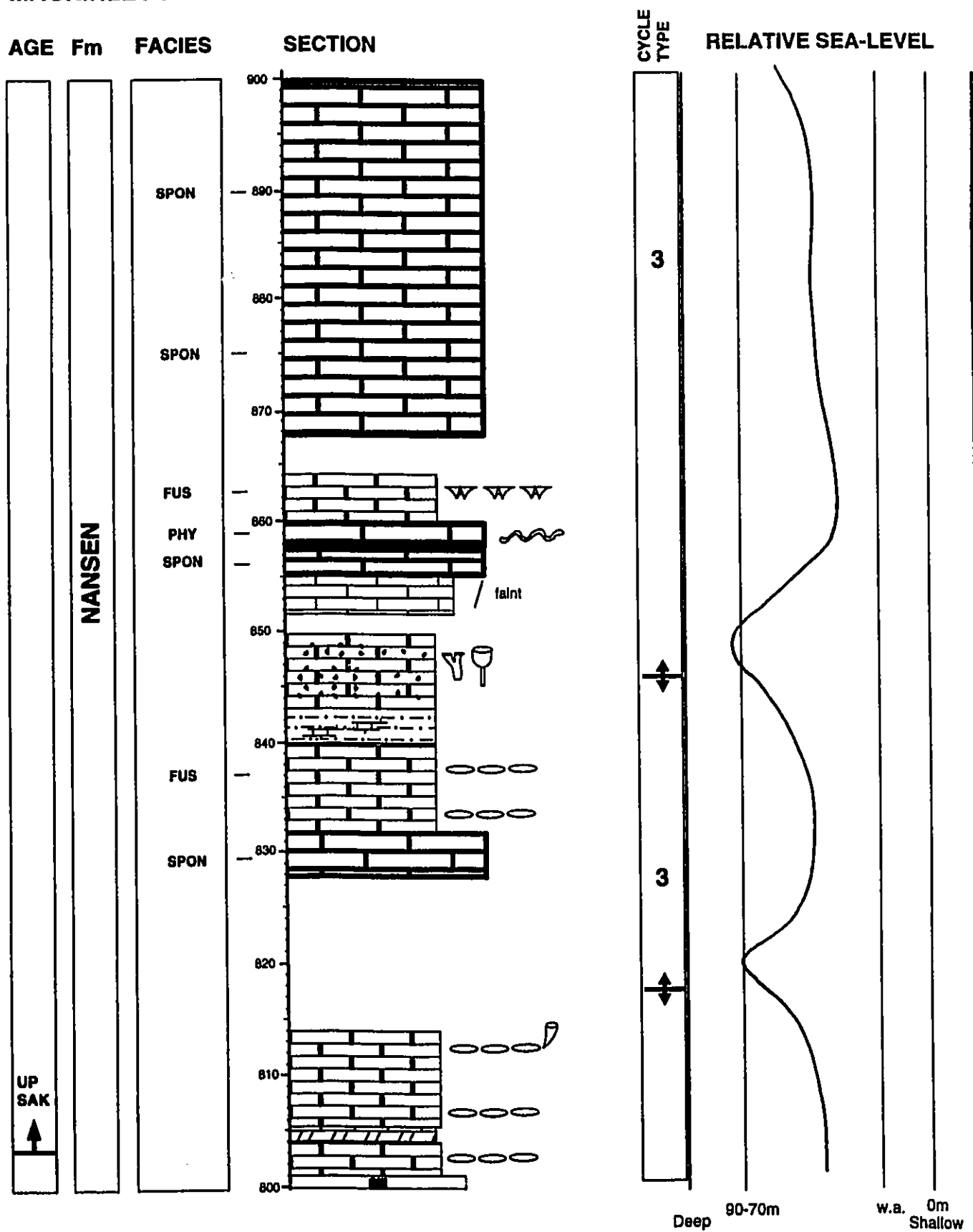
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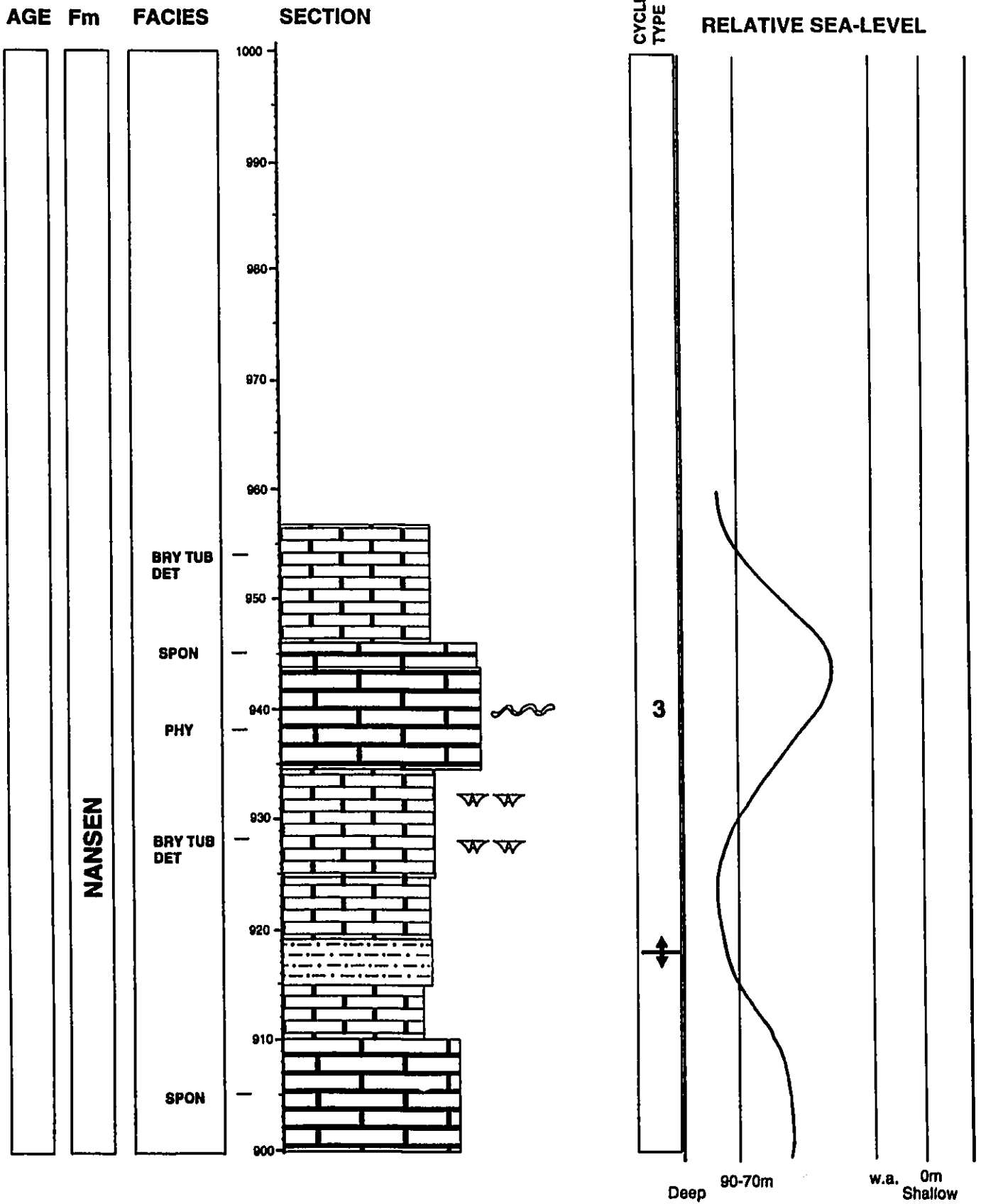
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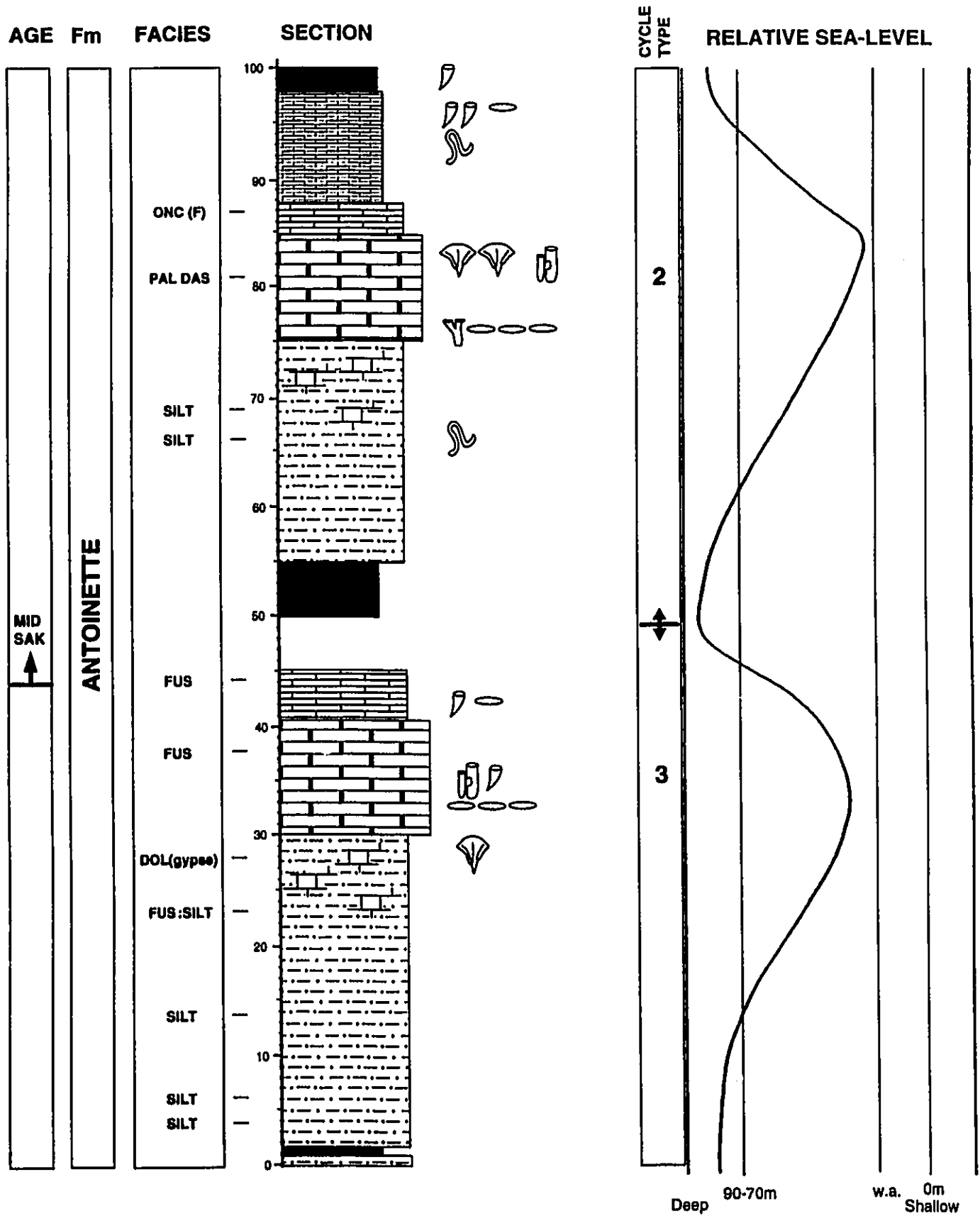
