LOWER PALEOZOIC T-R SEQUENCE STRATIGRAPHY, CENTRAL CANADIAN ARCTIC

Tim de Freitas, Ulrich Mayr, and J. Chris Harrison, Geological Survey of Canada, 3303 33rd Street NW, Calgary, Alberta, T2L 2A7, Canada

ABSTRACT

Five Upper Cambrian to Lower Silurian transgressive-regressive (T-R) sequences (sequences A to E) are identified and described along a north-south transect from the central Canadian Arctic Islands. The Late Cambrian sequence (sequence A) is a thick carbonate-clastic succession deposited over a rapidly subsiding, growth-faulted continental margin and thus is considered unique among the five sequences. A Lower and Middle Ordovician shelf-margin, microbial boundstone sill complex (sequences B and C) restricted shelf-interior circulation and contributed to the accumulation of great thicknesses of evaporites that occur in the regressive part of the sequences. Transgressive strata, in contrast, consist of open marine, sparsely fossiliferous limestone. During the Ordovician, the rate of basin subsidence was considerably less than during the Cambrian, but it is similar to that of the two youngest sequences (sequences D and E). The lower boundary of sequence D coincides with the simultaneous disappearance of the shelf-interior evaporites and shelf-margin rim facies. These facts, together with the paucity of shelf-interior and shelf-margin buildups, suggest significantly different depositional environments as compared to the underlying sequences.

Lower Paleozoic sequence boundaries are compared and placed within a hierarchy, based on several broad criteria. Second-order sequences occur above and below sequence A and below sequence D, while all other sequence boundaries are probably third-order.

INTRODUCTION

This summary report represents part of an ongoing, comprehensive basin analysis study of the Franklinian succession (de Freitas et al., 1992). Well log and outcrop data from the central Arctic Islands are used to construct a regional stratigraphic cross section and to interpret major Upper Cambrian to Lower Silurian transgressive-regressive (T-R) sequences (Fig.1). Biostratigraphic information comprises mainly conodonts, but these data are sparse or do not exist in the lower part of the succession under discussion.

The T-R sequence methodology used herein has recently been summarized by Embry (1993). In this method, sequence boundaries are represented by two stratal surfaces: (1) a subaerial unconformity and (or) ravinement surface in the basin flank and (2) a transgressive surface, occurring basinward of the unconformity (Fig.2). The transgressive surface is the conformable surface coinciding with the change of regression to transgression (Fig.2). The maximum flooding surface is a third stratal surface within each sequence (Fig.2), separating regressive and transgressive systems tracts. These stratal surfaces are readily identified in outcrop and in wells.

Most basins contain abundant transgressive surfaces and (or) subaerial unconformities, but the significance of each of them can be delineated according to several objective criteria (Embry, 1993, pp. 304-305). These include the change in the sedimentary regime, subsidence rate, subsidence pattern, and tectonism across sequence boundaries, and the areal extent of the subaerial unconformity. Based on these broad criteria, a hierarchal arrangement of lower Paleozoic sequence boundaries is presented.

CROSS SECTION

Information used to construct the cross section shown in Figure 1 is available from Christie (1973), Mayr (1978, 1980), Miall and Kerr (1980), and Stewart (1987). The Somerset Island portion is based on a reconnaissance study (Miall and Kerr, 1980), and some of these correlations are tentative. The outer-shelf part of the cross section is situated in an area of the Arctic Islands that experienced more than one episode of contraction deformation, and, thus, formation thicknesses, particularly those of the evaporite-rich units, are not regionally representative.

The cross section does not include shelf-margin and basinal facies that are exposed principally in the northeastern and southwestern Arctic Islands. However, a regional understanding of these successions is vital for interpreting sequence boundaries and sequence hierarchy. Most of this information is reported elsewhere, and pertinent stratigraphic data are summarized below.

