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LOWER TRIASSIC TAR SANDS OF NORTHWESTERN MELVILLE ISLAND, ARCTIC ARCHIPELAGO

(Report and 24 figures)

H. P. Trettin and L. V. Hills

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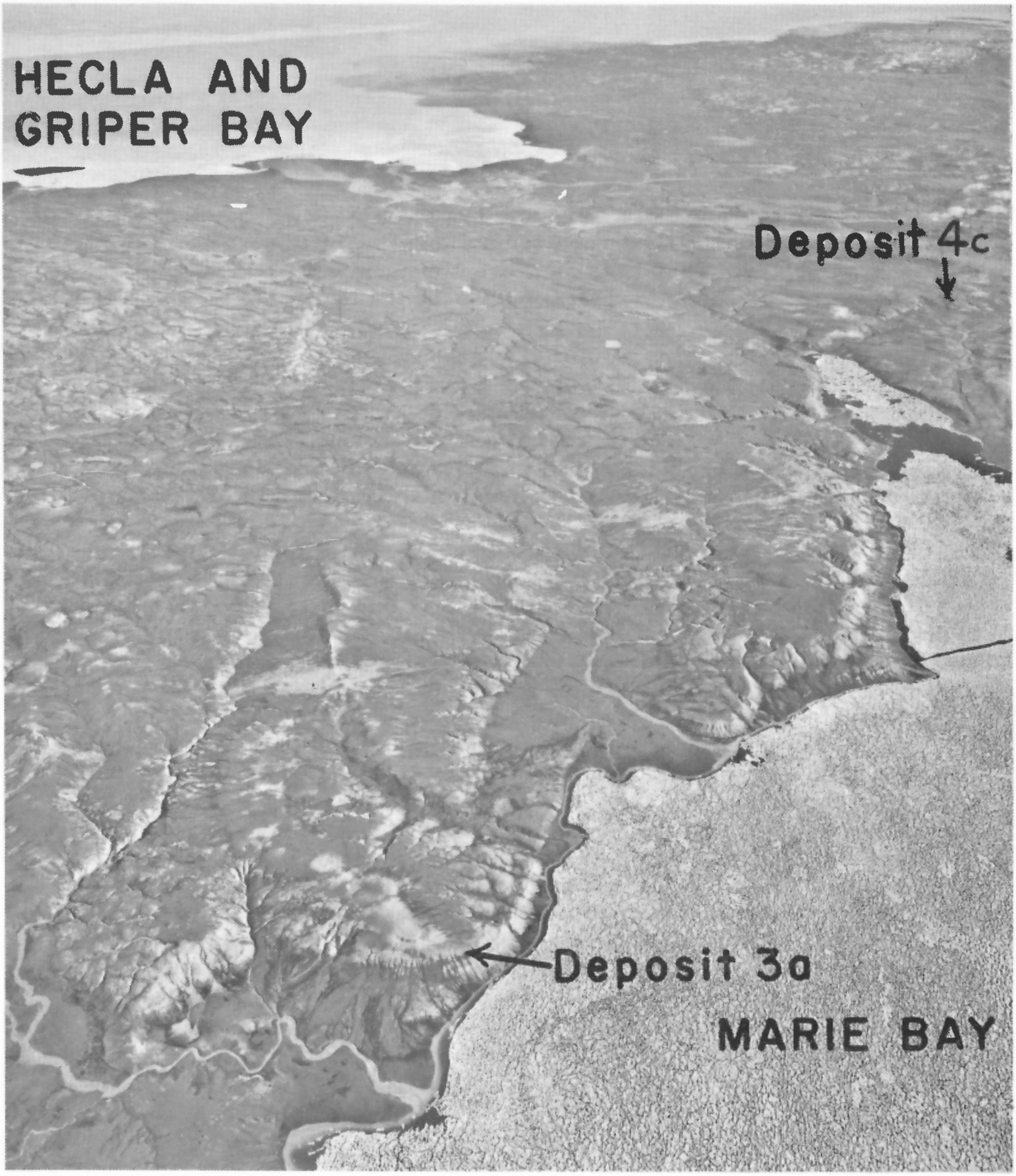
ABSTRACT

Bitumen deposits discovered in the Bjorne Formation of Melville Island, in 1962, are the first reported major showing of petroleum in the Arctic Archipelago. They have no present economic value, but are encouraging for petroleum exploration around the margin of the Sverdrup Basin.