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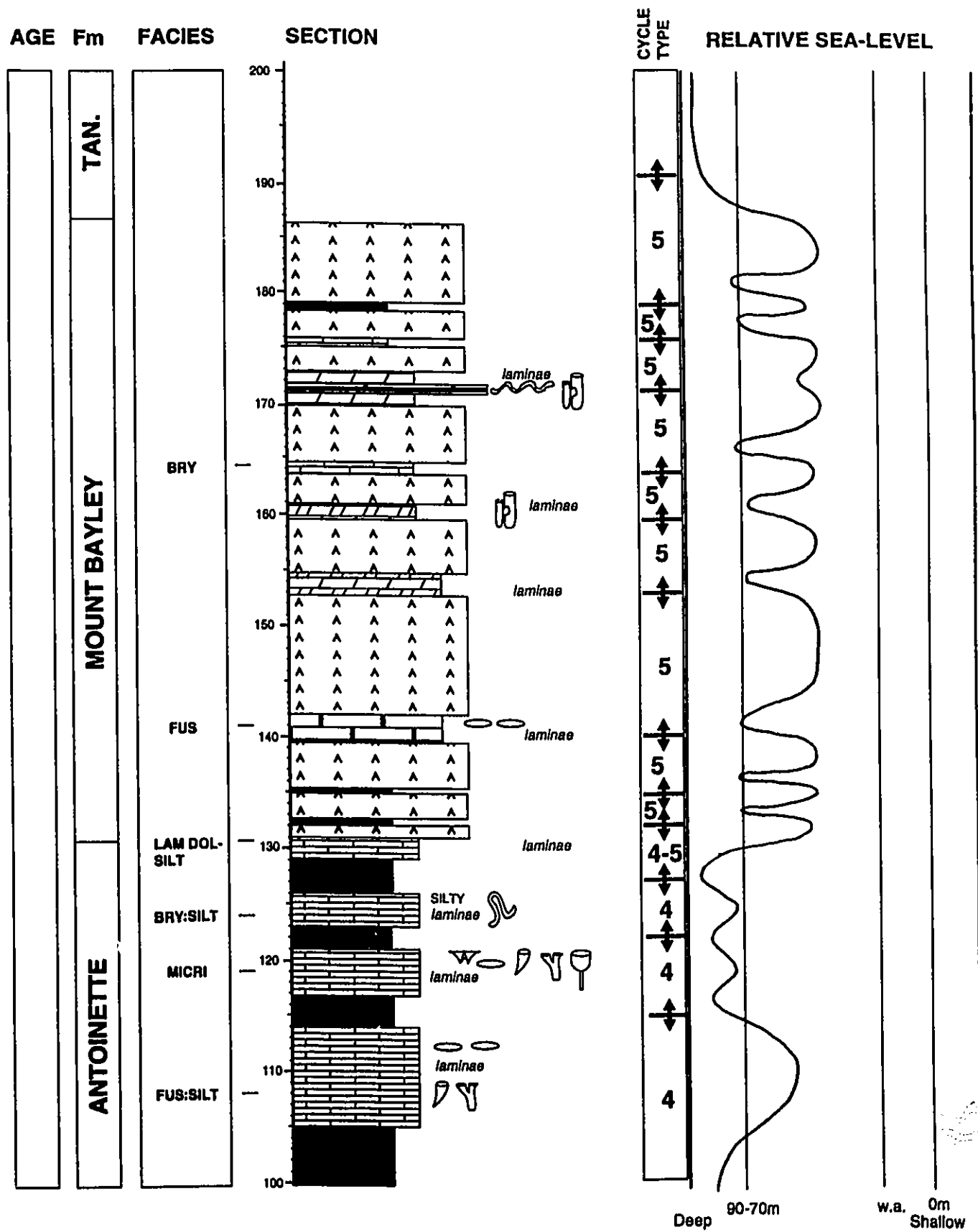
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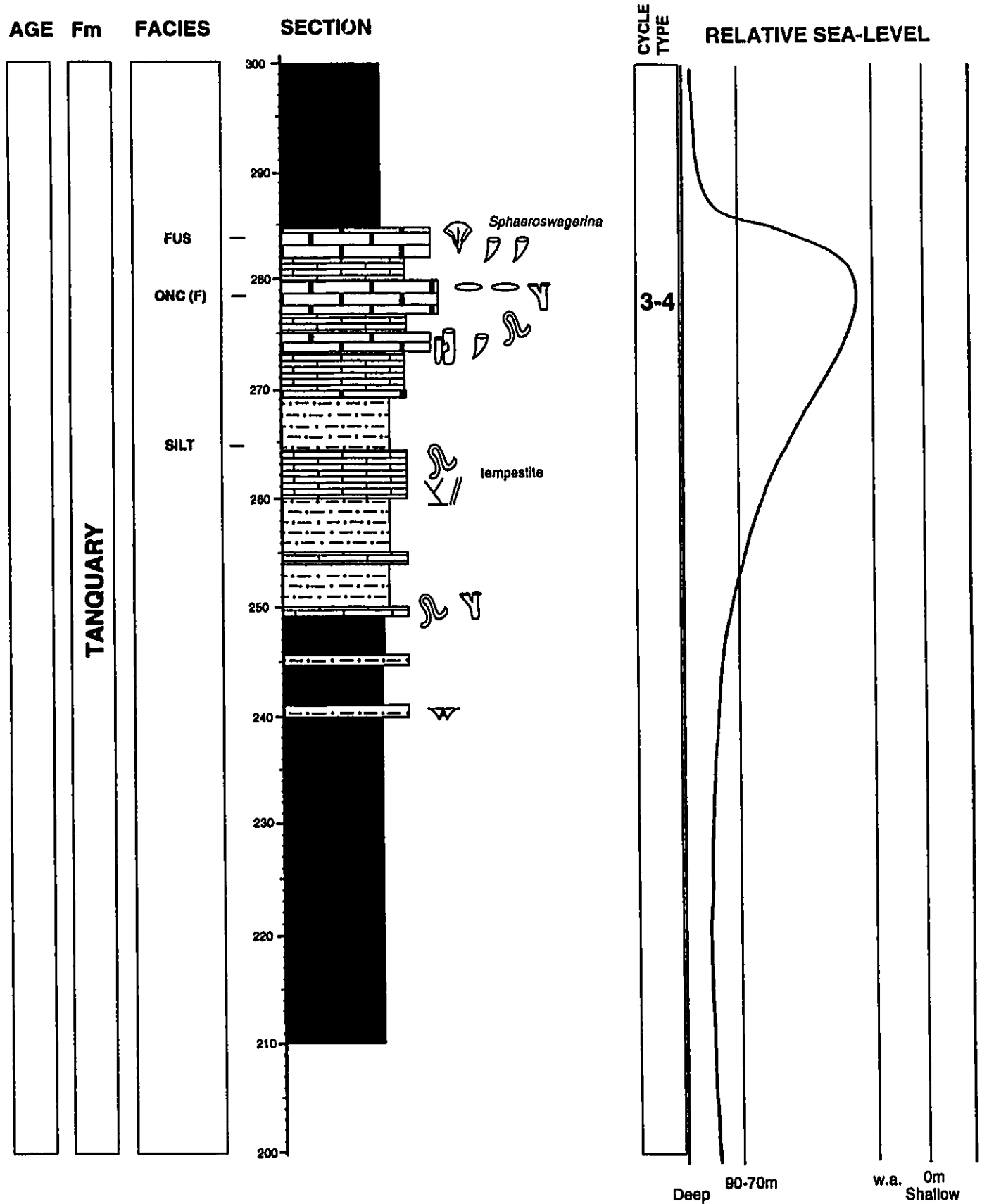
