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Bedrock Geology, Ellesmere Island Park Reserve

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5.1 Glossary of Geological Terms

Acknowledgments

I thank U. Mayr and A.F. Embry for cooperation in the compilation of the geological maps (released separately in the Open File series of the Geological Survey of Canada), and for the use of unpublished information.

5.1 Data Sources and Limitations

The first geological information about the Ellesmere Island Park Reserve (EIPR) was obtained by a British naval expedition that explored northeastern Ellesmere Island and northwestern Greenland in 1875 and 1876. Lasting contributions by this expedition are the recognition of metamorphic terranes on the north coast of Ellesmere Island, of Carboniferous strata south of Clements Markham Inlet, and of Tertiary plant-bearing sediments near St. Patrick Bay (Feilden and de Rance, 1878).

After a long interval, geological investigations resumed in the 1950s. The Danish geologist, J.C. Troelsen, reconnoitered the southern Hazen Plateau in 1940 (Troelsen, 1950). Systematic mapping by the Geological Survey of Canada was begun by Blackadar (1954) who investigated the region between Alert, Cape Columbia, and Eugene Glacier in 1953, and was continued by Christie who explored the north coast of Ellesmere Island in 1954 (1957), and parts of northeastern Ellesmere Island in 1957 and 1958 (1964). These far-ranging investigations, done on foot or with dogs and sledges, provided an overview of the distribution of sedimentary, volcanic, metamorphic and plutonic rocks and their broad ages although most of the Pre-Carboniferous succession remained poorly dated.

In the 1960s several reconnaissance programs, now supported by small helicopters and airplanes, were carried out in parts of northern Ellesmere Island by the Geological Survey of Canada. The entire Precambrian to Tertiary succession was studied, foundations for a coherent stratigraphic framework were laid, and some major faults were recognized, but the work still was restricted to relatively accessible areas. Contributions relevant for EIPR are by Frisch (1974), Nassichuk and Christie (1969), Petryk (1969), Sinha and Frisch (1976); Thorsteinsson (1974), Thorsteinsson and Trettin (1971), and Trettin (1969b, 1971).

A new program, intended to complete the stratigraphic and structural reconnaissance of all of northern Ellesmere Island, has been carried out by the Geological Survey since 1975. The use of helicopters with turbine engines has facilitated access to remote and rugged areas. Major operations took place in 1975, 1977, 1979, 1980, 1982, and 1988 and smaller projects in 1981, 1984, and 1986. This work has resulted in complete map coverage at the 1:125 000 manuscript scale and in completion of a coherent stratigraphic framework for most of the region. The maps and accompanying notes have been released mainly in the Open File series of the Geological Survey, the following pertaining to EIPR: Mayr, Trettin and Embry, 1982a, 1982b; Trettin 1981b, 1987b; Trettin, Mayr, Embry, and Christie, 1982. Relevant papers are by Embry and Osadetz (1988); Higgins and Soper (1983); Maurel (1989); Mayr (1976); Miall (1979, 1980); Osadetz (1982); Osadetz and Moore (1988); Trettin (1976, 1981a, 1987a); Trettin, Barnes, Kerr, Norford, Pedder, Riva, Tipnis, and Uyeno (1979); Trettin, Loveridge and Sullivan (1982); Trettin and Parrish (1987); Trettin, Parrish and Loveridge (1987).

The maps accompanying this chapter are revised versions of the earlier Open Files. The present brief summary is based mainly on recent reports that have not yet appeared in print (Embry, in press; Mayr, in press; Okulitch and Trettin, in press; Trettin, in press a, b, c, d; Trettin, Mayr, Long, and Packard, in press) as well as on unpublished field notes and laboratory data.

In summary, geological exploration, begun in the last century and carried out systematically from the early 1950s onward, has resulted in complete map coverage and a reasonably coherent stratigraphic and structural framework. However, the following limitations must be borne in mind. (1) Much of the mapping is based on air photo interpretation and requires additional ground work. (2) Most studies mentioned were not limited to EIPR but covered larger areas. (3) The stratigraphy and structure of the highly deformed Late Proterozoic to Middle Ordovician rocks in the north coast region is poorly known and requires more detailed work.

5.2 General Geology and Geological History

5.2.1 Introduction

EIPR contains a great variety of sedimentary, volcanic, metamorphic, and intrusive rocks and structures, formed during a time span of more than one billion years. These rocks and structures are of interest primarily in what they tell us about the geological history of the northern margin of the continent. In the following brief summary, therefore, it is attempted to explain the genesis of these features in the context of the geological history of the Arctic Islands and North Greenland. In order to give an account that is understandable not only for the specialist, many complicated subjects and problems have been left out, and only relatively simple terms have been used that are briefly explained in the text or in Appendix 5.1. For the underlying concepts, the reader is referred to introductory textbooks of recent vintage, such as Press and Siever, 1986. Mineral names are explained in numerous textbooks and encyclopedias.

Elementary knowledge of the rocks underlying this region also is a prerequisite for the understanding of landforms and soils, in turn required for the comprehension of ecosystems. Basic information for such purposes can be drawn from the accompanying geological maps; more detailed and technical information is contained in the various geological reports cited.

5.2.2 Stratigraphic-Structural Framework and Outline of Geological History

The stratigraphic-structural framework of the Arctic Islands has been developed by various authors, notably Schuchert (1923), and Thorsteinsson and Tozer (1960, 1970); current concepts have been summarized by Trettin (1989).

EIPR lies in the northernmost part of the Innuitian Orogen, a belt of deformed rocks of Precambrian to early Tertiary, predominantly Phanerozoic age that extends along the arctic continental margin from southwestern Prince Patrick Island to northeasternmost Greenland (Fig. 5.1; for time-stratigraphic nomenclature, see Fig. 5.2). The Cambrian to Devonian strata of the orogen were deposited on a tectonically unstable continental margin referred to as the Franklinian mobile belt.

The Franklinian mobile belt can be divided into two major depositional provinces, a southeastern shelf and a northwestern deep water basin, the latter, in turn, divisible into a southeastern sedimentary subprovince and a northwestern sedimentary-volcanic subprovince. Progressive downwarping of the outer shelf caused the shelf-basin boundary to migrate southeastwards in several major steps. Shelf and sedimentary subprovince are widely exposed in the Arctic Islands and North Greenland, but the sedimentary-volcanic subprovince is exposed only in northern Ellesmere and Axel Heiberg Islands.

In Ellesmere Island, north of the deep water basin, there lies an extensive terrane of Middle Proterozoic to Late Silurian rocks that has more in common with the Caledonian mobile belt of the North Atlantic region than with the Franklinian mobile belt. These relationships, combined with structural observations in northern Ellesmere Island, have led to the hypothesis that Pearya is a fragment of the Caledonides that was rafted to the Canadian Arctic by strike slip motion and accreted to the Franklinian mobile belt.

The accretion of Pearya, tentatively placed into latest Silurian time, coincided with deformation in some other parts of the Arctic Islands and ushered in a period of movements that culminated in latest Devonian - Early Carboniferous time with widespread folding and faulting (Ellesmerian Orogeny). The orogeny must have been caused by large-scale crustal motions that caused convergence or collision of North America with another crustal plate in the present Arctic Ocean region. That plate has not been identified with assurance -- the configuration of continents and oceans before Late Cretaceous time is poorly known.

In the Arctic Islands, the regions affected by the Late Silurian to Early Carboniferous deformation have been divided into a number of structural belts that differ in age of deformation, trend, or structural style. EIPR straddles three of these belts, the Pearya Terrane, the Clements Markham Fold Belt, and the Hazen Fold Belt (Fig. 5.3). The Clements Markham and Hazen Fold Belts correspond essentially to those parts of the sedimentary-volcanic and sedimentary subprovinces, respectively, that are exposed in northern Ellesmere Island; the adjacent Central Ellesmere Fold Belt corresponds essentially to an adjacent part of the shelf province. In defining the boundary between the Hazen and Central Ellesmere fold belts, the relatively stable position of the shelf margin from latest Early Cambrian to Late Ordovician time has been used. However, because of the migration of the shelf margin, the Hazen Fold Belt includes Early Cambrian shelf strata in its southeastern part, and the Central Ellesmere Fold Belt includes Silurian to Early Devonian deep water sediments in its northwestern part.

Following uplift and erosion in the earlier part of the Early Carboniferous, a large sedimentary basin, known as the Sverdrup Basin, developed on the bevelled structures of the Franklinian deep water basin from late Early Carboniferous to Late Cretaceous time. EIPR includes northeasternmost parts of that geological province.

Northeastern and central northern parts of the Arctic Islands were subjected to compressional deformation in latest Cretaceous and Paleogene time (Eurekan Orogeny). The compression evidently was due to counterclockwise rotation of Greenland, caused by seafloor spreading in the Baffin Bay - Labrador Sea region (cf. Kerr, 1967b; Peirce, 1982; Srivastava and Tapscott, 1986; Trettin, 1989). Late Cretaceous to Eocene clastic sediments produced by earlier phases of the orogeny were faulted and folded during the last, climactic phase, perhaps in Late Eocene to earliest Oligocene time. Some of these syntectonic deposits are preserved in EIPR. The compressional deformation was followed by differential uplift and erosion, which created the present physiography.

5.2.3 Cambrian to Silurian stratigraphy and depositional history, Franklinian Shelf and Deep Water Basin

The following brief account is based on studies by the writer (Trettin, Mayr, Long, and Packard, in press) and only additional information will be cited.

Excellent exposures of the northwestern margin of the **Franklinian shelf** are exposed on Judge Daly Promontory, southeast of head of Archer Fiord, 14 to 27 km southeast of EIPR (Kerr, 1967a, 1968; Fig. 5.4). A thick succession of clastic sediments, derived from the interior of the continent, was deposited during the middle to late Early Cambrian (Ellesmere Group). The uppermost part of this succession, the late Early Cambrian Kane Basin Formation, consisting of mudrock and minor sandstone (270 m +) of intertidal to subtidal origin, is exposed in the southeasternmost part of EIPR at St. Patrick Bay and on Bellot Island. The overlying late Early Cambrian to Early Silurian shelf succession, composed mainly of carbonates (limestone and minor dolostone) with lesser amounts of admixed and interstratified clastic sediments did not extend into EIPR as the shelf margin retreated to south of Archer Fiord in latest Early Cambrian time.

Strata of the **sedimentary subprovince of the deep water basin,** ranging in age from late Early Cambrian probably to late Early Silurian (Wenlock), are widely exposed in the southeastern part of EIPR. These rocks have been assigned to four major units that represent four different phases of sedimentation:

(1) Rapid deposition of shelf-derived carbonates (Nesmith beds, Early Cambrian; thickness unknown as only the uppermost part is exposed).

(2) Rapid deposition of sandstone, mudrock and minor pebble conglomerate (Grant Land Formation; middle to late Early Cambrian; thickness about 2 km).

(3) Slow deposition of carbonates, mudrock, chert, and minor sandstone (Hazen Formation; latest Early Cambrian to earliest Silurian [middle Llandovery]; 240 - 630 m +).

(4) Rapid deposition of sandstone and mudrock (Danish River Formation; Early Silurian [late Llandovery] to earliest Devonian; thickness 2.8 km at Caledonian Bay, Cañon Fiord, but Late Silurian and younger strata are probably eroded in this region).

The carbonates of phases 1 and 3 were derived from the Franklinian shelf and from the southeastern slope of the basin; the clastic sediments of phase 2 from the continental interior; and the clastic sediments of phase 4 from remote mountain belts to the northeast (Caledonides) and also to the northwest that were tectonically active at the time. Depositional environments comprised both slope and basin floor settings and the inferred water depths ranged from about 200 m to more than 1 km. The primary structures of the carbonates indicate that they were carried into the basin by submarine slumps and slides that developed into gravity-driven, sediment-charged currents ("sediment gravity flows"). Both the abundance of these carbonate deposits and their clast size decrease in directions away from the shelf margin. The sandstones and mudrocks also were transported by such flows. Sediments laid down by concentrated flows ("subaqueous debris flows") show poor size-sorting and poor stratification whereas sediments deposited by more dilute currents ("turbidity currents") show a characteristic sequence of primary structures (graded bedding -- horizontal lamination -- convolute lamination). Flow directions can be inferred from erosional sole marks such as flute casts, and extensive statistical studies of these "paleocurrent indicators" have been made.