The Bjorne Formation, the Lower Triassic marginal facies of the Sverdrup Basin, dips gently northeast, and forms a prograding, fan-shaped delta, characterized by radiating palaeocurrent directions, and concentric lithofacies, which received sediments from Palaeozoic strata, mainly Middle and Upper Devonian formations, immediately to the south.

Heavy aromatic oil occurs in six deposits, scattered throughout a narrow forty-mile-long belt. Outcrop mapping suggests that between 50 and 100 million barrels are present, with only 30 million barrels or less in concentrations of 6 per cent by weight or more. The oil, oxidized and polymerized at the surface, shows variations in nickel and sulphur content suggestive of variations in original gravity of between about 19° and 31° API.

The oil occurs mainly in porous only partly saturated sandstones, and also in conglomerates. It is concentrated: 1) invariably in the upper part of the formation, beneath disconformably overlying, relatively impermeable Jurassic strata; 2) commonly near the depositional limit of the formation; 3) commonly in basement-controlled sedimentary troughs. Regionally, it occurs within a homoclinal prism of arenaceous sediments, near its uptilted edge. On the blunt side of the prism, the fluviatile sediments probably grade to paralic and marine shales, which are the most obvious potential source, although fluids from other Pennsylvanian to Jurassic shales may have been channelled into the Bjorne Formation. Migration must have occurred in Middle Jurassic or later time.



Escarpment of the Bjorne Formation north of Marie Bay. The light coloured, relatively steep slopes are underlain by Triassic sand, sandstone, and conglomerate. Note the slightly darker coloration of the upper cliffs at deposit 3a, which is due to the bitumen. Oblique air photograph by RCAF (T 419 R-43).

LOWER TRIASSIC TAR SANDS OF NORTHWESTERN MELVILLE ISLAND, ARCTIC ARCHIPELAGO

INTRODUCTION

LOCATION AND ACCESSIBILITY OF AREA STUDIED

Melville Island, a little more than 16,000 square miles in area, is among the seven largest of the Canadian Arctic Islands. It lies in the western part of the Parry Islands (see Fig. 1), and its geographical centre is approximately at 75° 40'N latitude and 111° 22'W longitude.

The area studied lies in the northwesternmost part of Melville Island, and forms a narrow belt, some 50 miles long, and up to about 7 miles wide, which trends from the north shore of Marie Bay, on the west coast, to the vicinity of Hecla and Griper Bay, on the north coast (see Fig. 17). It is bounded approximately by latitudes 76° 02' and 76° 17'N, and longitudes 112° 41' and 115° 41'W.

There are no permanent settlements on Melville Island. The nearest settlement is Mould Bay, a jointly operated Canadian and American weather station, on the east coast of Prince Patrick Island, at latitude 76° 14'N and longitude 119° 20'W. Mould Bay is about 60 miles west of Marie Bay, and 440 miles northwest of Resolute on Cornwallis Island. Resolute, a weather station and air line terminal, is annually served by ships. The station at Mould Bay was established by air lift from Resolute in 1948, and is resupplied from the air; the gravel air strip is normally serviceable throughout the year.

Ships have reached the south coast of Melville Island several times since Parry the discoverer of the island wintered with his sailing vessels, *Hecla* and *Griper*, at Winter Harbour in 1819-20. However, ships have never negotiated the straits and channels that border the east, west, and north coasts of Melville Island, and ice conditions within these waters are especially adverse (see Canada; Dept. Mines & Tech. Surveys, Pilot of Arctic Canada, 1959, 1961; and Swithinbank, 1960).

At present, the most practical means of reaching northwestern Melville Island is by aircraft operating from Mould Bay or Resolute. In the spring, ski-wheel equipped Douglas DC 3 aircraft can be landed on unprepared snow surfaces. During July and August, and parts of June and September, only helicopters and relatively small airplanes, such as the de Havilland Otter and Beaver, the Cessna 180, and the Piper Super Cub equipped with oversized tires are used.