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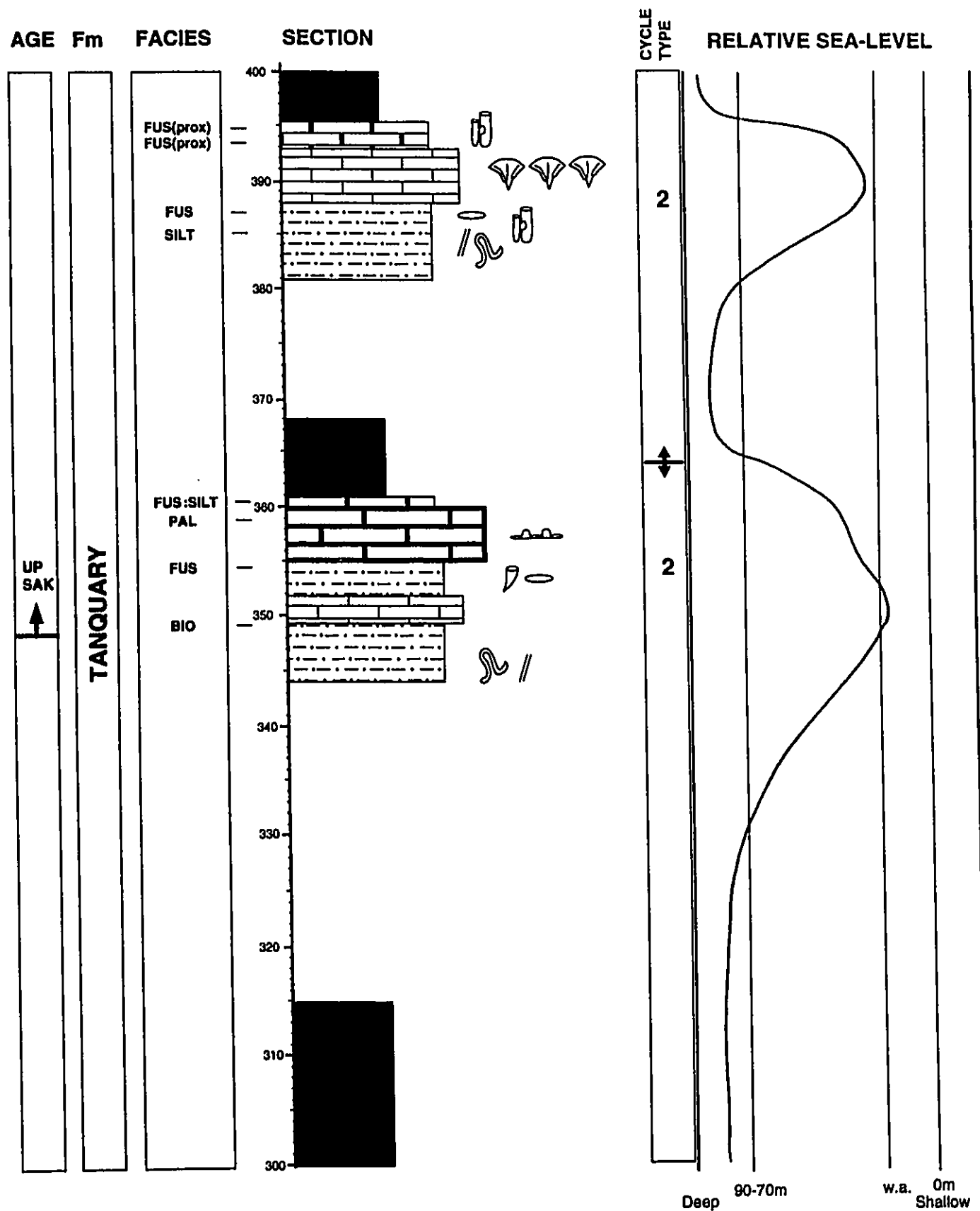
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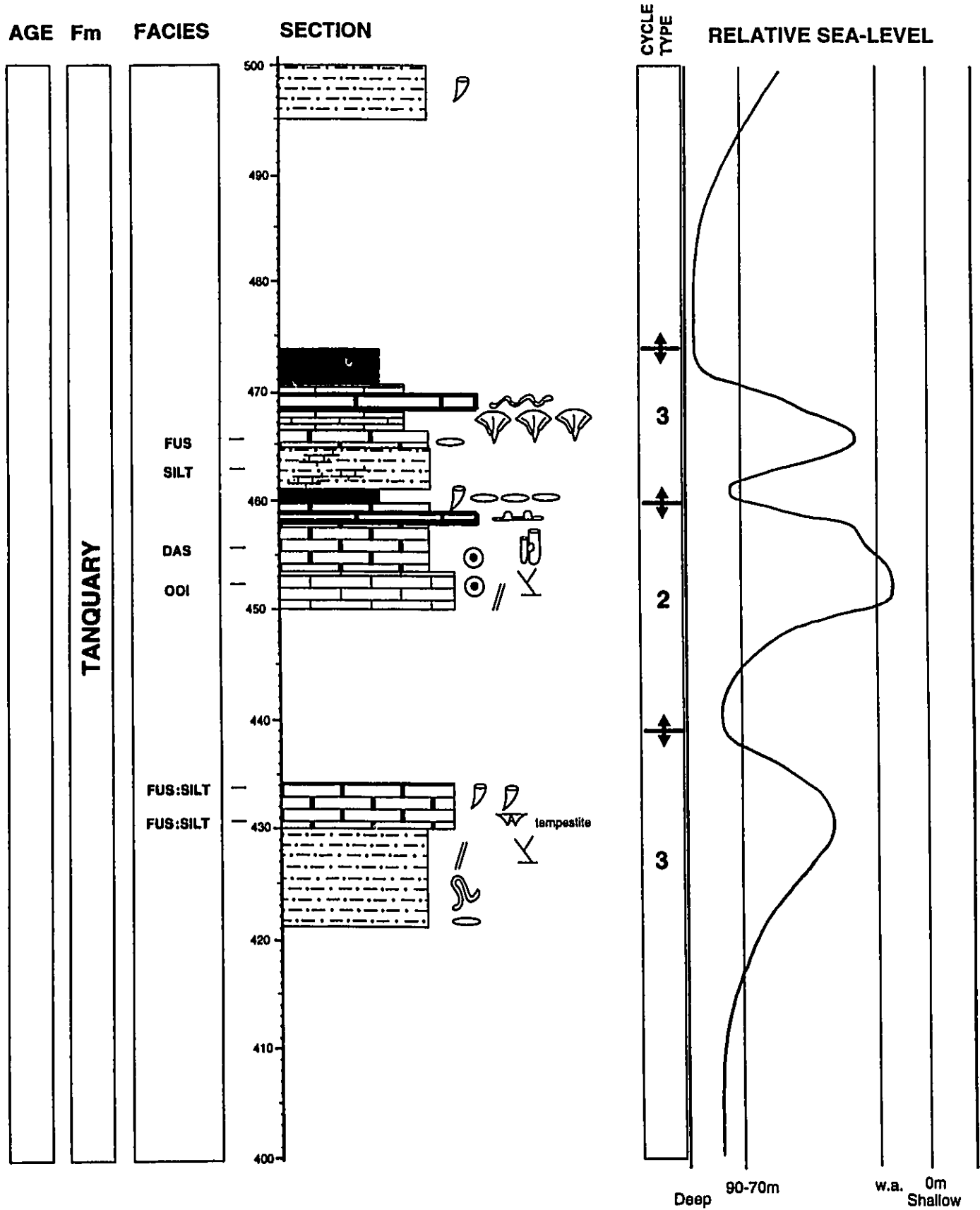