The chert beds were formed mainly by radiolarians -- microscopic organisms with siliceous tests that accumulate very slowly and form distinct rocks only where other forms of sedimentation are virtually absent. However, in some areas the Hazen Formation also contains chert due to chemical replacement of carbonates and mudrock by silica dissolved in formation waters.

The stratigraphic record of the **sedimentary-volcanic subprovince of the deep water basin** is rather incomplete and restricted to parts of Middle Ordovician to Late Silurian time. Five units, representing three major phases of deposition are recognized (Trettin, Parrish, and Loveridge, 1987; Trettin, Mayr, Long, and Packard, in press).

(1) The Mount Rawlinson assemblage consists of interstratified carbonate rocks, volcanics, and radiolarian chert of unknown thickness. The volcanics are siliceous to intermediate in composition and probably represent volcanic island arcs within an oceanic basin indicated by the radiolarian chert. The carbonates probably were deposited in shelf environments on the volcanic edifices. The volcanics have yielded a Middle Ordovician isotopic age of about 454 Ma (Ma = million years). Similar deposits with microfossils of Early to Middle Ordovician age in the carbonates have recently been identified at Fire Bay, Emma Fiord in northwesternmost Ellesmere Island. The full age range of the Mount Rawlinson assemblage is unknown and its upper and lower contacts are faulted. However, the assemblage must be correlative with a part of the Hazen Formation in the Hazen Fold Belt, i.e. with phase 3 as described above.

(2) The next phase of sedimentation, corresponding to phase 4 in the sedimentary subprovince, is represented by the Early Silurian (late Llandovery) Imina Formation and the late Early to earliest Late Silurian (Wenlock to early Ludlow) Lands Lokk Formation. Both consist of thinly interstratified sandstone and mudrock deposited by turbidity currents in deep sea settings but differ in sandstone-mudrock ratio and mineral composition. The precise thickness of these units is unknown, but the combined thickness must be greater than 1 km.

(3) The last preserved phase of sedimentation, of early Late Silurian (Ludlow) age, is characterized by carbonate sediments that have no equivalent in the sedimentary subprovince. Two different units are represented in the area northwest of Markham River (Markham River beds) and about 18 km farther southeast (Piper Pass beds). The Markham River beds, which overlie the Lands Lokk Formation disconformably, consist of dolostone with lesser proportions of conglomerate, sandstone, mudrock and sponge-spicule chert (170 m +). The inferred depositional environments range from subtidal shelf to intertidal or nonmarine

settings. By contrast, the Piper Pass beds consist of limestone with outer shelf and upper slope characteristics.

5.2.4 Proterozoic to Late Silurian Tectonic History and Stratigraphy, Pearya Terrane

The rocks of the Pearya Terrane have been assigned to four first-order units, informally referred to as successions I, II, III, and IV (Fig. 5.5; Trettin, 1987a and in press a), all of which are exposed in the northern half of EIPR (M'Clintock Inlet and Clements Markham Inlet map areas).

Succession I underlies a narrow, east-west trending belt between Cape Aldrich and the entrance of Disraeli Fiord. There, as in other parts of the Pearya Terrane, succession I consists mainly of granitoid gneiss with lesser proportions of amphibolite, marble, and quartzite (Frisch, 1974). Isotopic age determinations from this area and from another belt southwest of Milne Glacier, indicate metamorphism and granitic intrusion about 1.0-1.1 billion years ago (Sinha and Frisch, 1976; Trettin, Parrish, and Loveridge, 1987).

Succession II underlies three separate areas in the Clements Markham Inlet and M'Clintock Inlet map areas. The contact with Succession I is generally faulted but relationships east of lower Ayles Fiord and southwest of Milne Glacier suggest an angular unconformity that became a detachment surface during later deformations. Relationships with Succession I and an isotopic age determination on volcanics from the upper part (Trettin, Parrish and Loveridge, 1987) suggest an overall age range from Late Proterozoic to earliest Ordovician, but only lower and middle parts of this succession are exposed within EIPR. The stratigraphy of these deposits has not yet been established because of complex structure and absence of fossils and they have therefore been mapped by rock type. They consist of variably metamorphosed limestone, dolostone, mudrock, sandstone, conglomerate and siliceous to mafic volcanics. Of special interest is a unit composed of poorly sorted, matrix-rich sandstone ("wacke") and conglomerate ("diamictite") exposed between Clements Markham Inlet and Markham Fiord. These strata are comparable in texture and composition to glacial deposits of Late Proterozoic age in the Cordilleran and North Atlantic regions, especially in Spitsbergen. Similar rocks occur in the western part of the Pearya Terrane.

Succession III, consisting of variably metamorphosed sedimentary and volcanic rocks, is confined to northwestern and central parts of the M'Clintock Inlet area. It is in fault contact with succession II and unconformably overlain by early Late Ordovician (early Caradoc) strata of succession IV. This unfossiliferous unit clearly is older than late Middle Ordovician and may range in age from late Early to early Middle Ordovician (Arenig to Llandeilo). Isotopic age determinations have been initiated but stratigraphic studies have not yet been attempted because of the complex structure of the rocks. The sedimentary rocks, partly of shallow marine and partly of deep water aspect, include limestone, mudrock, and chert with minor sandstone and dolostone. The abundant volcanics represent flows and tuffs that, judging from their chemical composition, appear to have originated mainly in island arc settings.

Five fault blocks (or aggregates of fault slices) of ultramafic and mafic plutonic complexes with minor granitic components (Thores Suite) are structurally associated with succession III. They are referred to as the M'Clintock West, M'Clintock East, Thores River, Bromley Island, and Ootah Bay bodies. The lithology and structural setting of this suite suggests that it either represents fragments of oceanic crust (referred to as "ophiolites" in the geological literature) or an intrusive complex beneath a volcanic island arc. A granitic rock of the Thores Suite has given a late Early Ordovician isotopic age of 481 Ma (Trettin, Loveridge and Sullivan, 1982).

An angular unconformity at the base of succession IV represents a major deformation known as the M'Clintock Orogeny. The oldest strata above this unconformity are early Late Ordovician (early Caradoc) in age and the youngest rocks beneath it late Early or Middle Ordovician; thus the orogeny probably occurred in the early Middle Ordovician (Llanvirn-Llandeilo). At the head of M'Clintock Inlet the unconformity is overlain by Upper Ordovician strata (Figs. 5.6, 5.7, 5.8). The structures produced by this event are generally difficult to distinguish from later deformations, but complex folds and faults are apparent beneath the unconformity at some localities. The most important structure is a major fault that places succession III against succession II and has associated with it four ultramafic-mafic bodies of the Thores Suite. The orogeny is interpreted as the collision of a volcanic island arc (succession III) with a continent (successions I and II) and probably also involved fault slices of intervening oceanic crust (Thores Suite).

The orogeny was accompanied by low to medium grade regional metamorphism and by the intrusion of granitic plutons that have given Middle Ordovician isotopic ages (Markham Fiord Pluton: 462 Ma [Trettin, Loveridge and Sullivan, 1982]; Cape Richards Intrusive Complex: 463 Ma [Trettin, Parrish and Loveridge, 1987]).

Succession IV, exposed mainly in the northern and central part of the M'Clintock Inlet map area, consists of about 7-8 km of clastic, carbonate, and volcanic strata that range in age from early Late Ordovician (early Caradoc) to Late Silurian (late Ludlow or Pridoli). This succession, which is less deformed than successions I to III and has yielded numerous fossil collections, is amenable to stratigraphic treatment. It is formally known as the Challenger Mountains Supergroup and has been divided into two groups and a number of formations and informal units (Fig. 5.6). Only the most important features of this succession are briefly discussed here.

The lower part of the succession, the Egingwah Group, overlies Middle Ordovician and/or older strata with high angular unconformity. It includes more than 4 km of volcanics, carbonates, and clastics, assigned to the Cape Discovery, M'Clintock, and Ayles Formations. Its basal unit (member A of the Cape Discovery Formation) contains conglomerate up to boulder grade and volcanics that indicate an extensional tectonic regime ("rifting"). By contrast, the thick volcanic succession of the M'Clintock Formation consists of rock types typical of volcanic arcs, which are attributed to convergent regimes and subduction.

The Egingwah Group is separated from the overlying Harley Ridge Group by an unconformity that truncates upper parts of the Egingwah Group on Marvin and Egerton Pensinsulas and all of the Egingwah Group south of M'Clintock Inlet where the Harley Ridge Group lies directly on Middle Ordovician metamorphic rocks. The Harley Ridge Group is a thick succession of interbedded and mixed carbonate and clastic sediments, clastic sediments dominating the lower and upper parts (Taconite River and Lorimer Ridge Formations), and carbonates the middle part (Zebra Cliffs Formation). The Zebra Cliffs Formation is notable for its rich and varied fossil fauna.

The Harley Ridge Group is overlain by carbonate and clastic sediments representing shelf environments (Marvin Formation, Crash Point beds), submarine slope settings (Disraeli Glacier beds) and submarine fans (Cranstone Formation). The Cranstone Formation is comparable in age and origin to the Imina and Danish River Formations of the deep water basin, but differs in mineral and rock fragment composition. The Disraeli Glacier beds are comparable to marginal parts of the Hazen Formation.

Pearya is related to the Caledonian-Appalachian region by:

(1) The age of its crystalline basement -- about 1 billion years and comparable to that of the "Grenville Province" of the Appalachians, Labrador, Scotland, and Scandinavia.

(2) The Early Ordovician age of its ultramafic-mafic complexes; closely similar ages have been reported from "ophiolites" in Newfoundland and Scotland and broadly similar ages from Norway.

(3) The presence of a mid-Ordovician orogenic belt that is comparable in age and tectonic origin to orogenic belts in the Appalachians, and in Britain and Norway.

By contrast, the crystalline basement of the Franklinian mobile belt is older than 1.8 billion years, and the region was not deformed in the Ordovician. Affinities between Pearya and the deep water basin become apparent in latest Ordovician to Early Silurian time, but the Early Silurian clastic sediments, as mentioned, differ in composition.

5.2.5 Middle-Late Devonian Clastic Deposits

The latest Silurian (Pridoli) to Early Carboniferous (Tournaisian) stratigraphic record of northern Ellesmere Island is restricted to exposures of Devonian sediments in the Tanquary Fiord map area. The outcrops occur at Yelverton Pass and de Vries Glacier and have been assigned to the Okse Bay Formation (Mayr, in press). The exposed part of the Okse Bay Formation, about 1360 m thick, consists of interbedded conglomerate, sandstone, and mudrock with minor argillaceous limestone and includes conspicuous redbeds in the lower part. Bedding characteristics indicate deposition by northwestward flowing rivers. The sediments probably were derived from strata of the Hazen and Grant Land Formations in the United States Range, which supplied abundant chert and quartz, respectively. Microfossils (spores) indicate a late Middle to early Late Devonian (late Givetian - Frasnian) age.

The base of the unit is not exposed, but the fact that the Okse Bay Formation is markedly less deformed than the Late Silurian and older units in the region suggests that folding and faulting occurred some time prior to its deposition, i.e. that an angular unconformity exists somewhere within the concealed latest Silurian to Middle Devonian interval. In northern Axel Heiberg Island, such an unconformity occurs at the base of the Stallworthy Formation, which is Early Devonian (and possibly latest Silurian) in age (Trettin, 1969a). The upper contact of the Okse Bay Formation, with Carboniferous strata, is a well exposed angular unconformity that indicates tilting prior to the deposition of the overlying Carboniferous sediments.

5.2.6 Late Silurian to Early Carboniferous tectonic history, and structural features of Pearya Terrane, Clements Markham Fold Belt, and Hazen Fold Belt

A complex sequence of deformations occurred in the Arctic Islands in Late Silurian to Early Carboniferous time. In northern Ellesmere Island the course of events is poorly established because of the scarcity of outcrops of that age range but at least three phases can be distinguished that preceded, accompanied, or followed the deposition of the Okse Bay Formation. Various lines of evidence suggest the following scenario (Trettin, in press b, in press c).

(1) Latest Silurian - Early Devonian: deformation of Pearya Terrane, Clements Markham Fold Belt and northwestern parts of Hazen Fold Belt. These deformations probably accompanied the

accretion of Pearya, presumed to have been accomplished by a combination of southwestward strike slip and compression, but neither the timing nor the mechanism of transportation and accretion are well established.

(2) Late Middle - early Late Devonian: uplift of northwestern Hazen Fold Belt and subsidence of Clements Markham Fold Belt.