The shelf succession consists of three main facies belts. (1) An evaporite-carbonate succession was deposited in a shelf-interior basin and is thicker than the shelf-margin rim and the inner-shelf carbonate-clastic units (Fig.1; Harrison, in press). (2) A microbial boundstone rim facies likely formed a continuous shelf-margin facies tract that intermittently restricted shelf-interior circulation. Biostratigraphic

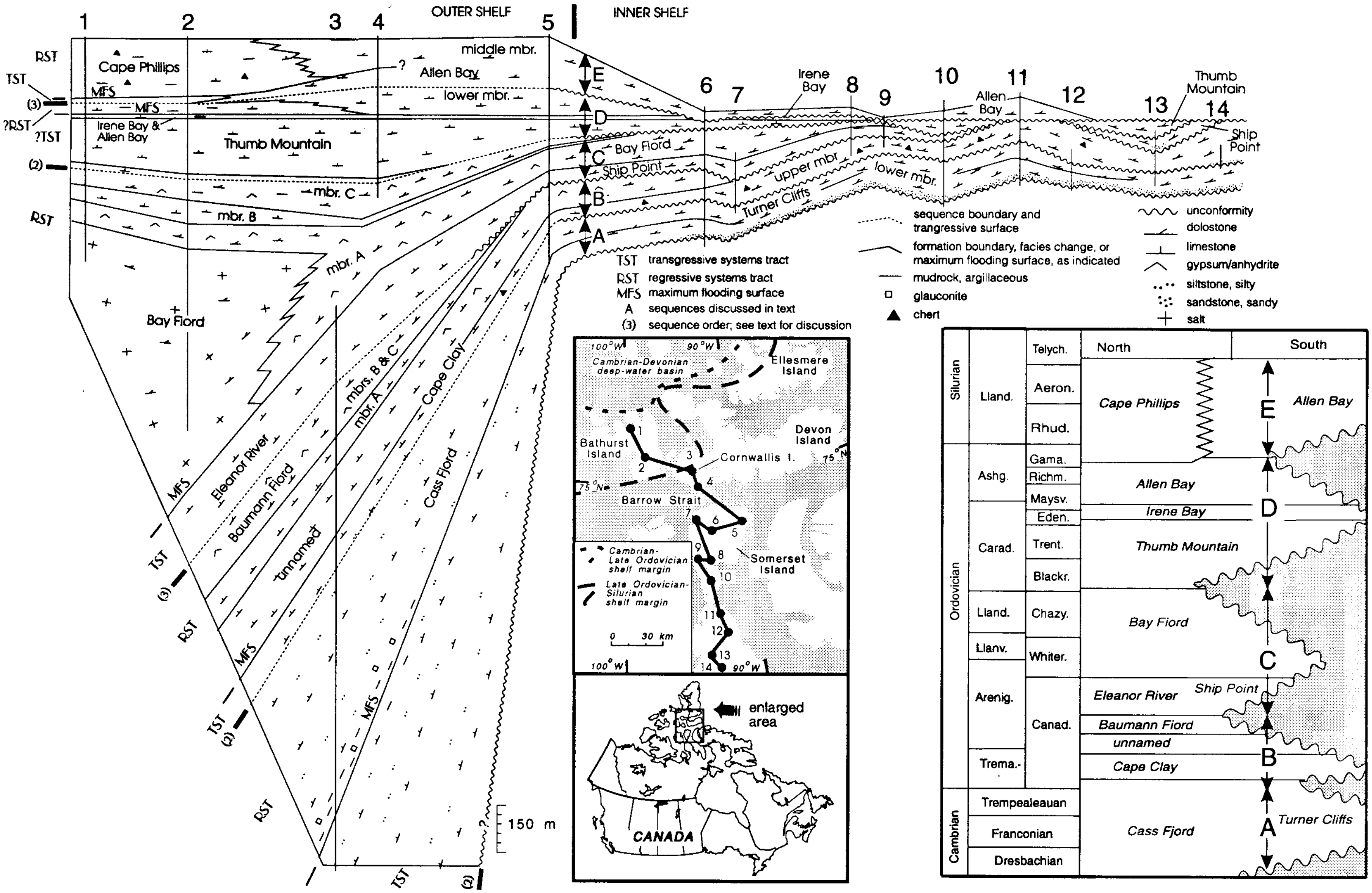

Fig.1. Stratigraphic and chronologic cross section and location maps. Inner-shelf deposits (south of Barrow Strait and loc. 5) and outer-shelf deposits (north) are summarized in the text. Localities 1 to 5 are wells and 6 to 14 are surface sections. South of locality 5, Cambrian strata rest on Precambrian crystalline basement but, to the north, the base of the Paleozoic succession is not exposed. Section 2 was drilled over an anticline, and the salt is assumed to have significant structural thickening. The total thickness (2,160 m) of the Cass Fjord Formation at locality 3 is not shown because of scale problems. Stratigraphic cross section based on Christie (1973), Mayr (1978, 1980), Miall and Kerr (1980), and Stewart (1987).