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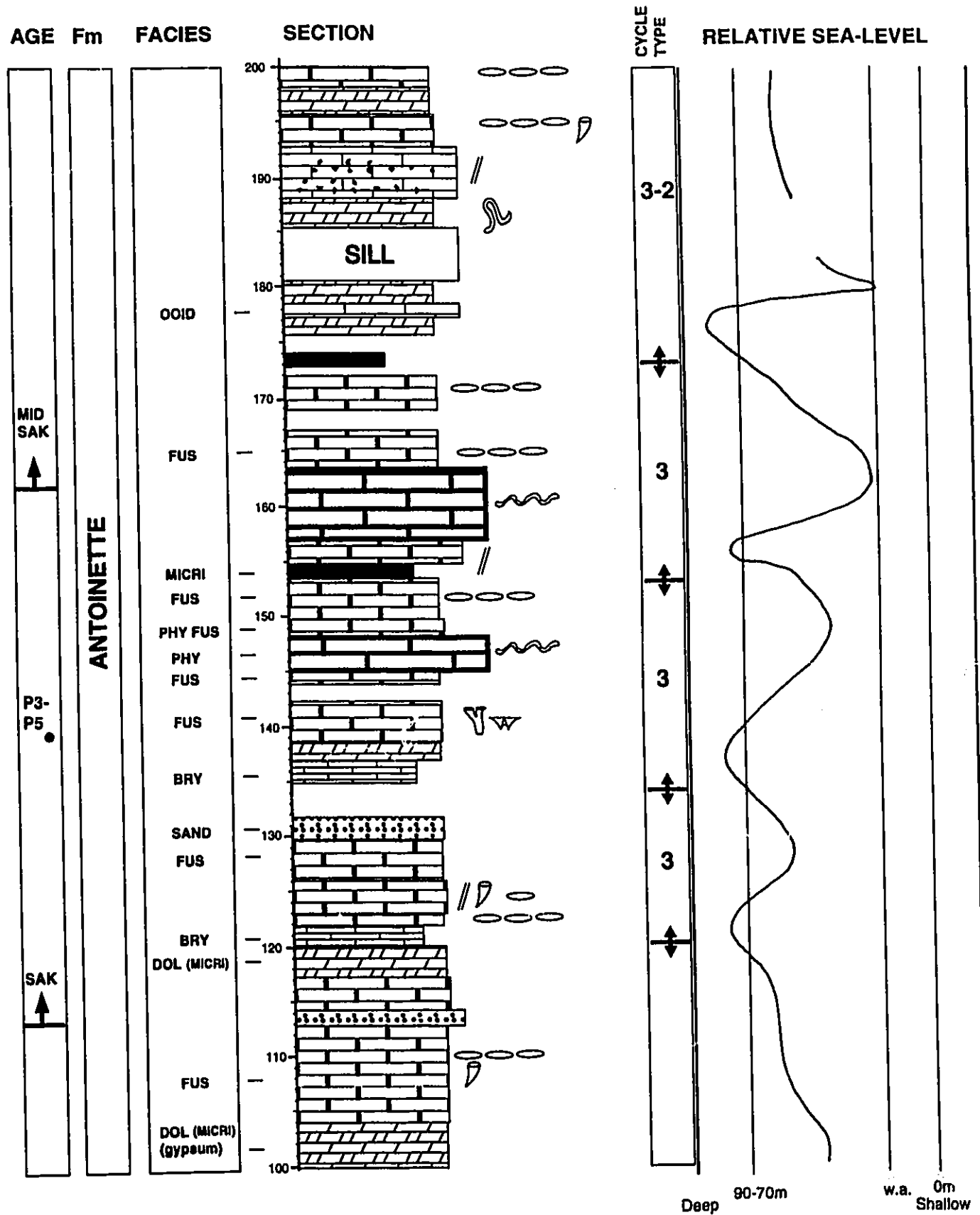
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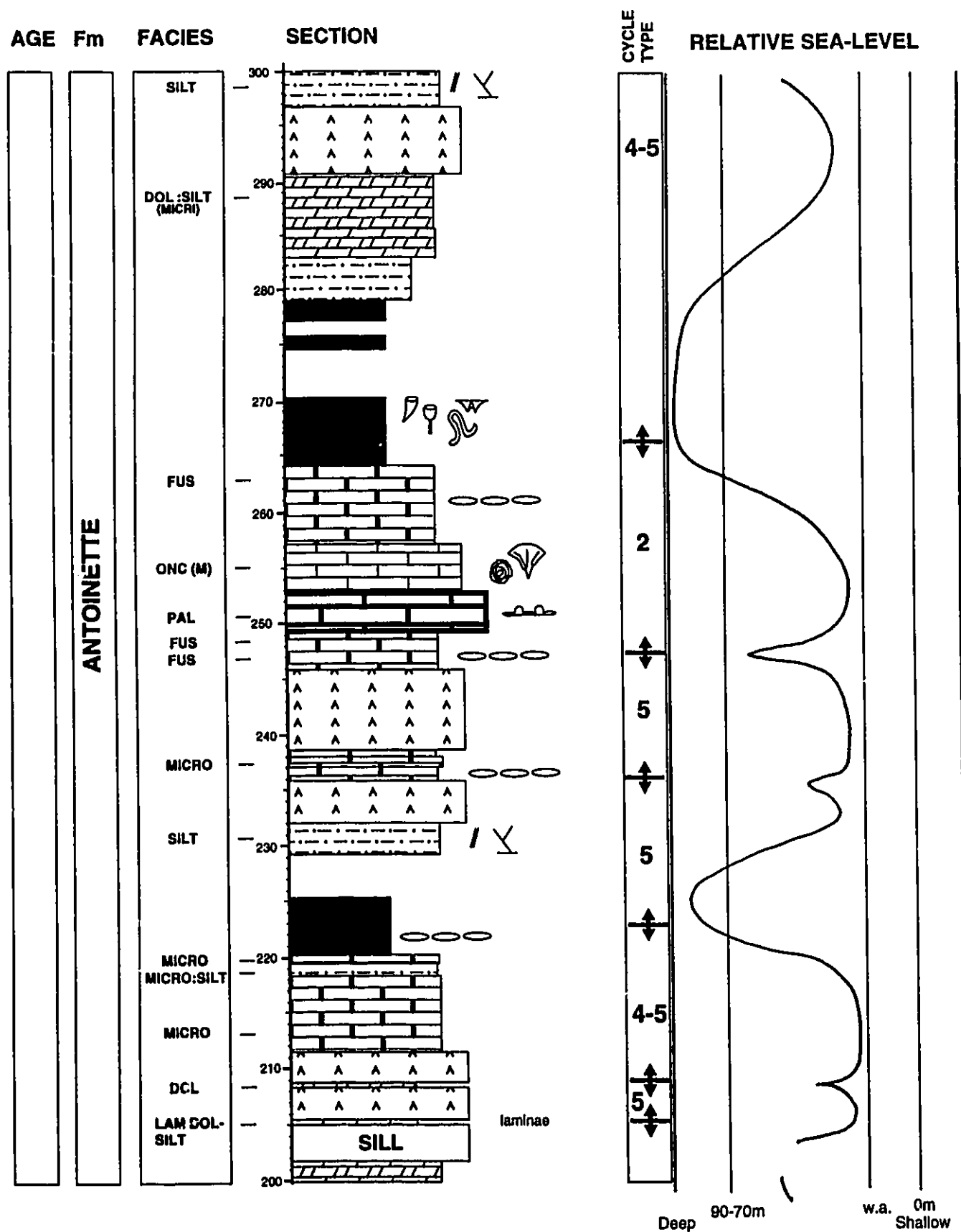