(3) Late Devonian - Early Carboniferous: extensive folding and faulting in much of the Arctic Islands and North Greenland (Ellesmerian Orogeny) with faulting predominant in those regions (i.e. Pearya Terrane, Clements Markham Fold Belt) consolidated by earlier folding.

The Pearya Terrane differs from the Franklinian mobile belt not only with respect to its stratigraphy and Proterozoic to Silurian tectonic history (5.2.4), but also with respect to its extremely complex structural trends -- the result of late Middle Proterozoic, Middle Ordovician and Late Silurian - Devonian deformations (see geological maps). For example, semicircular trends, convex to the west, characterize a large region between M'Clintock and Yelverton Inlets; east-west trends are dominant southern Marvin Peninsula; and several superimposed sets of trends are apparent between Clements Markham Inlet and Markham Fiord, the most prominent being northwest-southeast (Fig. 5.5). By contrast, the Clements Markham and Hazen Fold Belts have very regular southwesterly trends that swing into westerly directions in the western part of the Tanquary Fiord map area.

Most major faults in the region involve late Paleozoic strata, i.e. were active during the Paleogene Eurekan Orogeny, and their previous history is difficult to establish. However, there are reasons to suspect that several (listed below from north to south) were active during the time under consideration:

(1) The Parr Bay Fault, which bounds the Middle Proterozoic gneiss of the Cape Columbia belt on the south.

(2) The Mount Rawlinson and M'Clintock Glacier Faults, which separate the Pearya Terrane from the Clements Markham Fold Belt. Both are bordered on the southeast by exposures of the Early Silurian Imina Formation. The M'Clintock Glacier Fault is offset by major and minor crossfaults.

(3) The Porter Bay Fault, which forms the boundary between the Clements Markham and Hazen Fold Belts from Porter Bay to Barrier Glacier. Farther southeast this boundary is concealed by ice and younger strata.

The folds and faults in the northern part of EIPR are too complex to be discussed here. Suffice it to state that the folds formed in the Imina and Lands Lokk Formations of the Clements Markham Fold Belt (Fig. 5.9) are comparable in style to the folds formed in the

Danish River Formation of the Hazen Fold Belt (Fig. 5.11).

The Late Silurian - Early Carboniferous deformation of the Hazen Fold Belt was characterized by tight folding and associated minor faulting. (The superimposed major thrust faults of the Lake Hazen Fault Zone are Paleogene in age; see 5.2.9). The belt is divisible into three parts that differ in level of exposure and structural style.

(1) The northwestern part of the Hazen Fold Belt is dominated by Early Cambrian strata, mainly of the Grant Land Formation with some poorly exposed outcrop belts of the Nesmith beds, which probably form fan-shaped anticlinoria. The structure of the Grant Land Formation is generally too complex for mapping, except for some major anticlines and synclines formed in massive sandstones (Fig. 5.10.b).

(2) The central part is dominated by Silurian strata of the Danish River Formation (Fig. 5.11) with outcrops of the Hazen Formation (Fig. 5.12) on the northwestern, northeastern, and southeastern margins. In the marginal areas, the massive chert member of the Hazen Formation forms anticlines or anticlinoria , up to 17 km long, whereas the underlying carbonate member of the Hazen Formation and the uppermost part of the Grant Land Formation form exceedingly complex minor folds and faults (Fig. 5.10a). The Danish River Formation is strongly disintegrated by frost action and its structure therefore is poorly exposed over much of the Hazen Plateau but spectacular exposures are present on some deeply incised river valleys, lakes, and fiords. The folds of this unit are smaller and more complex than those of the chert member and approach the "chevron" type, characterized by straight limbs and sharp crests (Fig. 5.11).

(3) The southeastern part of the Hazen Fold Belt is a large, southwesterly plunging anticlinorium that exposes Ordovician and Cambrian strata of the Hazen and Kane Basin Formations. The northwestern flank of the anticlinorium is exposed in the southeasternmost part of EIPR, at St. Patrick Bay and Discovery Harbour and on Bellot Island, where structures are controlled by the chert member of the Hazen Formation.

5.2.7 Carboniferous to Cretaceous Stratigraphy and Depositional History, Sverdrup Basin

The Carboniferous to Cretaceous deposits of EIPR were deposited in the northeasternmost part of the Sverdrup Basin.

The following summary of the late Paleozoic (Carboniferous and Permian) deposits in EIPR is based entirely on a comprehensive report by Mayr (in press). The late Paleozoic stratigraphy in adjacent parts of the basin has been described by Thorsteinsson

(1974), Nassichuk and Davies (1980), Davies and Nassichuk (in press) and Beauchamp, Harrison and Henderson (1989a, 1989b), and a diagrammatic cross-section of western Ellesmere Island (Fig. 5.13) provides a key to the stratigraphic nomenclature also used in EIPR although the two regions are different in detail. The summary of Mesozoic stratigraphy and depositional history is based on studies by Embry (in Mayr, Trettin, and Embry, 1982a, 1982b; and in Embry, in press). Only additional publications will be cited.

The oldest deposits of the Sverdrup Basin, late Early Carboniferous (Visean) in age, are assigned to the Emma Fiord Formation. In northeastern Ellesmere Island this formation includes: (1) thin deposits (50-60 m) of nonmarine sandstone, conglomerate, and mudrock, exposed south of M'Clintock Glacier and southwest of Clements Markham Inlet; and (2) thick deposits (700 m) of lagoonal and shallow marine sandstone, mudrock and limestone, exposed on Feilden Peninsula. Elsewhere in the Arctic Archipelago, the Emma Fiord Formation is exposed only in three small areas, located in northwestern Ellesmere Island, northern Axel Heiberg Island, and northwestern Devon Island, respectively.

From a tectonic point of view, the Emma Fiord Formation marks the beginning of a regime of normal faulting (caused by crustal extension) that affected much larger areas in latest Early Carboniferous to early Late Carboniferous time. The sediments of that second phase of rifting (Canyon Fiord and Borup Fiord Formations) consist of very coarse (boulder conglomerate) to fine, commonly red, clastic sediments with lesser proportions of carbonates and rare evaporites. These strata were deposited in nonmarine and shallow marine settings. Large variations in recorded thickness (from 0 to more than 900 m within EIPR) indicate active normal faulting that produced uplifts (horsts) and downwarps (grabens).

Concentric sedimentary patterns developed during the subsequent, early Late Carboniferous to earliest Permian, interval (Figs. 5.13, 5.14). In the centre of the basin more than 1 km of mudrock, sandstone and evaporites (gypsum-anhydrite), assigned to the Otto Fiord Formation, were laid down in relatively deep waters. These sediments are overlain by sandstone and reefal carbonates, assigned to the Hare Fiord Formation. Both units are restricted to the earlier part of the Late Carboniferous and younger strata are not preserved in this region.

The "basinal belt" of northeastern Ellesmere Island, counterpart of a much larger basinal region in northwestern Ellesmere Island and central Axel Heiberg Island, was surrounded on the northwest, southwest and south by a "carbonate belt" characterized by dolostone of the Nansen Formation (preserved thickness 1-1.4 km). The carbonate belt, in turn, is bordered on the northwest and southeast by two "marginal belts" that contain evaporites (gypsum-anhydrite) and carbonate collapse breccias produced by solution of interstratified evaporites, in addition to normal limestone and dolostone. The evaporites and breccias have been assigned to the Mount Bayley Formation although they are somewhat older than the Mount Bayley Formation of the Greeley Fiord - Tanquary Fiord region (Late Carboniferous versus Early Permian). The stratigraphic nomenclature of that region has also been applied to the carbonates underlying and overlying the evaporites (Antoinette and Tanquary Formations) and to adjacent carbonate successions lacking evaporites (Belcher Channel Formation). Limestone and mudrock on the north coast, assigned to the Nansen Formation, constitute the "Cape Nares carbonate belt", which, according to Mayr (in press), probably was displaced by Paleogene dextral strike slip faulting.

The remainder of the Early Permian Epoch is represented by a thin sandstone unit exposed only near the head of Tanquary Fiord (Sabine Bay Formation) and by more widespread deposits of sandstone, mudrock, limestone and chert (Assistance Formation). The early part of the Late Permian Epoch is represented by about 500 m of sandstone in an area south of Piper Pass (Trold Fiord Formation) and by local occurrences of limstone and chert in western and northwestern parts of the region (Degerbols Formation). Minor disconformities are present throughout the Late Carboniferous - Early Permian succession. Strata of latest Permian age are absent, owing to a world-wide, very deep drop in sealevel.

The sea returned in the Early Triassic and intermittent deposition continued until the early Late Cretaceous. Within EIPR, exposures of Mesozoic strata are mostly confined to a belt extending from Tanquary Fiord and Yelverton Pass to Eugene Glacier, northeast of Lake Hazen, although small outcrop areas of Middle Triassic strata also occur on southern Marvin Peninsula (Fig. 5.15).

The Early Triassic to Early Cretaceous successsion (Fig. 5.16) consists of alternating units of sandstone and mudrock with a total thicknesses of 2 km at the head of Tanquary Fiord and of 1.3 km north of Lake Hazen. These relatively low values -- compared with thicknesses of more than 8 km in the centre of the basin -- indicate deposition on the basin margin. Other features indicative of such a position are higher sandstone/mudrock ratios and larger gaps in the stratigraphic record (disconformities). Contours of equal thickness ("isopachs") generally trend northeast, about parallel with the structural trend, and the projected basin margin (0 isopach) lies not far south of Lake Hazen.

The sediments were deposited in nonmarine to offshore shelf environments. Nonmarine deposits, mostly of fluvial origin, consist of interbedded sandstone, mudrock and minor coal characterized by upward-fining sequences, common crossbedding and nonmarine plants or spores. Important examples are the middle part (Fosheim Member) of the Heiberg Formation (Late Triassic - Early Jurassic) and the mid-Early Cretaceous Isachsen Formation. Shallow marine deposits consist of sandstone or interbedded sandstone and mudrock with characteristic sedimentary structures, fossils (e.g. oysters), or trace fossils (e.g. vertical burrows). Examples include the Bjorne Formation (Early Triassic), the Pat Bay Formation (Late Triassic), lower and upper parts (Romulus and Remus Members) of the Heiberg Formation (Late Triassic - Early Jurassic), the Hiccles Cove Formation (Middle Jurassic), the Awingak Formation (Late Jurassic), and the Hassel Formation (late Early Cretaceous). Shelf sediments deposited farther offshore consist of mudrock, with or without minor sandstone, and may contain characteristic fossils (e.g. ammonites) or microfossils. Examples are the Blind Fiord Formation (Early Triassic), Murray Harbour Formation (Middle Triassic), Barrow Formation (Late Triassic), McConnel Island and Ringnes Formations (Middle Jurassic), the Deer Bay Formation (Late Jurassic - Early Cretaceous), and the Christopher Formation (Early Cretaceous).

Varying rates of subsidence and sediment supply, combined with world-wide fluctuations in sea level have produced sedimentary sequences that are known as "third-order transgressive-regressive cycles" or "T-R cycles". In shallow marine deposits such sequences are characterized by upward-coarsening units with obvious disconformities at the top, but in offshore mudrock units the cycle boundaries may be subtle. Embry has recognized 30 T-R cycles in the Mesozoic record of the Sverdrup Basin and most are represented in the vicinity of Tanquary Fiord. Such sequences probably also are present in the Paleozoic record of EIPR (cf. Beauchamp, Harrison and Henderson, 1989b) and in the early Paleozoic shelf deposits but have not yet been investigated in this area.

However, not all disconformities are related to T-R cycles. Gaps in the Late Carboniferous to Late Triassic record in an area north and northeast of Tanquary Fiord are due to intermittent rise of the "Tanquary High", a fault-controlled structural and paleotopographic feature, about 50 km wide, that trends for about 100 km east-west across the southern margin of the Sverdrup Basin (Nassichuk and Christie, 1969; Maurel, 1989). At the crest of the high, Late Triassic strata of the Heiberg Formation and thin remnants of the Late Carboniferous - Early Permian Belcher Channel Formation overlie Early Cambrian strata of the Grant Land Formation.

Volcanism and intrusion occurred in parts of northern Ellesmere Island in late Early to early Late Cretaceous time. Northeast of Lake Hazen the Hassel Formation contains a few flows of basalt, and abundant mafic dykes and sills in the Tanquary Fiord - Lake Hazen region may represent feeder systems for these volcanics (Osadetz and Moore, 1988). A small granitic pluton on southern Marvin Peninsula has yielded isotopic ages averaging 93 Ma (early Late Cretaceous). Other intrusions and volcanics of Late

Cretaceous age are present in northwestern Ellesmere Island (Trettin and Parrish, 1987; Embry and Osadetz, 1988). All these intrusions indicate pronounced crustal extension ("rifting"), perhaps related to seafloor spreading in the Arctic Ocean Basin.