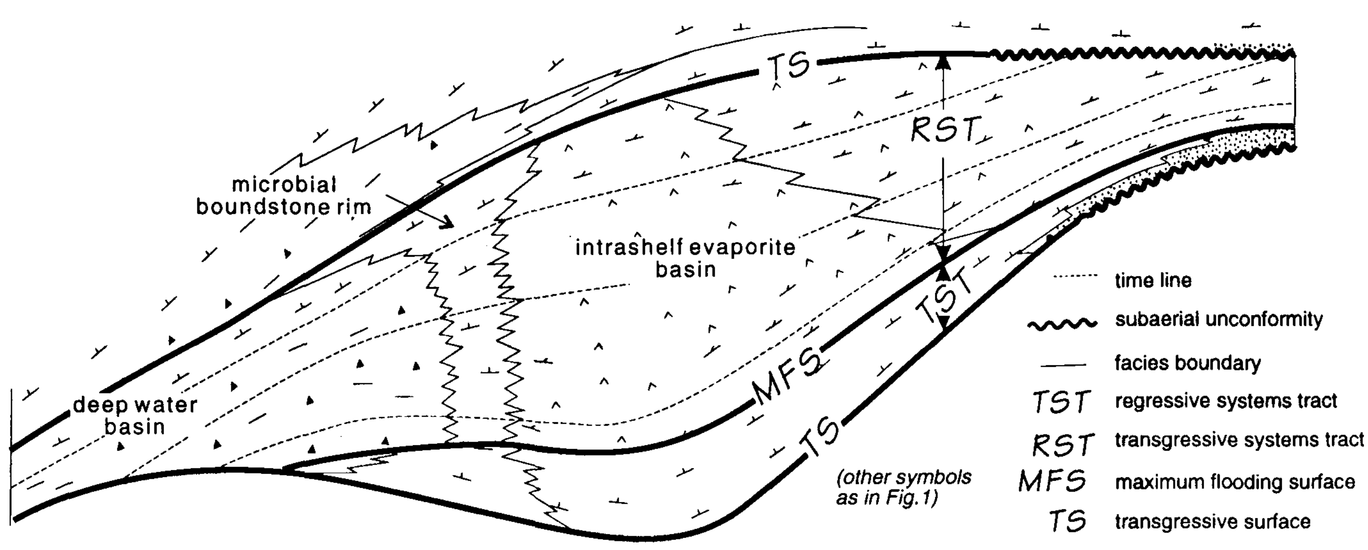

Fig.2. Schematic T-R (transgressive-regressive) sequence model for the Ordovician. This diagram also draws on information from other areas in the basin. Basinal facies and associated biostratigraphy are as discussed by Goodbody (in press). The rim facies, while not exposed along the transect, are discussed in detail by Trettin (in press) and Goodbody (in press).

information and contact relationships suggest that the rim facies is a correlative of the Baumann Fiord, Eleanor River, and Bay Fiord formations, and it is abruptly, but apparently conformably, overlain by the Thumb Mountain Formation. (3) Basinal facies are condensed generally and consist of bedded chert and fissile mudrock, punctuated by several thick, time-expanded, carbonate units, as described by Goodbody (in press). Based on a preliminary identification of graptolites and conodonts, carbonate units appear to be generally coeval with regressive shelf beds, but additional biostratigraphic work is needed to confirm the shelf-to-basin correlations, and, thus, these facies are presented in summary form (Fig.2).