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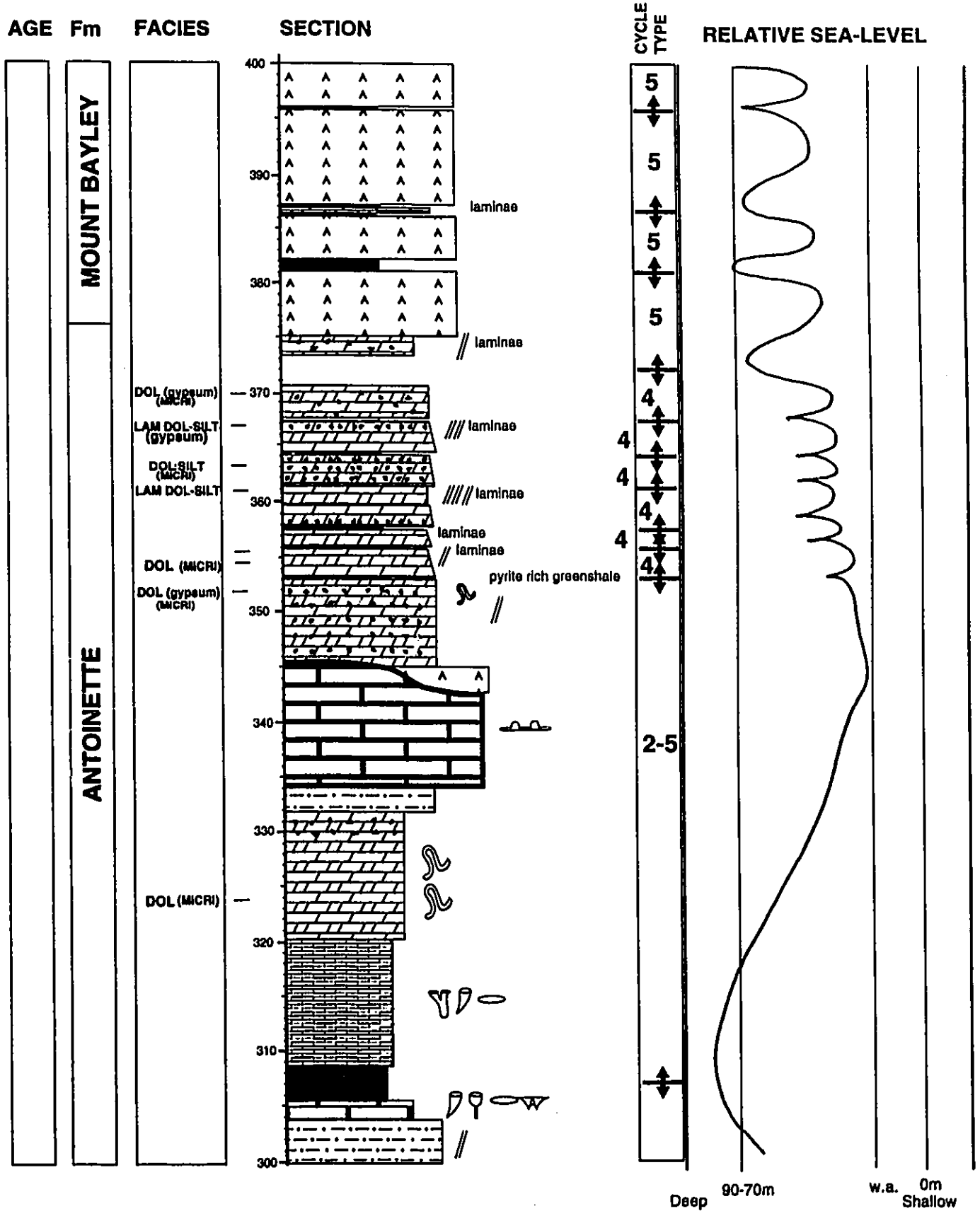
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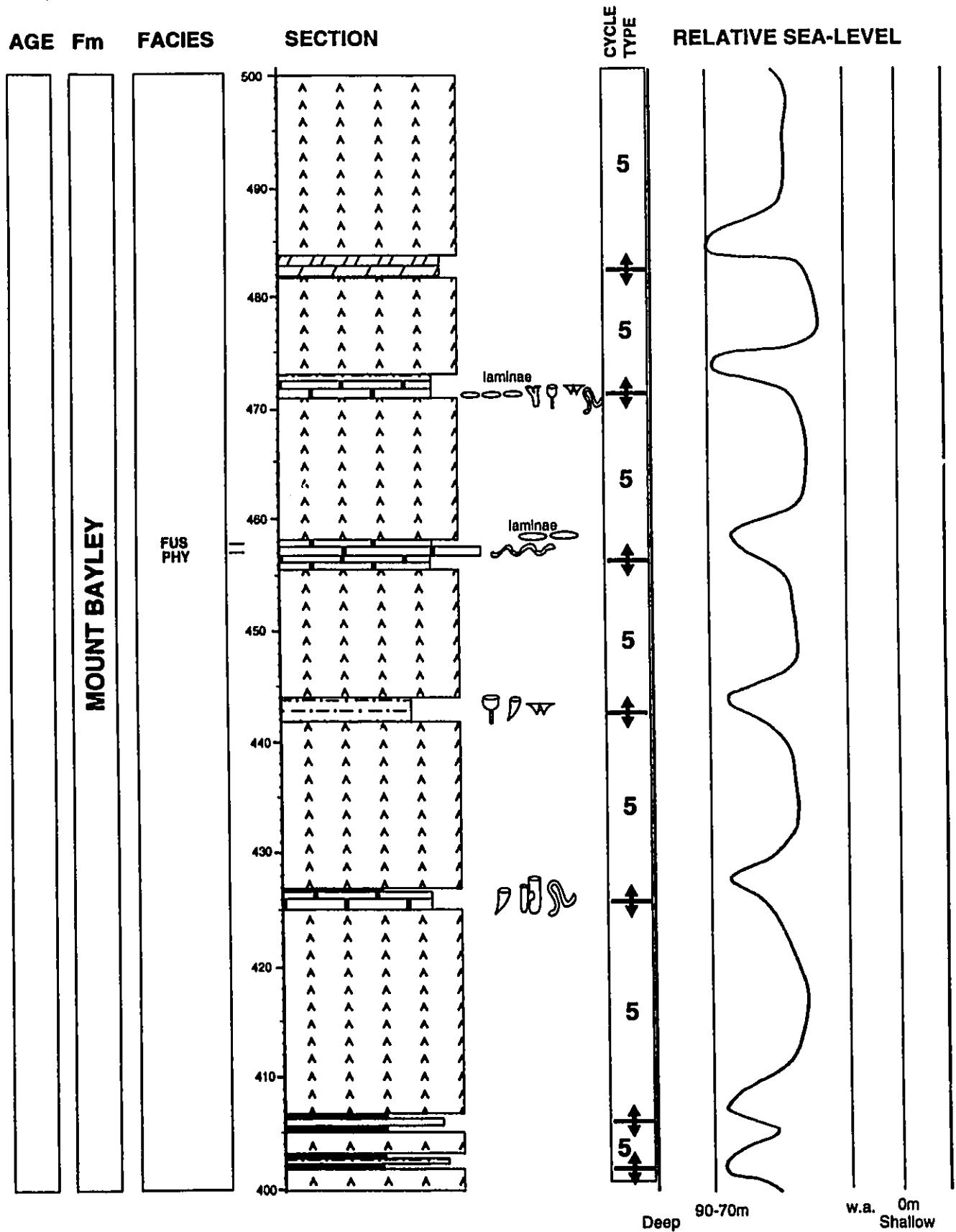