5.2.8 Paleogene Clastic Deposits

The latest Cretaceous (Maastrichtian) and early Tertiary (Paleogene) in the Arctic was characterized by crustal movements that produced large amounts of syntectonic clastic sediments, collectively assigned to the Eureka Sound Group (Miall, 1986). Within EIPR, fairly extensive exposures of the group occur in the region southeast of the United States Range with some smaller exposures northwest of the range in the M'Clintock Inlet map area (Fig. 5.17).

The deposits southeast of the United States Range are known mainly from studies by Miall (1979, 1980) and this summary follows his description, although the simpler nomenclature of Ricketts (1986) is used who assigns them to two widespread units, the Iceberg Bay and Buchanan Lake Formations. Within EIPR, the Iceberg Bay Formation is a nonmarine, largely fluvial fluvial unit that probably was deposited in two separate intermontane basins with internal drainage. The Lake Hazen Basin, preserved northeast and southeast of the lake, comprises up to 450 m of poorly consolidated sandstone and mudrock with minor conglomerate and coal and is probably of Eocene age. The Judge Daly Basin extended from Ritter Bay on Judge Daly Promontory to northeast of Discovery Harbour where about 100 m of sandstone and mudrock with a coarse basal breccia and a 6 m thick coal seam are exposed. These strata are Paleogene, possibly Paleocene in age.

The Buchanan Lake Formation, preserved only northeast of Lake Hazen, comprises about 450 m of coarse conglomerate and sandstone of Middle Eocene and younger (?) age (D. McIntyre and B. Ricketts, pers. com., 1989). The formation was deposited on alluvial fans adjacent to the Lake Hazen Fault Zone (see below).

In the Grantland Mountains a peculiar breccia, composed entirely of Carboniferous carbonate clasts, is associated with Late Carboniferous strata on Harley Ridge (southeast of M'Clintock Inlet) and east of upper M'Clintock Glacier (U. Mayr, pers. com., 1987). At the latter locality, spores of Oligocene (or possibly Miocene) aspect (Christie, 1964, p. 56; D. McIntyre, pers. com., 1985) have been recovered from interbedded siltstone.

A thick and coarse conglomerate unit, equivalent, perhaps, to Paleogene conglomerate west of Yelverton Bay (Wilson, 1976) occurs in two areas, east of lower Disraeli Fiord and east of lower Disraeli Glacier, respectively. In the first mentioned area it lies unconformably on the M'Clintock Formation, and in the second, on Permian strata. This unit, which requires stratigraphic study, is deformed, i.e. predates the end of the

Eurekan Orogeny.

5.2.9 Early Tertiary Deformation (Eurekan Orogeny) and Middle-Late Tertiary Tectonic and Physiographic Developments

Within EIPR, the Eurekan Orogeny strongly affected the Grantland Mountains. Here, as generally in the Arctic Islands, the Eurekan Orogeny consisted mainly of thrust faulting and associated folding, but dextral slip slip faulting appears to have occurred on Feilden Peninsula and farther southwest. The Carboniferous and Paleogene strata of the Hazen Plateau, on the other hand, are undeformed or affected only by minor normal faults. The following brief summary is based mainly on mapping by U. Mayr and the writer and on a summary by Okulitch and Trettin (in press); additional sources will be cited.

The most important Eurekan feature is the Lake Hazen Fault Zone, a belt of southeastward directed thrust faults that extends from the coast of Lincoln Sea north of Alert to north of central Hare Fiord (Fig. 5.17). The overall trend is southwest to west, but the Ekblaw Lake Thrust, north of Tanquary Fiord, curves into a northerly direction. The main fault of the Lake Hazen Fault Zone places the Grant Land Formation on units ranging in age from Cambrian to Cretaceous. Southeast of the main thrust, in the area northeast of Lake Hazen, a thrust sheet composed of Permian to Cretaceous strata has overridden the Eocene Iceberg Bay and Buchanan Lake Formations. Folds related to the fault zone include the Viking Anticline northeast of the head of Tanquary Fiord, the Lake Hazen Syncline north of Lake Hazen, and a fan-shaped array of unnamed folds northeast of Ekblaw Lake. The Lake Hazen Fault Zone is best exposed around the head of Tanquary Fiord where detailed studies have been made by Osadetz (1982) and Higgins and Soper (1983). The latter authors infer 7-8 km of shortening along a cross-section 34 km long (21-25%). Other important thrust faults occur southwest of Clements Markham Inlet (e.g. Crescent Glacier Fault) and southwest of Markham Fiord. The stratigraphic-structural relationships mentioned (cf. 5.2.6) indicate that the fault zone was active both during and after the deposition of the Buchanan Lake Formation, i.e. in Middle Eocene and (?) later time.

The Feilden Fault Zone of Feilden Peninsula and environs comprises the westerly to southwesterly trending Porter Bay and Guide Hill Faults, and a host of smaller faults between them that have a more southerly trend and give a "braided" aspect to the fault array. The configuration suggests dextral strike slip but no markers are known that could provide an estimate of offset. The Porter Bay Fault also has characteristics of a northwestward directed thrust but this does not conflict with the strike-slip interpretation. The fact that the Feilden Fault Zone offsets strata of the Sverdrup Basin strongly suggests that it was active during the Eurekan Orogeny, but earlier motions, for example during the latest Silurian to Carboniferous, cannot be excluded.

If the latter have occurred, they probably were sinistral rather than dextral (cf. 5.2.6). The Feilden Fault Zone disappears under glaciers in the southwestern part of the Clements Markham Inlet map area and has not been recognized in the exposed areas farther southwest; this poses a major structural problem.

Analyses of seafloor spreading in the Labrador Sea indicate that the compression that caused the Eurekan Orogeny probably terminated in the earliest Oligocene. The geological record of other mountain belts shows that compression, which results in crustal thickening, inevitably is followed by intermittent uplift and continuous erosion, processes that reduce the crust to a normal thickness. Such uplifts are most reliably inferred and dated from the sediments they generate but strata of middle and late Tertiary (Oligocene to Pliocene) age are not preserved in this region. However, a major uplift in late Miocene - early Pliocene time can be inferred from conglomerate preserved in other parts of the Arctic Islands (Beaufort Formation). If the mountains produced by Eocene compression had been erased by subsequent erosion, they were rejuvenated at this time. The present fiords and seaways probably represent a Tertiary drainage system that was deepened and straightened by glacial erosion (Fortier and Morley, 1956; Pelletier, 1966), presumably in the earlier part of the Pleistocene (Trettin, in press d). Our mapping has not provided any evidence supporting the alternative view, that they are the direct result of graben faulting.

5.3 Evaluation

5.3.1 Resources

In geological contexts, the term, resources, refers to mineral or fuel-bearing rocks from which the mineral or fuel can be extracted profitably under given economic circumstances (cf. Bates and Jackson, 1984; p.428, 430; Economic Geology Division, Geological Survey of Canada, 1980). The term usually is qualified by an adjectives indicating the level of certainty about their existence (e.g. "proven", "known", "probable", "potential", "speculative"). The assessment of resources normally precedes the selection of National Parks to make certain that the latter do not include economically valuable deposits and this has been done, in a preliminary fashion, for EIPR (Departmement of Energy, Mines and Resources, Geological Survey of Canada and Department of Indian and Northern Affairs, 1981). After a Park Reserve has been established, mineral and oil exploitation, of course, are prohibited and the only conservational task left is the regulation of sample collecting. The latter subject, briefly mentioned below, is discussed more thoroughly in section 5.3.2.

Metallic minerals. EIPR has not been prospected systematically and its resources are virtually unknown. There are various geological indications -- structural, tectonic, and lithological -- that the potential may be considerable (Economic Geology Division, Geological Survey of Canada, 1980; Sangster, 1981; Gibbins, in press). In regions broadly adjacent to EIPR, a significant showing of lead and zinc (galena and sphalerite) has been found in Upper Cambrian or Lower Ordovician carbonate rocks on Judge Daly Promontory, and a minor showing of copper (chalcopyrite) in the Hazen Formation north of Hare Fiord. It is possible, therefore, that showings of metallic minerals, especially sulfides of lead, zinc, and copper will be discovered by geologists or other visitors in the future. Such discoveries may have implications for the potential of areas outside of EIPR and should be reported to the Geological Survey of Canada for investigation by specialists.

Within EIPR, the only relevant deposit reported so far is a small showing of tennantite $[(Cu, Fe, Zn, Ag)_{12}As_4S_{13}]$ in the M'Clintock Inlet map area (see geological map), north of Thores River (Trettin, 1981a). When discovered, the surface of the deposit, perhaps 10 m to a few tens of metres in diameter, was strewn with fragments of dolostone weathered in place that contained scattered crystals, or lumps of crystals, of tennantite, surrounded by haloes of malachite and minor azurite (green or blue copper carbonates). The deposit is interesting from a geological point of view because it occurs close to a major fault zone that involves ultramafic rocks of the Thores Suite (cf. 5.2.4). Tennantite is not rare, but this is the only reported occurrence in the Arctic Islands. The most conspicuous surface material has been removed and is curated by the Geological Survey of Canada; what remains should be left to mark the site. It is likely that there is more material at depth.

In addition, insignificant showings of malachite have been seen here and there. Such occurrences are common in areas containing intrusions and carbonate rocks. They are not important by themselves but may lead to the discovery of other, less conspicuous, copper minerals.

Nonmetallic materials. The Lower Ordovician serpentinites of the M'Clintock Inlet region (Thores Suite) probably contain some asbestos and talc ("soapstone"), but no commercially significant quantities have been reported so far.

Gypsum and anhydrite of Late Carboniferous and Permian age are common in parts of the Sverdrup Basin (Otto Fiord and Mount Bailey Formations, Fig. 5.13; Thorsteinsson, 1974; Nassichuk and Davis, 1980), including the M'Clintock Inlet and Clements Markham Inlet map areas. The largest body within EIPR occurs east of upper M'Clintock Inlet (see geological map). In places these bodies are cut by veins with large, clear gypsum crystals ("selenite"). Such crystals are attractive to collectors, but not valuable scientifically or economically.

Garnet, a potential gem mineral, occurs in schists of the Pearya Terrane, for example in the area south of Cape Columbia. The mineral is so common that it does not merit special attention. The same applies to quartz, chalcedony, and opal.

Coal and amber. Scanty surface data suggest that the early Tertiary Eureka Sound Group (Iceberg Bay Formation) in the Lake Hazen region contains about 600 million tons of high volatile bituminous coal (Bustin and Miall in press, Table 1).

Pale yellow amber nodules are abundant in the coal seams at Lake Hazen, and reworked amber occurs on the beaches of the lake (Christie, 1964, p. 72-73). This resinous substance, potential gem material, may contain insects that are of paleontological interest. Any material with insects should be forwarded to Dr. J.V. Matthews, Geological Survey of Canada, Ottawa.

Oil and gas. No seismic work or drilling has been carried out in the area. Surface studies by U. Mayr and A.F. Embry indicate a limited potential for hydrocarbons in Carboniferous, Permian, and Mesozoic strata (cf. Department of Energy, Mines and Resources, Geological Survey of Canada and Depoartment of Indian and Northern Affairs, 1981, p. 12).

5.3.2 Geological research and collecting practices

As pointed out in this chapter, much of the geological work done so far has been of reconnaissance type and many problems remain to be solved. The lower Paleozoic geology of the north coast region is significant for the tectonic history of the entire circum-polar region and will attract national and international scientists and organizations.

The important function of regulating such studies now has fallen to Parks Canada. Geological fieldwork, especially if supported by aircraft, has implications for the preservation of animals, plants, and soils but these aspects are discussed in other chapters. Here we are concerned with bedrock preservation, and how it may affect regulations for scientific collecting. Generally, the damage inflicted to the bedrock by geologists -- bashing away with their hammers -- is neglibible compared with the havoc wreaked by erosion, and the samples removed by geologists are minuscule compared with the masses of sediments dumped into the sea by rivers. Nevertheless, attention must be paid to exceptional fossil or mineral sites. Usually, the scientists who discover such sites will be the first to point out the need for protection -- unless they are apprehensive of excessive regulation.

The following notes on geological collecting and curation practices are intended as background information for administrative policies.