PREVIOUS GEOLOGICAL INVESTIGATIONS

The history of the geographical and geological exploration of Melville Island is given in a report by E. T. Tozer and R. Thorsteinsson (1964, pp. 2-17). That report is mainly a reconnaissance geological study of not only Melville Island, but also Prince Patrick, Brock, Borden, and Mackenzie King Islands, and is based on field work carried out mainly in 1954 and 1958, and is accompanied by a geological map on the scale of eight miles to the inch. The structural and stratigraphic framework established by Tozer and Thorsteinsson for Melville Island, and particularly the Sverdrup Basin succession in the northwestern part, provides a basis for the discussion of the problems surrounding the origin of the Melville Island bituminous sandstones. Especially important in this regard are Tozer's investigations of the Triassic system in the Arctic Islands (see Tozer, 1960, 1961, and 1963).

The original discovery of oil impregnated Triassic sandstones on northwestern Melville Island was made independently by two persons in 1962: first by A. Spector (see Jenness, 1963, p. 7), then a seasonal employee of the Dominion Observatories Branch, Department of Mines and Technical Surveys, and later that same year, by H. L. Stephens, a member of a geological field party of J. C. Sproule and Associates Ltd., headed by G. V. Lloyd. A second discovery by the same field party followed, but poor weather conditions prevented further investigations during the 1962 field season.

In 1963, a field party of J. C. Sproule and Associates Ltd. under J. H. Stuart Smith returned to the area, made additional discoveries of oil impregnated sandstones, and investigated the geological setting of the deposits. Two summary reports, including a highly reduced geological map, a regional cross-section, and a structural contour map have been published by Sproule and Lloyd (1963), and J. C. Sproule and Associates Ltd. (1964). Much of the information obtained during this investigation, however, is contained in confidential reports. One of these, written by J. H. Stuart Smith (J. C. Sproule and Associates Ltd., 1963), was purchased by the Department of Northern Affairs and National Resources, and made available to the present authors.

The principal contributions of Stuart Smith's valuable report may be summarized as follows. A detailed geological map on the scale of two miles to the inch was prepared. The distribution, and some important aspects of the stratigraphic and structural setting of the bitumen deposits were established. About 20 composite stratigraphic sections of the Bjorne Formation were measured, partly in the field, and partly by photogrammetric methods. The outcrop belt of the formation was divided into several subareas, and within these subareas, several members were established.

PRESENT STUDIES

Field work was carried out by the authors between June 17 and August 11, 1964, and consisted of foot traverses from five light camps established by a Piper Super Cub airplane. The aircraft, under contract to the Geological Survey, was supplied by Bradley Air Services Ltd. The work was hampered by the unusually adverse weather conditions prevalent in most parts of the Arctic Archipelago during the summer of 1964.

As much of the pertinent information available to the writers is contained in the unpublished report by Stuart Smith, it is in order to mention the additions to previous knowledge made by the present study. Only minor contributions to the general geology of the area, and the distribution and structural and stratigraphic setting of the deposits could be made. The data presented in this paper, although solely based on the writers' own observations, are in good agreement with Smith's report, from which they have benefited. Emphasis was placed by the writers on those problems that needed further elucidation: the sedimentology of the Bjorne Formation, and the quantity, chemistry, and origin of the bitumen. New contributions of the present paper are: a stratigraphic subdivision of the Bjorne Formation applicable to the entire northwestern Melville Island outcrop belt; combined palaeocurrent-lithofacies-isopach maps illustrating the pattern of sedimentation; various petrographic analyses elucidating problems of provenance, environment of deposition, and diagenesis; the discovery of two minor deposits here referred to as deposits No. 2 and 5; a provisional estimate of bitumen reserves; various chemical analyses; demonstration that most deposits occur in sedimentary troughs; and the interpretation of the origin of the oil. Most significant conclusions were reached jointly in the field (Trettin and Hills, 1965). The present report was compiled and written by Trettin, who was in charge of the project.