Sequence A

Inner-shelf rocks rest unconformably on Archean and Proterozoic rocks. Transgressive beds overlying the subaerial unconformity consist of sandstone; laminated, bioturbated, and stromatolitic dolostone; intraclast conglomerate; and pebbly sandstone, whereas coeval transgressive strata of the outer shelf consist of siltstone, argillaceous limestone, very fine-grained sandstone, dolomitic sandstone, and limestone (Fig.1). The latter beds have yielded lower Dresbachian trilobites (Mayr, 1978; Miall and Kerr, 1980). The inner-shelf maximum flooding surface rests on a thin unit of thick-bedded, open marine, bioturbated, dolomitized lime mudstone, and the overlying regressive strata consist of thin-bedded, stromatolitic, laminated, intraclastic, locally silty dolostone. The outer-shelf maximum flooding surface rests below a condensed, 175-m-thick glauconitic mudrock unit (Fig.1). Regressive strata above this surface consist of calcareous mudrock; micaceous siltstone; limestone; gypsum; red, very fine-grained sandstone; and micaceous, calcareous mudrock. Late Trempealeauan age trilobites occur approximately 80 m above the maximum flooding surface in the outer shelf, whereas similar age conodonts were collected 30 m above the interpreted maximum flooding surface of the inner shelf (Mayr, 1978; Miall and Kerr, 1980).

Sequence A forms an abrupt, northward-thickening carbonate-clastic prism, but the base of the outer-shelf succession is not exposed or was not penetrated by wells. A substantial thickness of Lower and Middle Cambrian and perhaps Proterozoic strata may exist below, based on gravity modelling (Sobczak et al., 1986) and on what is known of this succession on Ellesmere Island (Trettin et al., 1991). Also, farther west, the probable subsurface correlative of the Cass Fjord Formation shows abrupt, northward thickening across several growth faults, as indicated on seismic cross sections (Harrison, in press). In eastern North Greenland, the upper boundary is associated with a substantial unconformity attributed to peripheral bulge uplift resulting from an early phase of Caledonian deformation (Surlyk, 1991).

Sequence B

Outer-shelf transgressive beds consist of cherty, stromatolitic limestone (microbial boundstone), and dolostone, whereas the correlative beds of the inner shelf are composed of resistant, bioturbated, thick bedded, cherty limestone and dolostone. These beds have yielded Lower Ordovician (Tremadoc) conodonts within and outside the study area (Miall and Kerr, 1980; Thorsteinsson and Mayr, 1987; Mayr et al., in press).

A regionally extensive quartz arenite occurs at the base of the transgressive systems tract in parts of the Arctic Islands and North Greenland (Bryant and Smith, 1990). Quartzose sediment derived from peripheral bulge uplift of eastern North Greenland was deposited basinward, forming a 700-m-thick turbidite sequence, and shelfward, producing a thin sandstone unit that can be correlated along strike for more than 300 km (Bryant and Smith, 1990).

The inner-shelf regressive systems tract was eroded beneath sequence C, but a substantial thickness of regressive strata occurs in the subsurface of the outer shelf. The maximum flooding surface is equivalent to the upper contact of the Cape Clay Formation, an interpretation based on outcrop data from Ellesmere Island, because pertinent well log information for this interval is absent in locality 3 (Fig.1). Outer-shelf regressive beds consist of limestone, sandy limestone, and calcareous mudrock, while inner-shelf regressive beds contain abundant gypsum, gypsiferous dolostone and limestone, calcareous mudrock, and minor intraclastic limestone. The proportion of gypsum increases generally toward the top of the sequence, but overall regression was punctuated by at least one significant transgression, and the transgressive systems tract contains an approximately 50-m-thick open marine limestone unit (member B of the Baumann Fiord Formation). Conodonts from regressive strata are lower Arenig in age (Thorsteinsson and Mayr, 1987; Mayr et al., in press).