Fossils. Systematic paleontological studies invariably lead to the definition of new taxa (genera, species, varieties, etc.) but introduction of new names requires a thorough examination of all related forms to avoid confusion and duplication. To clarify such matters, a paleontologist may have to study collections made more than 100 years ago -- if they can still be located. The Geological Survey of Canada sets a good example of how fossils should be treated. All collections are catalogued, identified by experts, and stored systematically. Specimens of particular value, for example those representing new taxa, are placed in a type collection. All collections are accessible to scientists from other institutions who may loan or photograph them, or may obtain artificial duplicates. Although other organizations, such as universities, may have qualified specialists, they rarely have adequate museums. Consequently, collections by scientists from organizations lacking proper museums, should be curated by the National Museum or by GSC when the studies have been compoleted. A museum established within EIPR could not provide the services required, but redundant material could be given to such a museum for educational purposes.

In most cases the fossils taken form only a neglible fraction of the fossils contained in the rocks and site protection is unnecessary, but some sites require special care. Fossil forests in the lower Tertiary Eureka Sound Group, for example, should be left intact, to preserve the original configuration. Such forests have been found in central Axel Heiberg and Ellesmere Islands and may also be present in the Lake Hazen region, but none have been reported so far.

When collecting permits are issued, estimates of the amount of material to be collected should be left to the scientists: because of the exorbitant costs of shipping, they will tend to keep their collecting within limits.

Microfossils have become increasingly important for dating, especially conodonts (microscopic tooth-like forms of phosphatic material), palynomorphs (pollen and spores), and organic cysts of dinoflagellates (unicellular oganisms). They are recovered from ordinary sediments, such as limestone and mudrock, that are abundant and do not require protection. Palynomorphs and dinoflagellates require only small samples whereas the optimum conodont sample weighs 2 kg. Hundreds of samples may be collected in the course of one field season. Most of the source rock is destroyed during analysis but the microfossils should be curated like macrofossils.

Samples for isotopic dating. Igneous, metamorphic, and in some instances, sedimentary rocks, are used for isotopic dating --

either of the whole rock or of particular minerals. The dating is done with the aid of mass spectrometers and based on the decay rates of unstable isotopes of elements such as potassium, rubidium, uranium, or certain rare earths. The most commonly analyzed minerals are hornblende, mica, and zircon; less commonly used minerals include sphene and feldspar. The sample size, depending on the method or mineral used, may vary from 1 to 100 kg. The samples are selected carefully but do not represent rare rock types. The samples are largely destroyed during the analysis but excess material and representative specimens are kept. Several dozen samples of this kind may be collected during one field season.

A related method, fission track dating, is of more limited use. It is essentially a statistical, optical analysis of "tracks" within certain minerals, such as apatite or zircon, caused by isotopic decay. A few dozen samples of 2 kg may be taken in a field season.

Lithological samples are taken to study the mineral composition, faunal or floral content, chemical composition, or texture of the rocks in order to elucidate their mode of origin. They may be of fist size or larger, and hundreds of samples may be collected during one season. Examination of thin sections under the petrographic microscope is a standard procedure; other methods include X-ray diffraction analysis, chemical analysis, and various types of analyses carried out with the aid of electron microscopes.

At the Institute of Sedimentary and Petroleum Geology of the Geological Survey of Canada, rock samples are curated in a similar fashion as fossils. Some may be restudied in later years or loaned to geologists from other institutions. However, in view of the abundance of the source material, there is no need to apply to rock samples the same strict rules mandatory for the curation of fossils.

Rare minerals or rock types have not yet been reported from EIPR. Special site protection will be required should such material be encountered in the future.

5.3.3 Educational sites

EIPR contains sedimentary, volcanic, metamorphic, and intrusive rocks of considerable variety and at least four generations of structures, that together represent a record of more than one billion years of geological history. Although the interior of the area is covered by extensive ice caps, excellent exposures are provided by seacliffs and deeply incised valleys. These exposures are of a high educational value both for the professional geologist and the geologically interested layman. A brief catalogue of the nine most attractive sites (Fig. 5.19) will be followed by recommendations for their treatment.

(1) **Environs of head of Tanquary Fiord.**

Access: on foot from Tanquary base; boats may be required to cross major rivers during times of high runoff.

Geological features:

- Cambrian to Silurian sediments of Franklinian deep water basin
- Carboniferous to Cretaceous sediments of Sverdrup Basin
- Cretaceous dykes and sills
- Complex folds and faults in Cambrian to Silurian formations (Fig. 5.10)
- Thrust faults of Lake Hazen Fault Zone

(2) **Environs of Hazen Camp**

Access: on foot from Tanquary base or by STOL plane or helicopter

Geological features:

- Lower Cambrian sediments of Franklinian deep water basin
- Pennsylvanian to Cretaceous sediments of Sverdrup Basin
- Cretaceous volcanics (see Osadetz and Moore, 1988, Figs. 4a, 4b, 4d)
- Early Tertiary syntectonic sediments of Eureka Sound Group (see Miall, 1979, Plates 1, 2, 4, 5; Figs. 5A, 5B)
- Lake Hazen Fault Zone (see Trettin, 1971, Fig. 7; Miall, 1979, Plate 3)

(3) **Entrance to Piper Pass**

Access: on foot from Lake Hazen or by STOL plane or helicopter

Geological features:

- sediments of Franklinian deep water basin
- Permian to Cretaceous sediments of Sverdrup Basin
- Cretaceous volcanics (see Moore and Osadetz, 1988, Fig. 4c)

- Lake Hazen Fault Zone

(4) **St. Patrick Bay - Fort Conger area**

Access: on foot from Lake Hazen or by STOL plane or helicopter

Geological features:

- Cambrian to Silurian sediments of Franklinian deep water basin

- early Tertiary sediments of Eureka Sound Group

- folds in Cambrian to Silurian strata (see Trettin, 1971, Fig. 19)

(5) **Northern part of Piper Pass**

Access: by STOL plane or helicopter

Geological features:

- Cambrian to Silurian sediments of Franklinian deep water basin

- Carboniferous and Permian sediments of Sverdrup Basin, including gypsum

- Complex folds in Cambrian to Silurian strata

- Feilden Fault Zone

(6) **Environs of Gypsum River**

Access: by STOL plane or helicopter

- late Proterozoic and/or Cambrian sediments of Pearya Terrane (succession II), including Proterozoic glacial deposits

- Carboniferous and Permian sediments of Sverdrup Basin, including gypsum

- Mount Rawlinson Fault

(7) **Cape Columbia**

Access: by STOL plane or helicopter

Geological features:

- gneissic basement of Pearya (succession I; see Frisch, 1974, Fig. 2)

(8) **East side and head of M'Clintock Inlet**

Access: by STOL plane or helicopter

Geological features:

- late Proterozoic - Cambrian metamorphosed sediments of Pearya (succession II; Figs. 5.7, 5.8)
- Lower Ordovician ultramafic, mafic, and granitic rocks (Thores Suite; Trettin, 1987a, Fig. 14)
- Mid-Ordovician unconformity and Upper Ordovician sediments (Figs. 5.7, 5.8)
- Carboniferous and Permian sediments, including gypsum (Trettin, 1969b, Fig. 9)

(9) **West side of M'Clintock Inlet**

Access: by STOL plane or helicopter

Geological features:

- Ordovician sedimentary and volcanic rocks
- Lower Ordovician ultramafic, mafic, and granitic rocks (Thores Suite; Trettin, 1987a, Fig. 13)
- Carboniferous sediments
- folds, faults, and arcuate structural trends.

Geologists will be able to obtain the necessary background information from the published literature whereas laymen may need educational aids, perhaps guidebooks, and informative displays at the Tanquary base. Most important are sites 1 and 2 because of their accessibility, but sites 7, 8, and 9 are also highly relevant. Site 4 is not as significant from a geologic point of view but of special historical interest.

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APPENDIX

5.1 Glossary of Geological Terms

accretion - the process by which large blocks of the crust are added to a continental margin.

amphibolite - metamorphic rock composed of minerals of the amphibole group (e.g. hornblende) and plagioclase.

angular unconformity - see unconformity.

anticline - a fold that is convex up.

anticlinorium - a major anticline composed of smaller folds.

Caledonides - mobile belt of Late Proterozoic to Devonian age exposed on the margins of the North Atlantic (Svalbard, East Greenland, Norway, Britain), continuous with the Appalachian mobile belt of eastern North America (see mobile belt).

chert - rock consisting mainly of quartz crystals less than 0.03 mm in diameter. The quartz may be derived from skeletons of radiolarians, sponges, or diatoms, or may be an inorganic precipitate.

correlative - of the same age

disconformity - see unconformity

dolostone - a carbonate rock composed mainly of the mineral dolomite. (The name dolomite is also used for this rock type).

dextral - see strike slip fault.

dyke - a tabular intrusive body that cuts across the intruded strata

graben - a block of the earth's crust, usually longer than wide, which has dropped down relative to blocks on either side and is bounded by normal faults.

granitic rock - term is used loosely for igneous rocks composed predominantly of feldspar and quartz with lesser proportions of mica and/or hornblende. Granite, in the strict sense, has fairly abundant potassium feldspar (orthoclase, microcline) and quartz.

granitoid gneiss - high grade metamorphic rock with layered structure that has a granitic composition (quartz, feldspar, biotite, etc.) but may be of either sedimentary or intrusive origin.

horst - a block of the earth's crust, bounded by normal faults, that has moved upward relative to flanking blocks.

mafic - adject. applied to rocks that are relatively rich in iron or magnesium-bearing silicates such as pyroxene, olivine, or amphibole but also contain substantial proportions of feldspar (plagioclase).

metamorphic grade - the intensity of metamorphism as indicated by characteristic structures and mineral assemblages.

metamorphism - the mineralogical, chemical, and structural adjustment of solid rocks to physical and chemical conditions which differ from the conditions under which they originated.

mobile belt - a long (hundreds or thousands of km), relatively narrow, segment of the crust characterized by tectonic instabilty over relatively long intervals of time (hundreds of millions of years).

mudrock - generalized term for clastic sediments finer than sandstone, i.e. less than 0.0625 mm in particle size.

normal fault - fault with inclined fault plane characterized by downward motion of the upper block.

orogen - a linear or arcuate belt that has been subjected to folding and other deformation during one or several orogenies.

orogeny - literally, the genesis of mountains; in present usage, a major period of deformation that includes folding, faulting, and commonly metamorphism and granitic plutonism. These processes are accompanied and followed by uplifts that create mountains but the latter are subsequently erased by erosion whereas the structures of deeper crustal levels are preserved.

plunge - the inclination of a fold axis or other linear feature, measured in the vertical plane.

pluton - an igneous intrusion (other than dyke or sill).

seafloor spreading - growth of ocean basins by upwelling of magma along linear midoceanic ridges.

shelf - a horizontal or slightly inclined surface, covered by the sea, normally with water depths between 0 and 200 m.

sill - a tabular intrusive body that is parallel with the intruded strata.

sinistral - see strike slip fault.

stratigraphy - the science of rock strata; the arrangement of strata as to geographic position and chronologic order in given areas.

stratum - a layer of sedimentary or volcanic rock; plural: strata.

strike-slip fault - a fault that had mainly horizontal movements. Dextral motion indicates relative movement to the right, and sinistral motion relative movement to the left if you are looking at the block on the far side of the fault.

subduction - descent of one lithospheric plate (i.e. plate composed of crust and solid upper mantle) beneath another.

syntectonic - simultaneous with deformation.

tectonics - a discipline of geology dealing with the major structural features of the crust and with their relationships, origin, and evolution; adject.: tectonic.

thrust fault - a fault with inclined fault plane, characterized by upward motion of the upper block.

trace fossil - a primary structure, such as as a burrow or a track, formed by an animal.

ultramafic rock - rock composed largely or entirely of iron and/or magnesium-bearing silicates such pyroxene, olivine, or serpentine.

unconformity - a surface within a stratigraphic succession that represents a significant gap in the stratigraphic record, due to intervening erosion or nondeposition. If the strata above and below that surface are parallel at the outcrop scale, the term disconformity is applied; if they are not parallel, the unconformity is said to be angular. An angular unconformity indicates an episode of folding and/or faulting followed by uplift, erosion, and renewed deposition.