ACKNOWLEDGMENTS

The authors wish to express their indebtedness and thanks to various persons who have contributed technical information and laboratory results to the present study. Most chemical and physical analyses of the bitumen were carried out under the direction of D. S. Montgomery in the laboratories of the Fuels and Mining Practice Division of the Mines Branch, by R.G. Draper, M.F. Millson, H.A. Barber, and F.E. Goodspeed. An analysis for porphyrins by G.W. Hodgson of the Alberta Research Council was, unfortunately, unsuccessful. A carbon isotope determination was received from Imperial Oil Ltd., and six sulphur-isotope determinations will be made by the Isotope and Nuclear Geology Section of the Geological Survey, under the direction of R.K. Wanless.

A size analysis of ten samples of sand was undertaken by G.R. Turnquist, then a Technical Officer of the Geological Survey. Several

X-ray analyses of clay minerals were made by Anne P. Sabina, and one of limonite by R. N. Delabio. J. L. Bouvier made a chemical analysis of a limonitic sandstone. F. P. Agterberg devised a computer program for some palaeocurrent data. F. P. Agterberg, J. L. Bouvier, R. N. Delabio, and Anne P. Sabina are all members of the Geological Survey of Canada.

The organic fraction of several samples of mud was analyzed by T. P. Chamney. W. A. Bell determined a plant fossil, and J. W. Kerr, and R. Thorsteinsson graptolites in cobbles of the Bjorne Formation. T. P. Chamney, J. W. Kerr, and R. Thorsteinsson are members of the Geological Survey, and W. A. Bell is the well-known retired palaeobotanist and former Director of the Geological Survey.

The writers have received valuable advice from several colleagues at the Geological Survey, and from the following scientists working for other institutions: D. S. Montgomery of the Mines Branch, D. W. Spencer then with Imperial Oil Ltd., and J. H. Stuart Smith of J. C. Sproule and Associates Ltd.

Special thanks are extended to M. A. Carrigy of the Alberta Research Council for critically reading the manuscript.

SUMMARY OF THE REGIONAL GEOLOGY OF NORTHWESTERN MELVILLE ISLAND

The following summary account of the regional geology of northwestern Melville Island is based mainly on Tozer and Thorsteinsson (1964), but has been revised, here and there, on the basis of field work by Nassichuk (1965), and the present authors (1964).

Tozer and Thorsteinsson have assigned the Palaeozoic and Mesozoic sediments of northwestern Melville Island to two major stratigraphic-structural provinces, the Franklinian miogeosyncline, and the Sverdrup Basin.

STRATIGRAPHY

Franklinian miogeosyncline

The Franklinian miogeosyncline forms an elongate belt, which trends in an easterly direction through the Parry Islands, and in a northeasterly direction through central Ellesmere Island and northwestern Greenland. The strata of this belt range in age from Late Proterozoic to Late Devonian, but on Melville Island only Ordovician, Silurian, and Devonian strata are exposed.

Lower Ordovician to Lower Devonian

The Ordovician, Silurian, and Lower Devonian strata of the miogeosyncline are predominantly carbonate and argillaceous sediments. On northwestern Melville Island, the carbonate facies is represented by the Lower Ordovician Canrobert Formation of the Canrobert Hills, the Middle Ordovician Cornwallis Formation of McCormick Inlet area, and unnamed Ordovician and Silurian limestone and dolomite strata of the western Raglan Range. The Raglan Range carbonates as shown on Figure 20, are in fault contact with the Bjorne Formation. They were, however, not studied during the present investigation.

In the eastern part of northwestern Melville Island, near McCormick Inlet, the predominantly argillaceous facies is represented mainly by Upper Ordovician to Lower Devonian strata assigned to the Cape Phillips Formation and in the western part, by Lower Ordovician to Lower Devonian strata assigned to the Ibbett Bay Formation. In eastern Canrobert Hills, the Ibbett Bay Formation is about 3,000 feet thick, and consists of dark grey to black shale, calcareous shale, argillite, dolomite, chert, and minor limestone. The formation is present in the western part of the area mapped, near bitumen deposits 1 and 2. There it is generally poorly exposed, but some outcrops of very thin bedded to laminated dark grey graptolitic siltstone and shale, and light grey and dark grey thin-bedded chert are present. The relatively high proportion of bedded chert in these strata may indicate proximity to the eugeosyncline.