Sequence C

This sequence comprises systems tracts that are comparable to those of the underlying sequences. The inner-shelf transgressive beds consist of a basal, locally developed sandstone and an upper, open marine, bioturbated dolostone. These strata overlie a prominent subaerial erosion surface in the study area, but to the east, they overlie crystalline basement (Trettin, 1975). Outer-shelf transgressive strata consist of burrow-mottled, thick-bedded, locally cherty and fossiliferous limestone of open marine character. High-order T-R sequences within the transgressive systems tract are represented by alternating restricted marine dolostone and open marine limestone, comprising locally mappable members of the Eleanor River Formation (Thorsteinsson, 1986). Transgressive strata yield middle Arenig conodonts (Thorsteinsson and Mayr, 1987; Mayr et al., in press).

Inner-shelf regressive strata consist of thin-bedded, intraclastic, laminated, locally argillaceous and stromatolitic dolostone, whereas the correlative strata of the outer shelf contain salt, gypsiferous dolostone, and argillaceous dolostone. Salt is absent in the upper part of the regressive sequence, and gypsiferous dolostone predominates. Regressive strata contain Whiterockian age conodonts (Miall and Kerr, 1980; Thorsteinsson and Mayr, 1987; Mayr et al., in press).

Sequence D

The outer-shelf transgressive surface in the upper part of the Bay Fiord Formation coincides with a prominent lithological contact between well-bedded, laminated, gypsiferous dolostone of the upper part of sequence C and sparsely fossiliferous, burrow-mottled, dolomitic limestone of the lower part of sequence D (de Freitas et al., 1993). However, placement of the overlying maximum flooding surface is subjective. Two possibilities exist: (1) the maximum flooding surface may be placed at the top of a 10-m-thick, resistant, bioturbated, sparsely fossiliferous limestone bed in the upper part of member C of the Bay Fiord Formation. Above this surface, an areally extensive, less than 10-m-thick, mudrock unit occurs throughout the outer-shelf succession; (2) a preferred alternative is to place the maximum flooding surface at the Cape Phillips-Irene Bay/Allen Bay formational contact, so that the maximum flooding surface coincides with a substantial, latest Ordovician carbonate platform step back. In the latter interpretation, the outer-shelf transgressive systems tract is long ranging and unusually thick, but these characteristics are consistent with onlap patterns and ages of correlative transgressive units within and outside the basin. Stratigraphic relationships outside the study area (e.g., Norris, 1993; Sanford, 1993) indicate protracted transgression that produced one of the most significant onlap successions on the North American craton. Transgression spanned at least Blackriveran to Edenian time (Miall and Kerr, 1980; Trettin, 1975; Thorsteinsson and Mayr, 1987), based on identified macrofossil and conodonts above the basal unconformity. The transgressive systems tract is bounded above by the maximum flooding surface that coincides with the most extensive carbonate platform step back in the Arctic Islands.

The inner-shelf regressive systems tracts were eroded below the overlying sequence, but outer-shelf carbonates consist of predominantly subtidal, locally restricted, mudmound-bearing limestone and dolostone deposited on a progradational carbonate ramp (Mallamo, 1989). Basinal regressive rock units (Cape Phillips Formation) contain a thin, regionally extensive limestone-siltstone succession of Gamachian age, apparently deposited during eustatic sea-level fall, related to the Late Ordovician glaciation (Melchin et al., 1991). This event is represented in the inner shelf by a substantial unconformity, and some older units have been eroded.