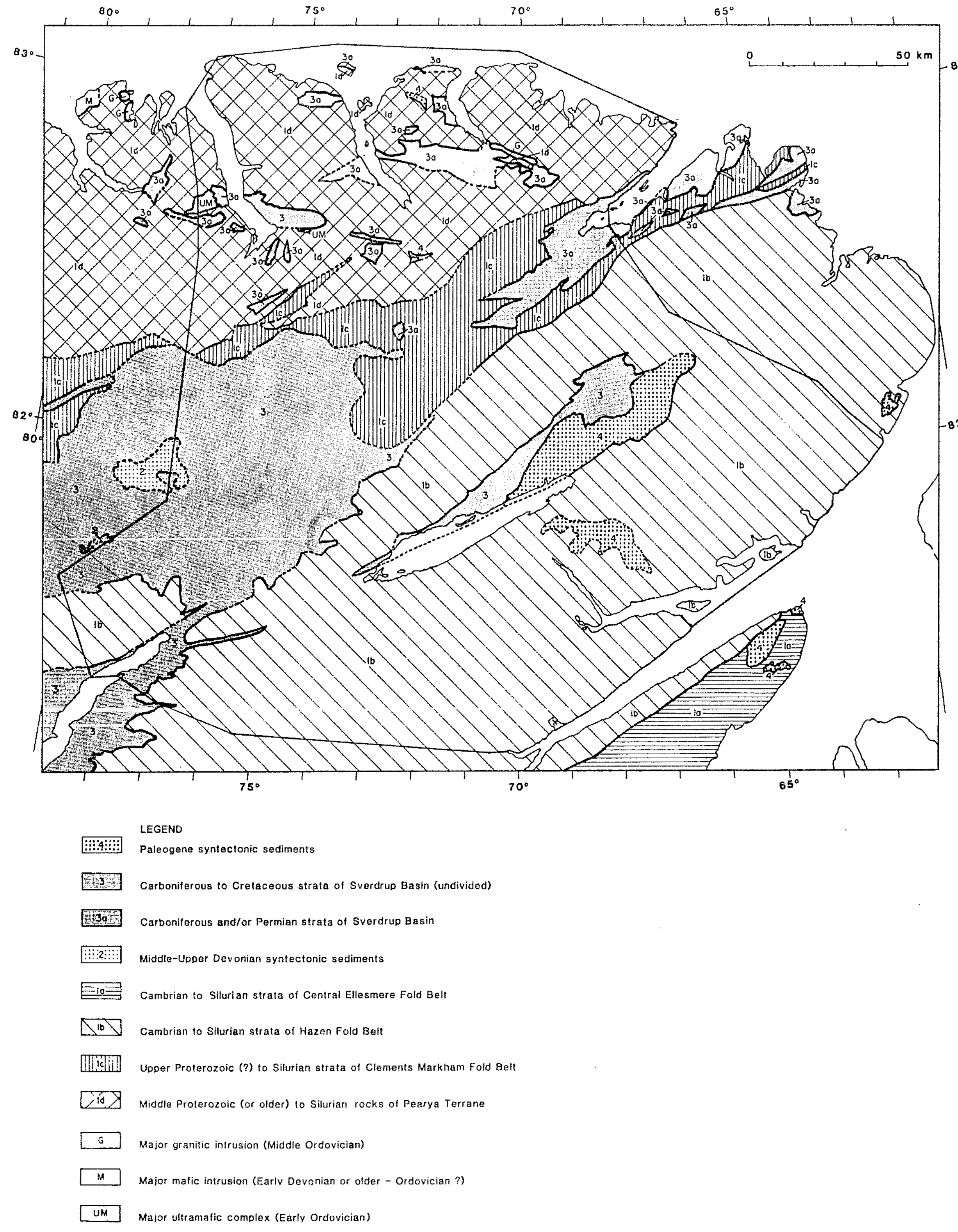

Figure 5.3 Major stratigraphic-structural elements, northeastern Ellesmere Island.

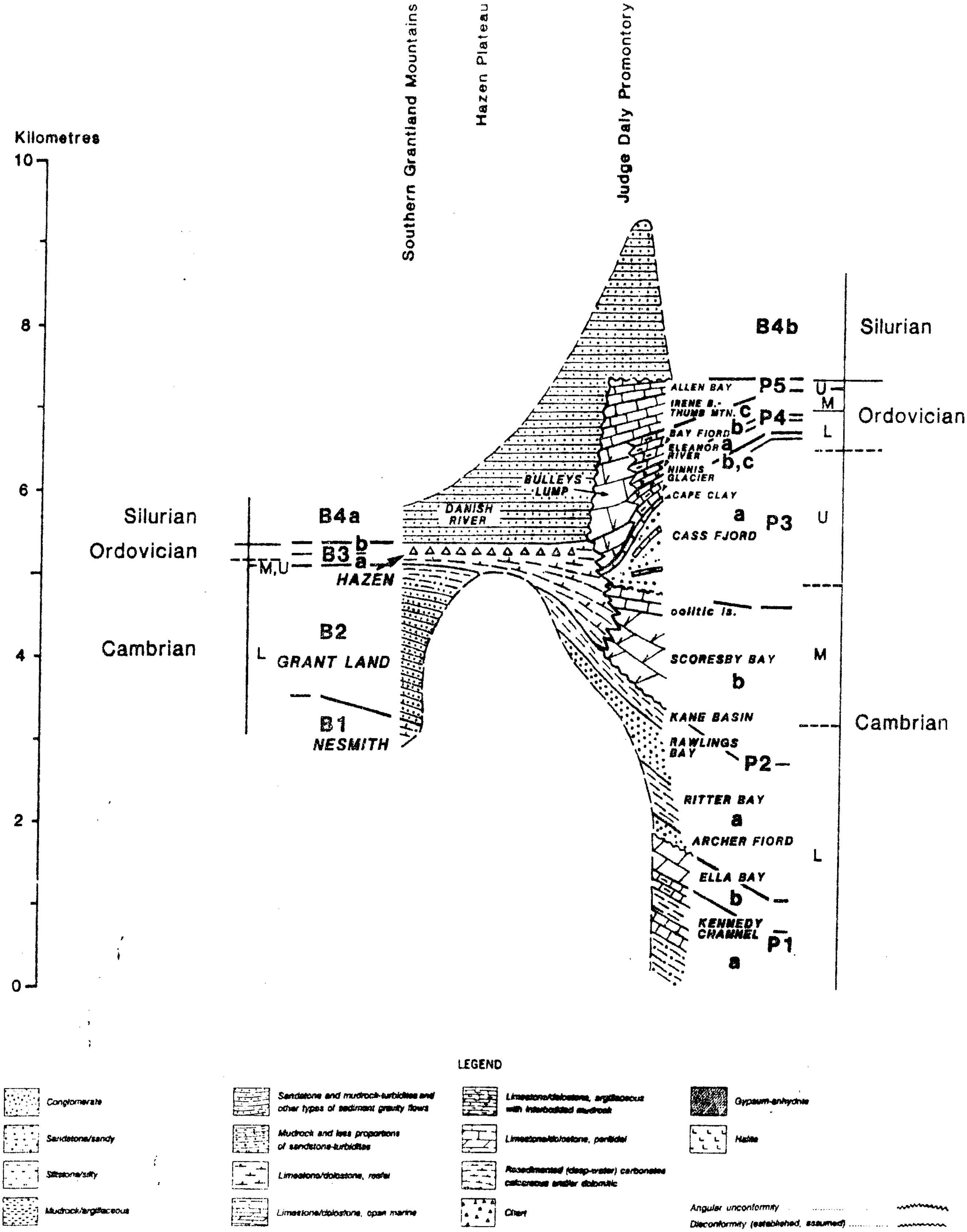

Figure 5.4 Restored stratigraphic cross section, Cambrian to Silurian, Hazen Plateau to southwestern Judge Daly Promontory, northeastern Ellesmere Island (Trettin, 1989, Fig. 5). Major depositional units recognized throughout the Arctic Islands are denoted by letters and numbers (B1 to B4 for deep water basin, P1 to P5 for Franklinian Shelf and Arctic Platform). Formational names are shown in italics.

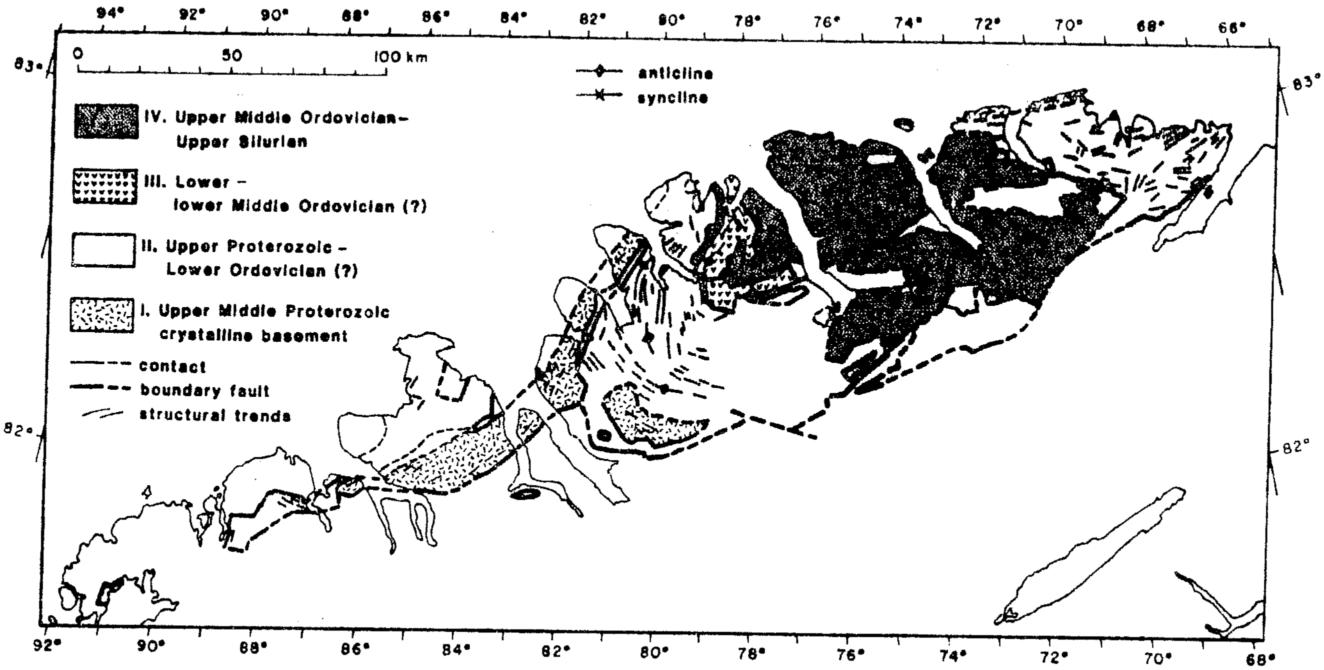

Figure 5.5 Peary Terrane: major successions and generalized structural trends (Trettin, 1989, Fig. 6). Lines