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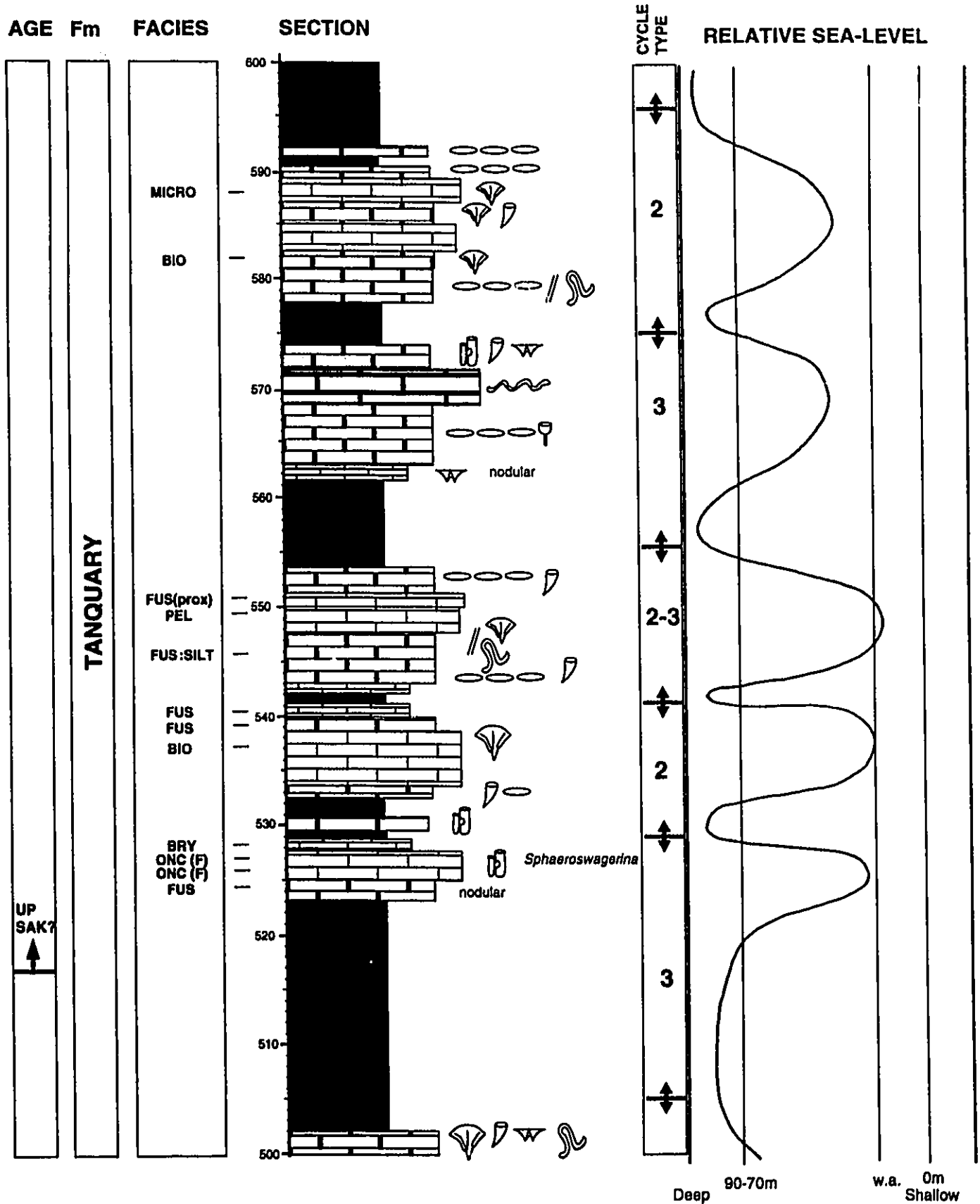
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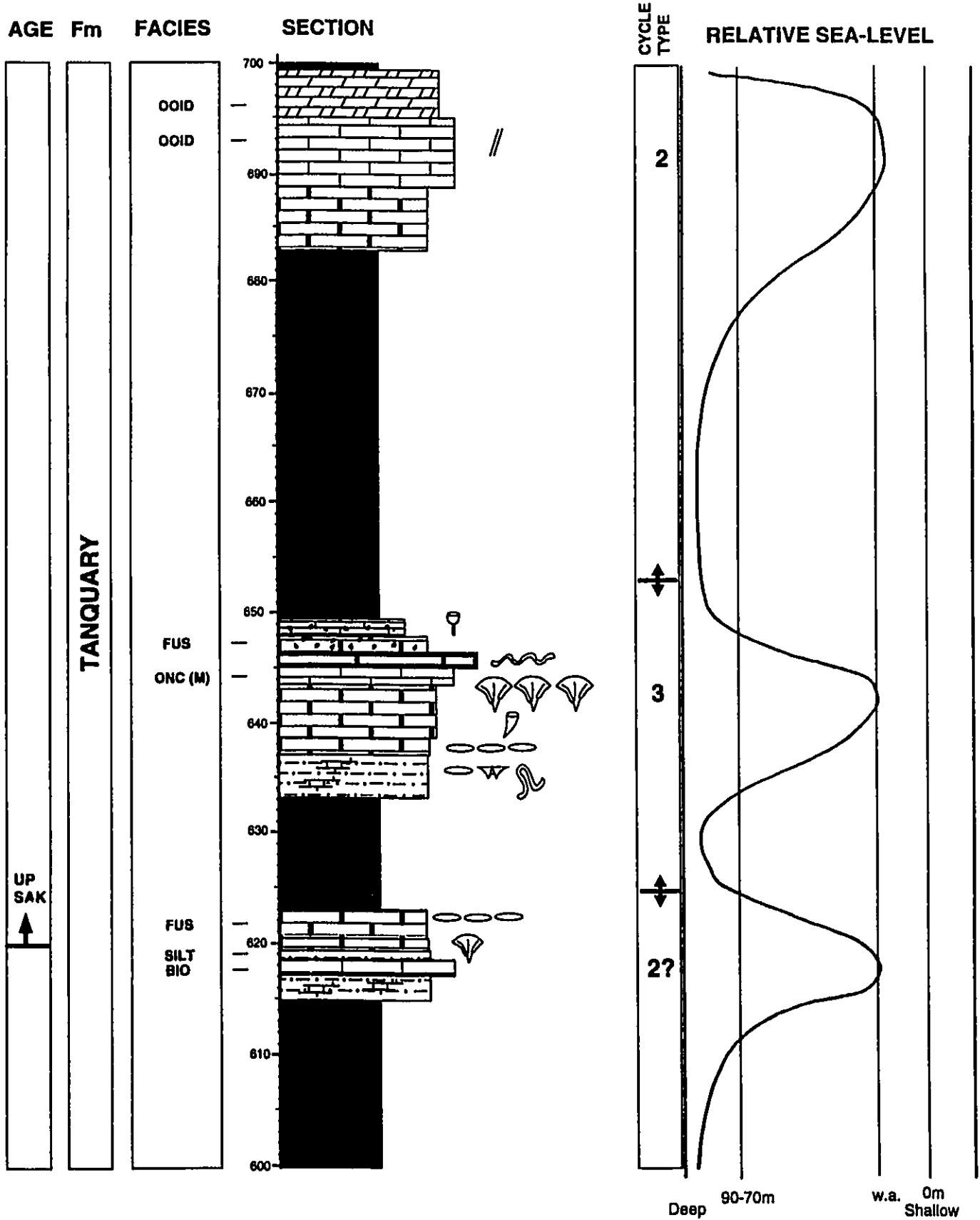
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