Sequence E

Sequence E of the inner shelf is poorly exposed or unexposed, but detailed biostratigraphic and lithostratigraphic data is presented by Mallamo (1989). Measured stratigraphic sections of the shelf-margin sequence show a thin transgressive sequence (about 20-30 m) consisting of crinoidal, bioturbated limestone bounded above by a maximum flooding surface that is overlain by a thin sequence of early Llandovery age, graptolite-bearing mudrock. Regressive shelf-margin strata consist of thin- to medium-bedded, laminated dolostone containing polygonal mudcracks, halite pseudomorphs, gypsum molds, microbial laminites, and patterned carbonate. Transgressive strata of the overlying sequence contain late Llandovery graptolites (Mallamo, 1989; Melchin, 1989).

SUMMARY

The nature of the basin fill, tectonism, interpreted subsidence patterns, and the areal extent of subaerial unconformities differ for each of the described sequences. According to Embry (1993), these criteria, together with data from outside the study area, can be used objectively to establish a hierarchal system of sequence boundaries. Sequence A is unique among the lower Paleozoic sequences and is characterized by high rates of sedimentation, growth faults in the western Arctic (Harrison, in press), and by a very thick carbonate-clastic succession in the study area. In eastern North Greenland, the upper sequence boundary is considered to represent a peripheral bulge unconformity related to early Caledonian deformation (Surlyk, 1991). Unusual subsidence patterns, sedimentary regime, and tectonism associated with sequence A indicate that its lower and upper boundaries represent second-order sequence boundaries.

In comparison to sequence A, subsidence rates of sequences B and C were less, nonuniform, and not affected by growth faulting; however, increased climatic aridity and nonuniform shelf subsidence combined to produce an extensive intrashelf evaporite basin. Seismic reflection profiles from the western Arctic (Harrison, in press) and evaporite unit thicknesses that are greater than coeval shelf-margin carbonates indicate that the intrashelf basin experienced a greater rate of subsidence than the shelf margin. Shelf-interior circulation was inhibited by a substantial shelf-margin microbial boundstone sill complex, a feature that is unique to sequences B and C. Subsidence patterns and systems tracts are very similar in sequences B and C, but the basinwide subaerial unconformity that separates them is a significant onlap surface and a third-order sequence boundary.

The carbonate shelf changed significantly during the Late Ordovician (sequence D). The microbial sill complex did not exist or, at least, it was not a continuous barrier to shelf-interior circulation. This fact, combined with apparently reduced climatic aridity, resulted in the deposition of a lithologically homogeneous carbonate platform succession throughout the basin. However, this sequence lacks reefs, otherwise ubiquitous in Silurian and Middle Ordovician sequences. We speculate that physiological stress on Late Ordovician reef-building benthos may have inhibited reef growth and contributed to the apparent demise of the shelf-margin microbial sill, but the cause of the stress is uncertain. A changed water column (e.g., increased nutrients, decreased water temperature) may cause physiological stress of reef building benthos (Jackson, 1977) and also a reduced rate of carbonate sedimentation. This was also a time of considerable cratonic onlap in North America and extensive "oil shale" deposition on the platform (Dewing and Copper, 1991). These characteristics combined with stressed environments of the carbonate platform may have promoted extensive platform retreat, an important stratigraphic event that coincides with the maximum flooding surface in the upper part of sequence D.

The boundary between sequences D and E is a subaerial unconformity throughout the shelf, locally associated with a substantial hiatus (Fig.1). Biostratigraphic data from regressive basin strata (Melchin et al., 1991) indicate that the unconformity coincides with a latest Ordovician glacioeustatic lowstand. However, lithofacies and subsidence patterns are similar in sequences D and E, and the boundary between them is a third-order boundary.

ACKNOWLEDGMENTS

Ashton Embry offered helpful suggestions for improvement. GSC contribution number 45193.

REFERENCES

Bryant and Smith, I.D., 1990. A composite tectonic-eustatic origin for shelf sandstones at the Cambrian-Ordovician boundary in North Greenland. Journal of the Geological Society, London, v. 147, pp. 795-809.