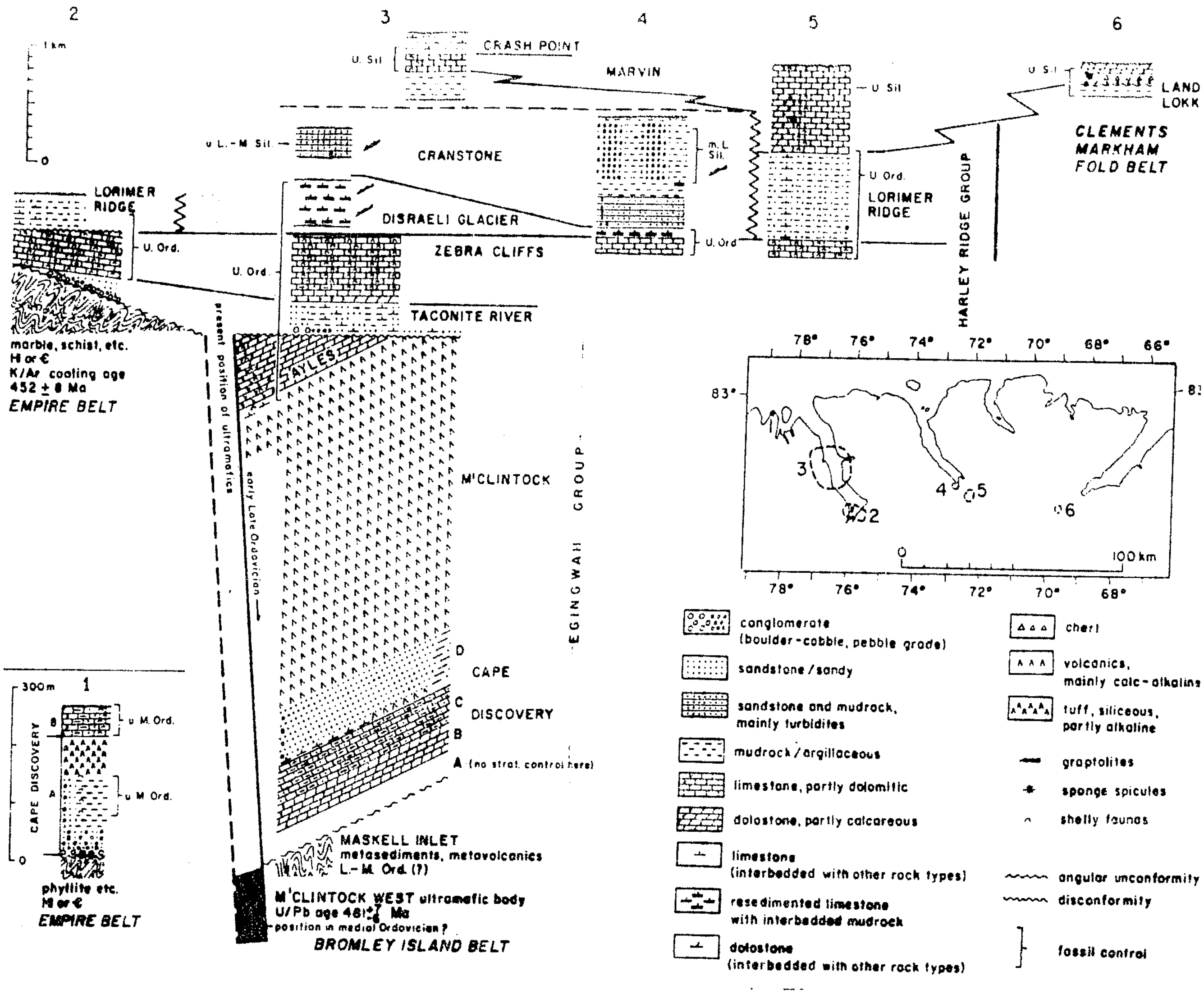

Figure 5.6 Stratigraphy, Challenger Mountains Supergroup, Middle Ordovician to Late Silurian, Pearya Terrane. (Trettin, 1987, Fig. 17. The carbonates overlying the Lands Lokk Formation at loc. 6 are now referred to as the Markham River beds.)

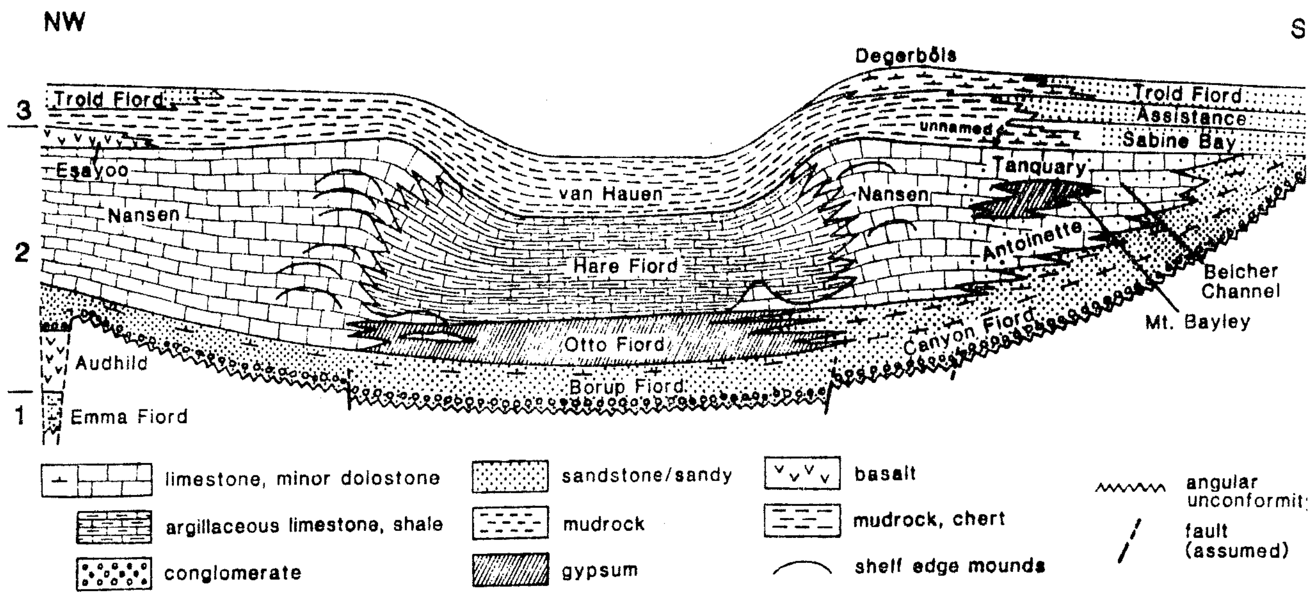

Figure 5.13 Diagrammatic stratigraphic cross section of Carboniferous and Permian units, northeastern Sverdrup Basin (not to scale; by Davis and Nassichuk in Trettin, 1989, Fig. 10)

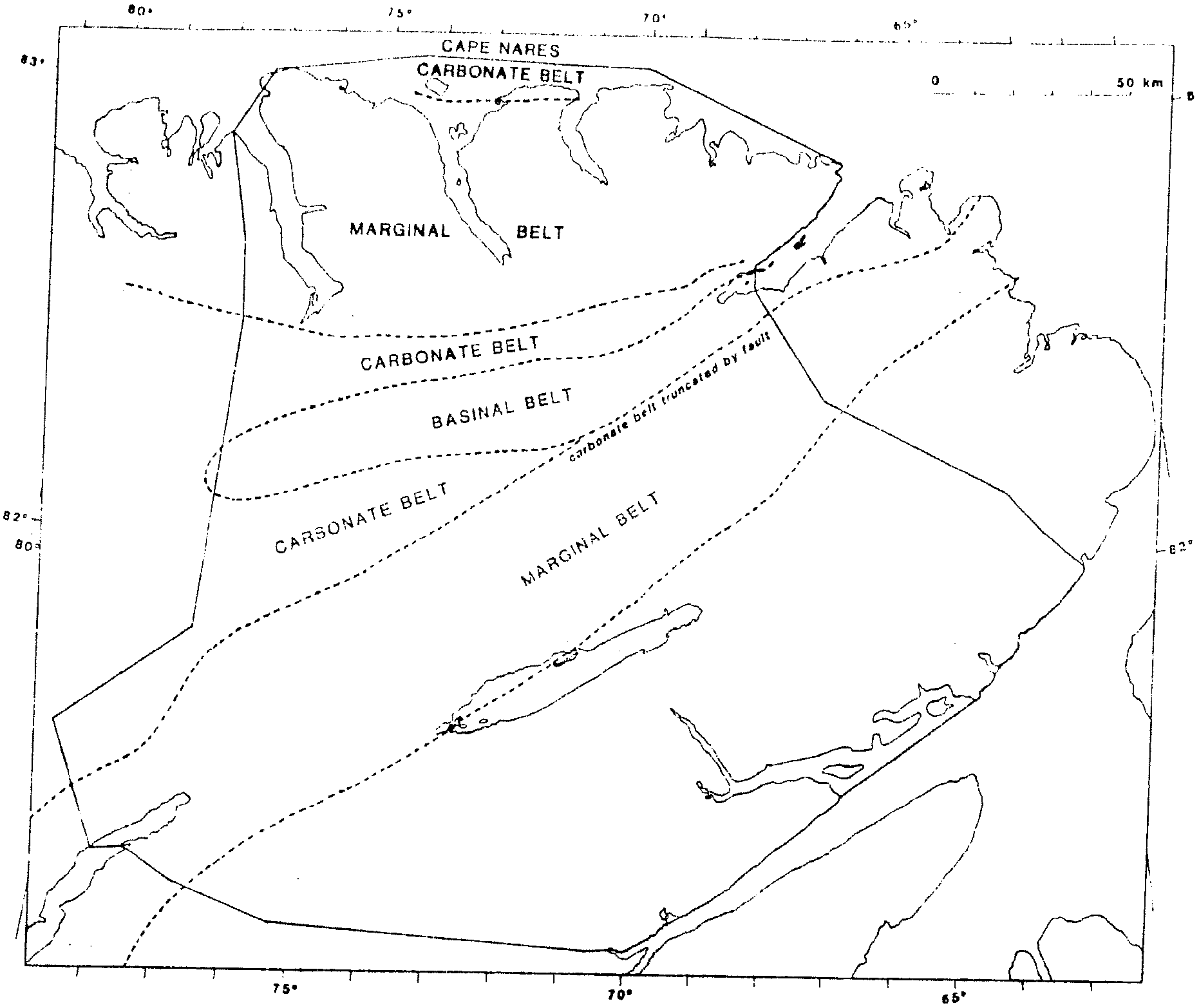

Figure 5.14 **Late Carboniferous - Early Permian** depositional belts, northeastern Ellesmere Island (adapted from Mayr, in press).

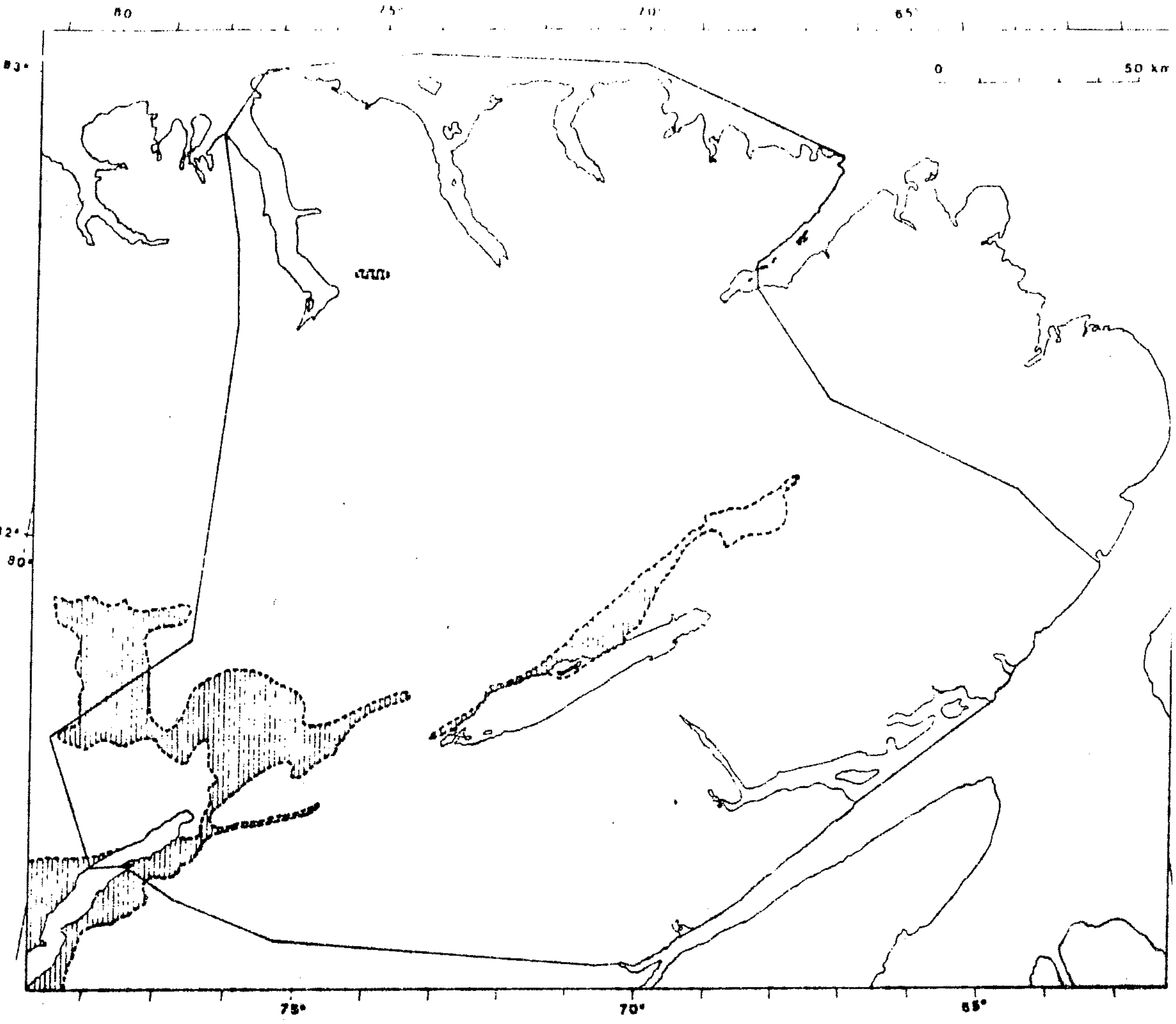

Figure 5.15 · Generalized outcrop areas of Mesozoic strata, northeastern Ellesmere Island.