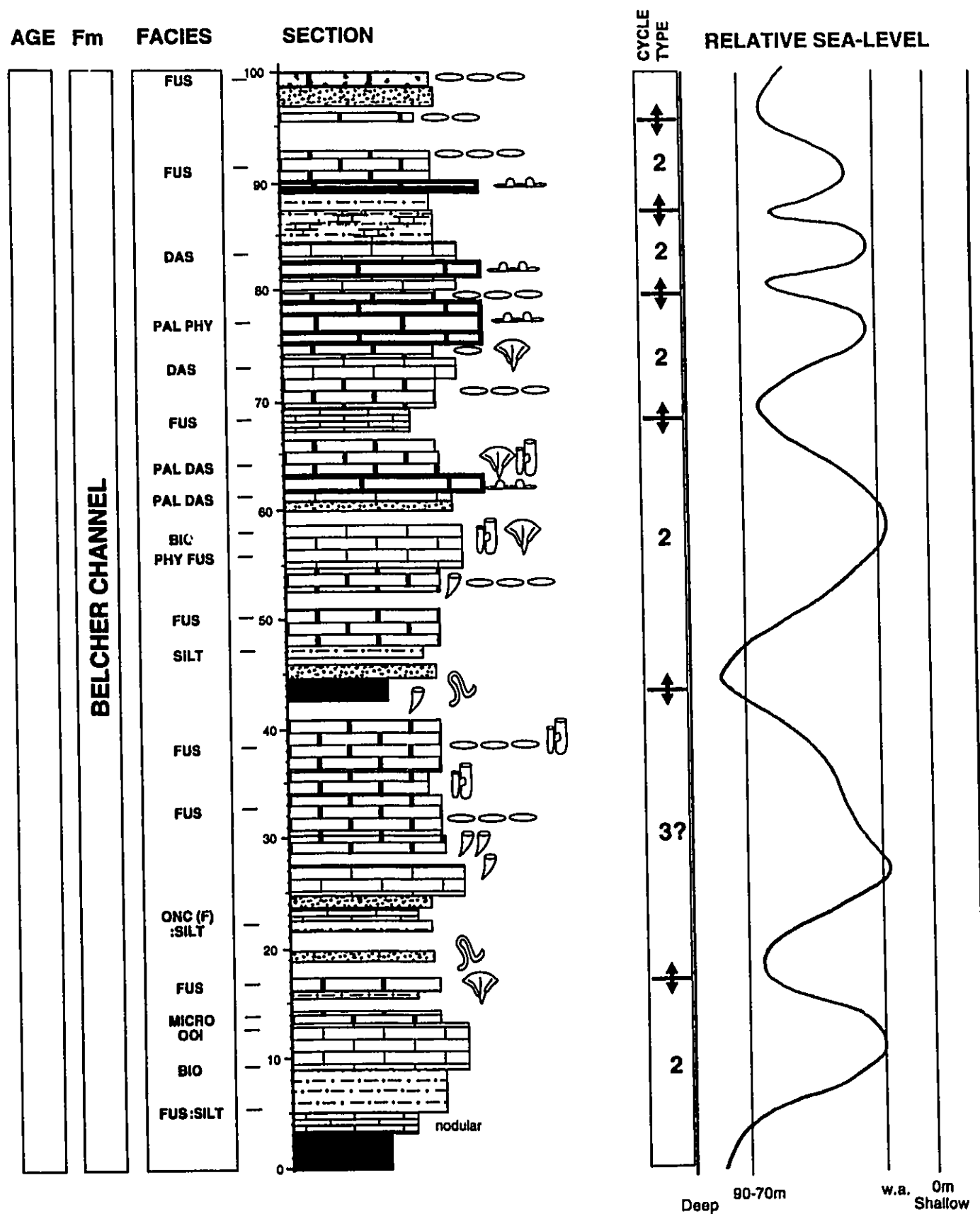
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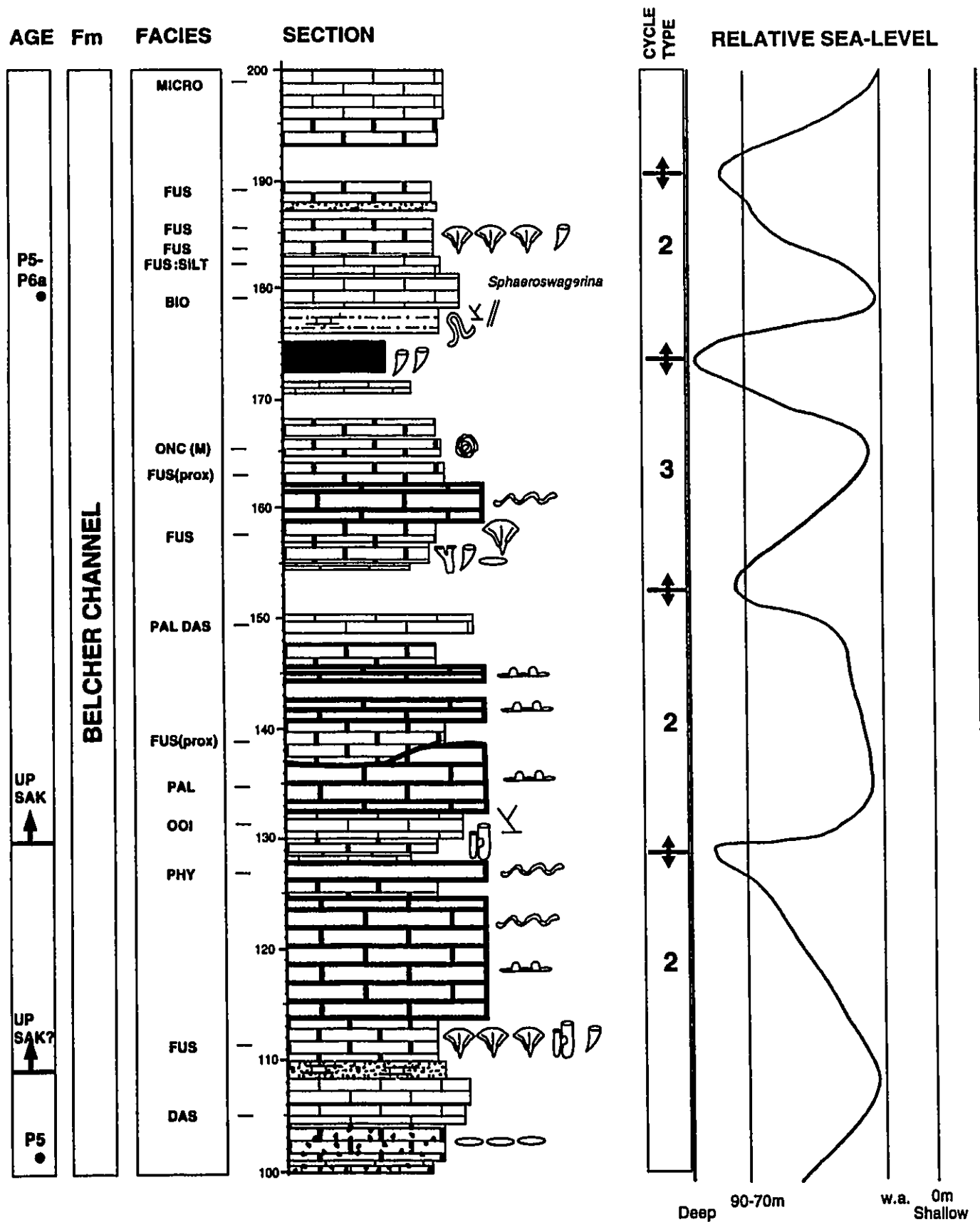
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