Middle and Upper Devonian

On northwestern Melville Island, the Middle and Upper Devonian is represented by the Melville Island Group, a thick sequence of marine and non-marine clastic sediments with a high proportion of sandstone in the upper part. This group exceeds 13,500 feet in thickness, and has been divided into three formations, the Weatherall, Hecla Bay, and Griper Bay. The lower and middle members of the Weatherall Formation probably underlie some of the westernmost parts of the area studied (E. T. Tozer, personal communication). However, during the present study, which was concentrated on the Bjorne Formation, outcrops of these units were not seen and on Figure 17, these areas are shown as Quaternary possibly underlain by Weatherall Formation. The Hecla Bay and Griper Bay Formations are present in the southeasternmost parts of the area investigated (Fig. 20), where they occur mainly as felsenmeer.

Sverdrup Basin

The Sverdrup Basin was the site of pronounced subsidence from Carboniferous to early Tertiary time (Thorsteinsson and Tozer, 1960; Tozer, 1960). The basin was centered in the Sverdrup Islands, and received alternations of fine and coarse clastic sediments, with carbonates and evaporites in the Pennsylvanian and Permian. The marginal parts of the basin differ from the central parts by the presence of numerous disconformities, coarser grades and lower thicknesses of clastic sediments, and a higher proportion of clastic strata as compared with carbonates. Northwestern Melville Island lies on the southwestern margin of the basin, and displays all these features.

Middle Pennsylvanian

The oldest formation of the Sverdrup Basin on Melville Island is the Middle Pennsylvanian (Moscovian) Canyon Fiord Formation, that rests with angular unconformity on the lower Palaeozoic rocks. At McCormick Inlet (Nassichuk, 1965, p. 11), it attains a thickness of 3,300 feet, and consists mainly of sand, conglomerate, and thinly bedded sandy limestone. The formation is absent north of Raglan Range, where Permian strata rest directly on Devonian beds. Within the area mapped, the Canyon Fiord occurs at two localities: at the point about 6 miles west of the head of Marie Bay, and near section 4 (Fig. 17). At both localities exposure is poor. The formation consists of muddy and sandy, largely unconsolidated sediments, some of which weather in brilliant hues of red. It probably also underlies some drift covered areas in the westernmost parts of the belt studied.

Upper Permian

On northwestern Melville Island, the Permian is represented by strata previously assigned to the Assistance Formation (Tozer and Thorsteinsson, 1964), subsequently designated as "formational unit B" (Nassichuk, 1965), and now referred to a new formation, established on Ellesmere Island, for which Thorsteinsson (manuscript and personal communication) has proposed the name Trold Fiord Formation. According to Nassichuk, Furnish, and Glenister (1966, pp. 3, 49), this unit is probably Guadalupian in age. On northwestern Melville Island, according to Nassichuk, the formation consists mainly of pale green, glauconitic sandstone with minor interbedded limestone that thins from about 200 feet near McCormick Inlet to a feather edge near bitumen deposit 1. The base of the unit is a regional unconformity. In some places, the formation rests on the Canyon Fiord Formation, and in others, on Devonian and older strata.

Lower Triassic

Of the entire Triassic system, only the Lower Triassic marginal facies of the Sverdrup Basin, the Bjorne Formation (see Tozer in Fortier et al., 1963, p. 367), is represented in the area mapped. There, as elsewhere in the Arctic Archipelago, and most parts of the world, the base of the Lower Triassic series is a disconformity. In most of the area, the Bjorne Formation overlies Permian strata, but in the westernmost parts, it rests on the Canyon Fiord Formation at some localities, and elsewhere on lower Palaeozoic beds (Fig. 17). The Bjorne Formation consists of sand, sandstone, conglomerate, gravel, and mud, and in the area mapped, ranges from less than one foot to some 400 feet in thickness. The geology of the Bjorne Formation is described in detail in Chapter III.