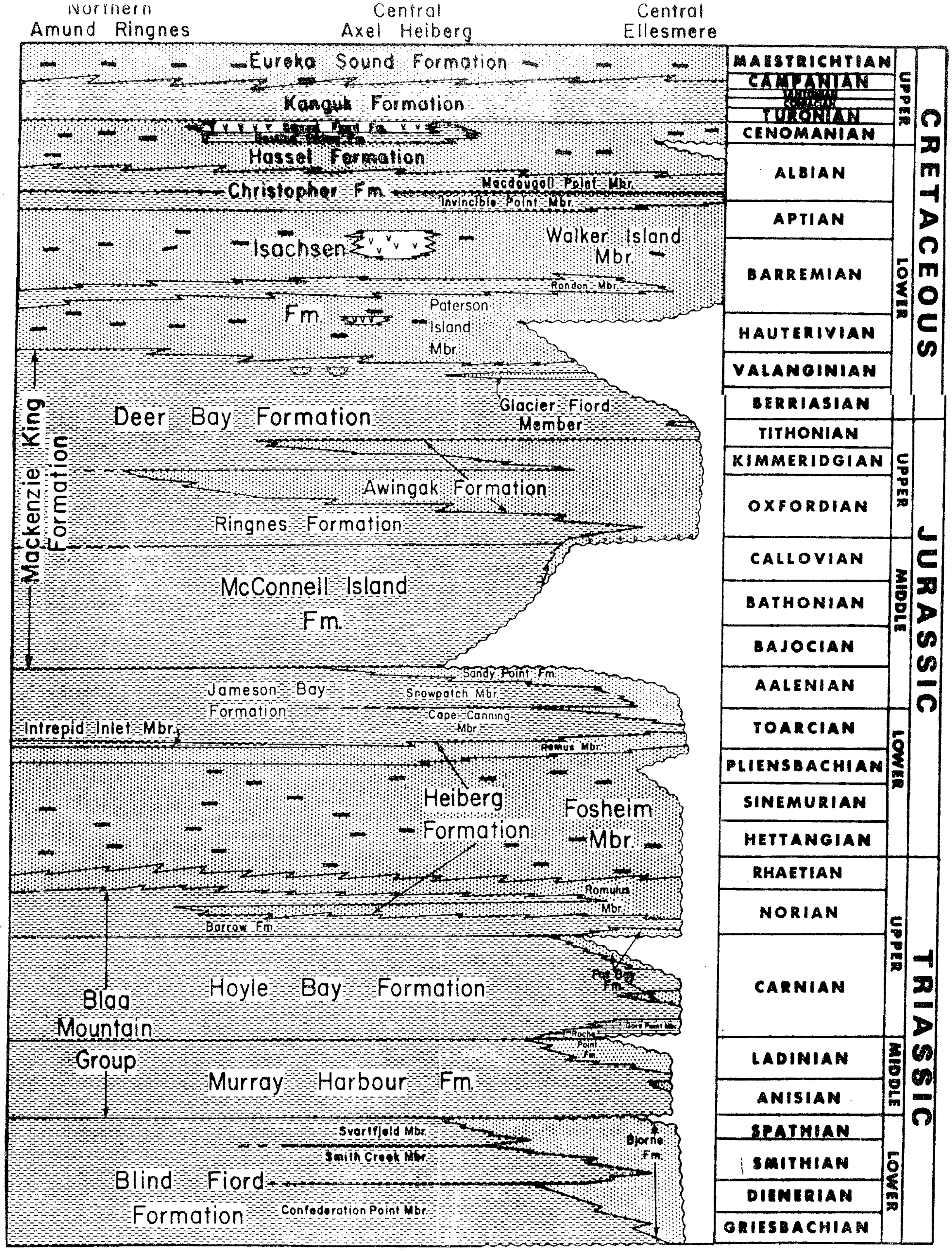

Figure 5.16 Mesozoic stratigraphic nomenclature, central and eastern Sverdrup Basin (from Embry, in press). (Stippled: sandstone; short dashes: mudrock; long, heavy dashes: coal; brick pattern: limestone.)

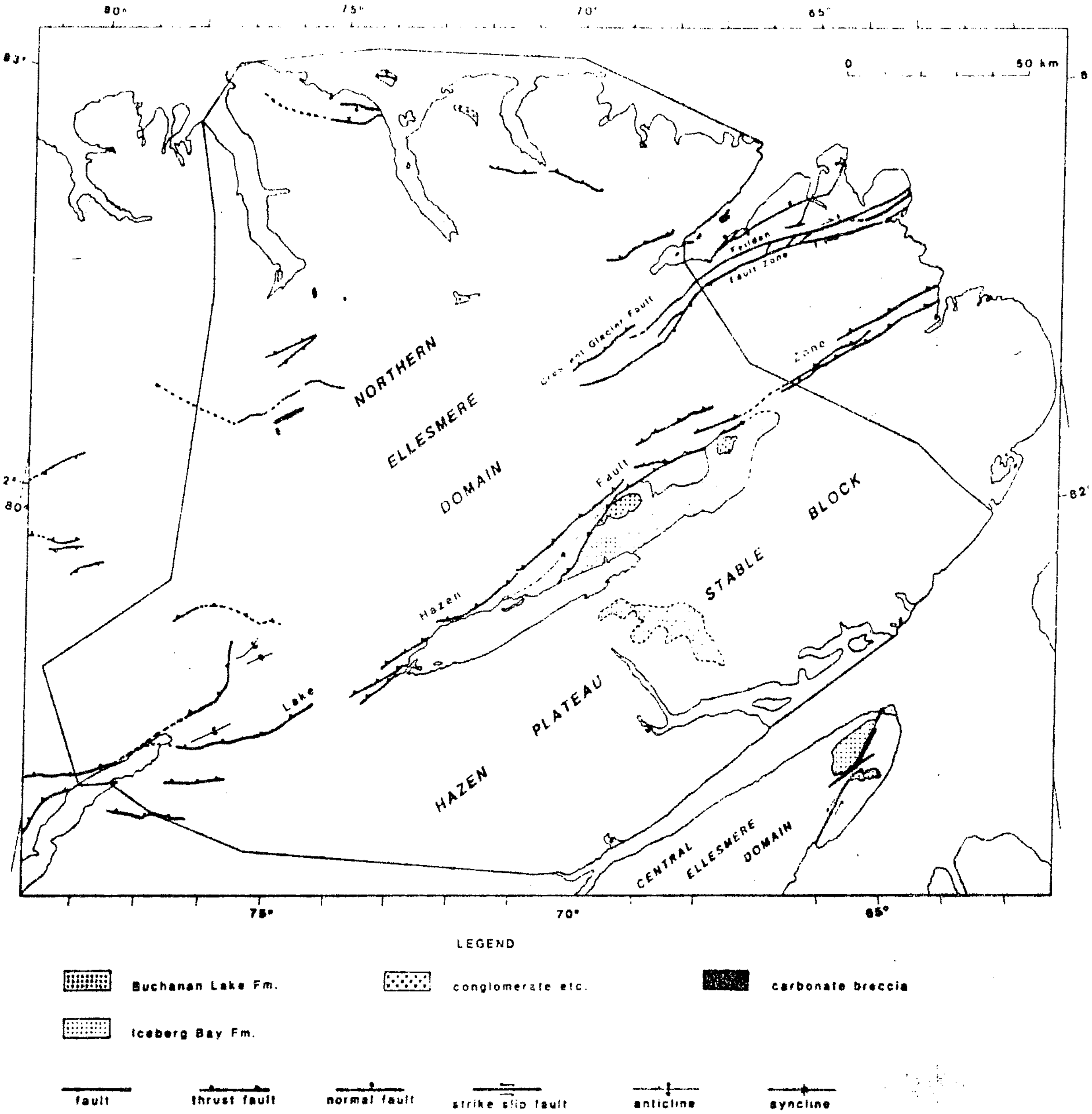

Figure 5.17 Paleogene deposits and major structural features, northeastern Ellesmere Island.

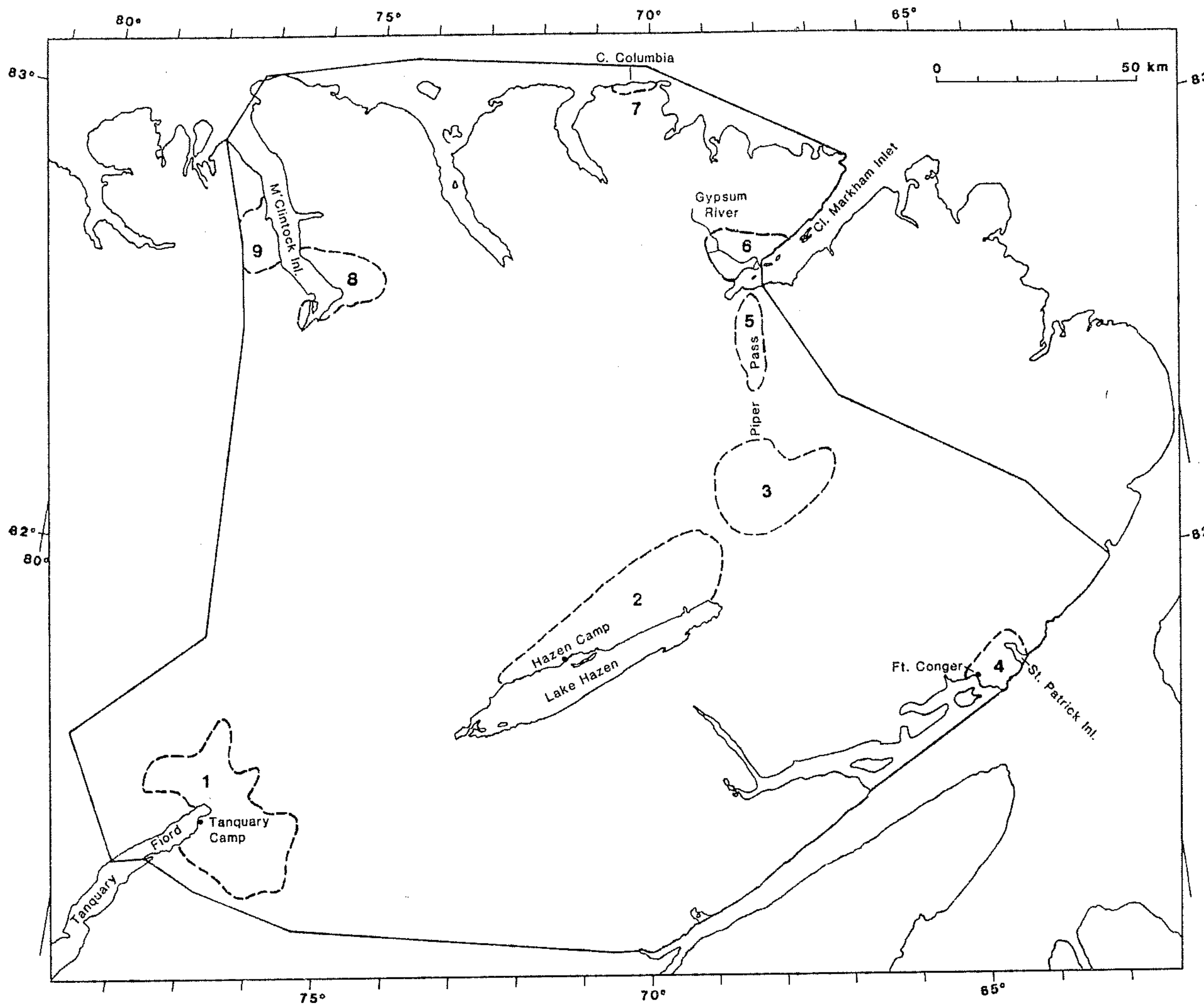

Figure 5.18 Educational sites.