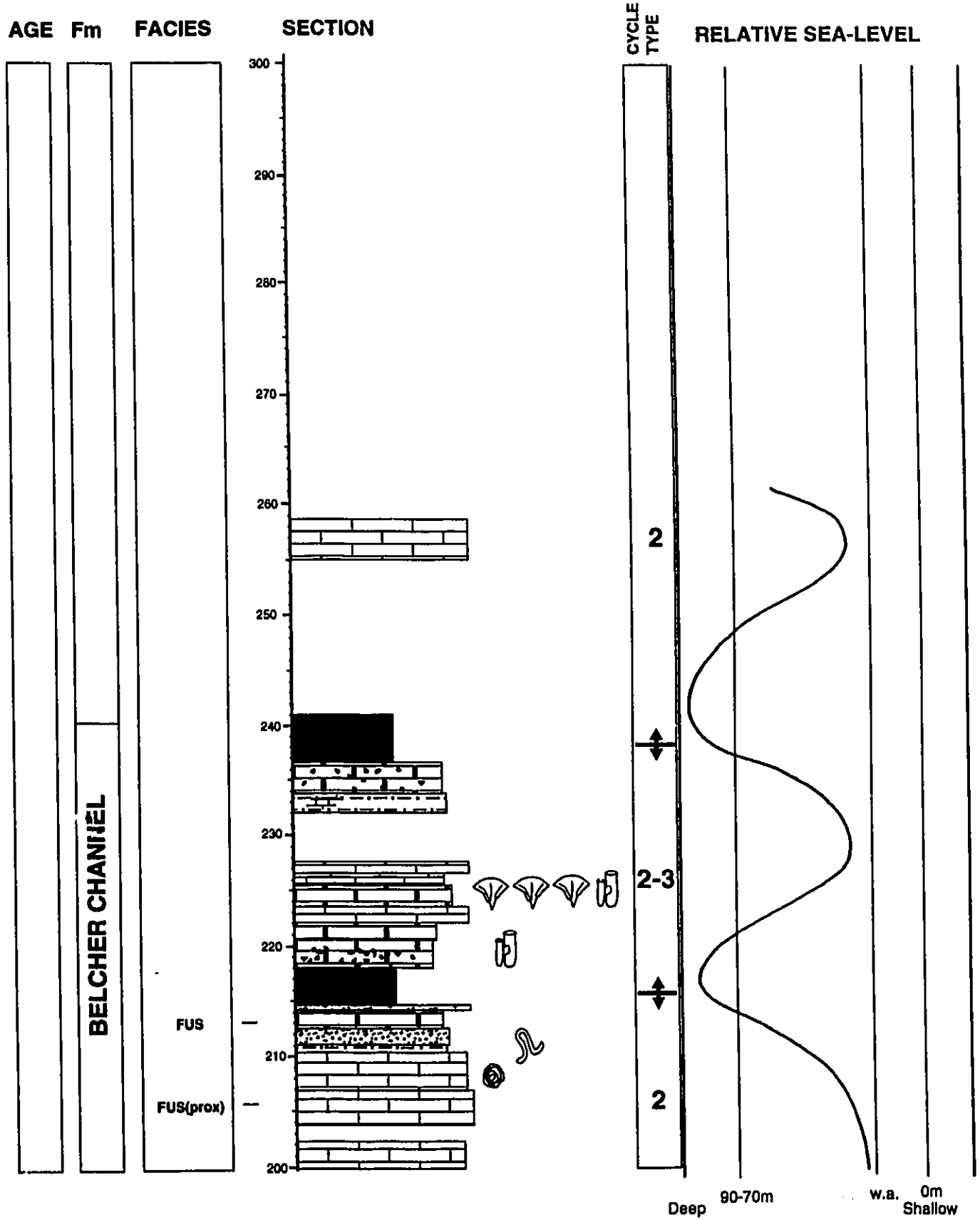
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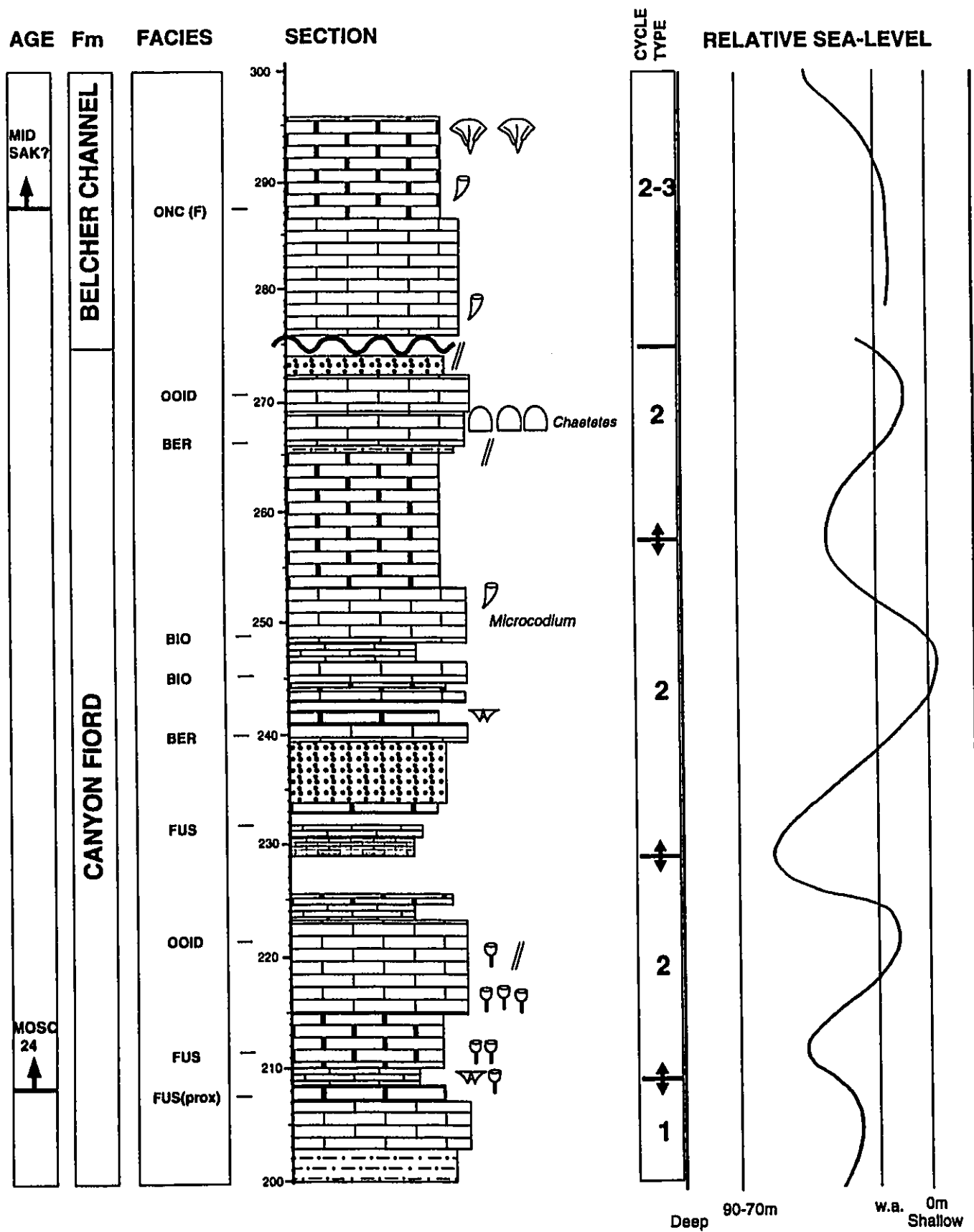
VACHE-QUI-PLEURE



VACHE-QUI-PLEURE



NOTCH LAKE



NOTCH LAKE