Christie, R.L., 1973. Three new lower Paleozoic formations of the Boothia Peninsula region, Canadian Arctic Archipelago. Geological Survey of Canada, Paper 73-10, 31 pp.

de Freitas, T., Harrison, J.C. and Mayr, U., 1992.

Sequence stratigraphy and sedimentology of the Cambrian to lower Middle Devonian succession, Canadian Arctic Islands. International Conference on Arctic Margins, Anchorage Alaska, September 2-4, 1992, ICAM Abstracts, p. 17.

de Freitas, T., Harrison, J.C. and Thorsteinsson, R., 1993. New field observations on the geology of Bathurst Island, Arctic Canada: Part A, stratigraphy and sedimentology of the Phanerozoic succession. Geological Survey of Canada, Paper 93-1B, pp. 1-10.

Dewing, K. and Copper, P., 1991. Upper Ordovician stratigraphy of Southampton Island, Northwest Territories. Canadian Journal of Earth Sciences, v. 28, pp. 283-291.

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

Goodbody, Q., in press. Lower and middle Paleozoic stratigraphy of Melville Island. In: J. McMillan and R.L. Christie (Editors), The Melville Project, Preliminary Accounts. Geological Survey of Canada Paper.

Harrison, J.C., in press. Melville Island's salt-based foldbelt. Geological Survey of Canada, Bulletin.

Jackson, J.B.C., 1977. Competition on marine hard substrata: the adaptive significance of solitary and colonial strategies. American Naturalist, v. 111, pp. 743-766.

Mallamo, M.P., 1989. Ordovician and Silurian stratigraphy, sedimentology, and paleoecology, central Canadian Arctic Islands. Unpublished M.Sc. Thesis, University of Western Ontario, London, Ontario, Canada, 197 pp.

Mayr, U., 1978. Stratigraphy and correlation of lower Paleozoic formations, subsurface of Cornwallis, Devon, Somerset, and Russell islands, Canadian Arctic Archipelago. Geological Survey of Canada, Bulletin 276, 55 pp.

Mayr, U., 1980. Stratigraphy and correlation of lower Paleozoic formations, subsurface of Bathurst Island and adjacent smaller islands, Canadian Arctic Archipelago. Geological Survey of Canada, Bulletin 306, 52 pp.

Mayr, U., Packard, J.J., Goodbody, Q.H., Okulitch, A.V., Rice, R.J., Goodarzi, F. and Stewart, K.R., in press. The Phanerozoic geology of southern Ellesmere and North Kent islands, Canadian Arctic Archipelago (Craig Harbour, Baad Fiord, and part of Cardigan Strait map areas, NTS 49A, 49B, and 59A). Geological Survey of Canada, Bulletin.

Melchin, M.J., 1989. Llandovery graptolite biostratigraphy and paleogeography, Cape Phillips Formation, Canadian Arctic Islands. Canadian Journal of Earth Sciences, v. 26, pp. 1726-1746.

Melchin, M.J., McCracken, A.D. and Oliff, F.J., 1991.The Ordovician-Silurian boundary on Cornwallis and Truro islands, Arctic Canada: preliminary data. Canadian Journal of Earth Sciences, v. 28, pp. 1854-1862.

Miall, A.D. and Kerr, J.W., 1980. Cambrian to Upper Silurian stratigraphy, Somerset Island and northwest Boothia Peninsula, District of Franklin, N.W.T. Geological Survey of Canada, Bulletin 315, 43 pp.

Mossop, G.D., 1979. The evaporites of the Ordovician Baumann Fiord Formation, Ellesmere Island, Arctic Canada. Geological Survey of Canada, Bulletin 298, 52 pp.

Norris, A.W., 1993. Hudson Bay Platform - Geology. In: D.F. Stott and J.D. Aitken (Editors), Sedimentary Cover of the Craton in Canada. Geological Survey of Canada.