Lower and early Middle Jurassic

In the area mapped, the Bjorne Formation is overlain disconformably by Lower and early Middle Jurassic clayey and silty sediments characterized by poor exposure, recessive slopes, mostly olive grey soil, and a relatively rich vegetation. In most parts of western Marie Bay area, that is between bitumen deposit 3b and the northwestern extremity of the area mapped (except for section 11), there are a few feet of interbedded light grey and red-brown mud at the base of the Lower Jurassic succession (Fig. 17). This unit is similar to the uppermost part of member A of the

Bjorne Formation, and different from most Jurassic sediments, but has been referred to the Jurassic, because it seems to rest disconformably on strata of the Bjorne Formation that differ in age from one locality to the next. The grey and red muds are overlain by a predominantly recessive sequence composed mainly of very fine grained sand with considerable proportions of admixed and interbedded clay and silt, and lesser fractions of fine and medium grained sand. The predominant clay minerals in this suite are illite and kaolinite, with subordinate chlorite (see Appendix 3, Table 3). The sands contain varying proportions of glauconite. Interbedded with these unconsolidated sediments are a few beds of relatively well indurated ferruginous sandstone, rich in fossils. The ferruginous beds form ledges, or the tops of buttes and mesas. Some strata contain phosphatic nodules. In the western part of Marie Bay area, the thickness of this recessive unit is 250 to 300 feet.

The stratigraphy of the Lower and early Middle Jurassic is problematic. In the western part of Marie Bay area, near section 12 of this report, E. T. Tozer collected the ammonite Arietites of Lower Sinemurian (early Lower Jurassic) age (Tozer and Thorsteinsson, 1964, p. 124), about 10 to 20 feet above the base of the Jurassic. The Bajocian (early Middle Jurassic) fossil Leioceras opalinum has been found in the eastern and western parts of the area mapped, between 100 and 250 feet above the base of the Jurassic. This fossil is characteristic of the lower member of the Wilkie Point Formation. The apparent absence of Pliensbachian and Toarcian fossils on northwestern Melville Island, and the apparent absence of Pliensbachian fossils in the entire Arctic Archipelago suggested to Tozer and Thorsteinsson that these two formations are separated by a disconformity. Two major problems exist: 1) the contact between the two formations which, on northwestern Melville Island, are similar in lithology, has not yet been located. 2) the extent of the Borden Island Formation is unknown. Regionally, the distribution of the Borden Island Formation appears to be more restricted than that of the Wilkie Point. It could coincide with that of the basal Jurassic red mud mentioned above, because the only diagnostic Sinemurian fossil found so far lies within the area where this lithology occurs. On the other hand, on the basis of lithology and poorly preserved fossils, Tozer suspected that the Borden Island is represented near section 22 of this report (op. cit., p. 124). The lithology of section 22 would seem to extend for at least several miles farther to the east.

In summary most strata described above would seem to be early Middle Jurassic beds of the lower member of the Wilkie Point Formation, but some are early Lower Jurassic strata of the Borden Island Formation. In the area investigated, the latter formation is definitely less than 100 to 150 feet, and possibly less than 35 feet thick (see Appendix 3, Table 3, clay mineral analyses), and limited to the western part. The presence of marine fossils, and much glauconite leaves no doubt that the sediments are largely or entirely marine.

Medial Middle Jurassic to Lower Cretaceous

The remaining parts of the Sverdrup Basin succession, lying north of the map-area, will be treated only briefly.

The upper part of the lower member of the Wilkie Point Formation, which is mainly Bathonian (medial Middle Jurassic) in age, is relatively resistant and contains some medium grained, silica-cemented sandstones. The occurrence of ammonites indicates that this part of the lower member is also of marine origin. The upper, non-marine member consists of about 150 feet of partly crossbedded sand and sandstone.

The Upper Jurassic and early Lower Cretaceous Mould Bay Formation disconformably overlies the Wilkie Point Formation. It is about 450 feet thick, and consists of shale, mudstone, sand, and sandstone.

The Lower Cretaceous Isachsen and Christopher Formations occupy the northernmost parts of western Melville Island. The Isachsen consists of about 400 feet of sand, gravel, silt, shale, ironstone and coal seams, and is probably overlain by the argillaceous Christopher Formation.

STRUCTURAL GEOLOGY

Three important periods of earth movements mark the geological history of Melville Island. The first took place between Late Devonian (Famennian) and Middle Pennsylvanian (Moscovian) time, and represents the final orogeny of the Franklinian miogeosyncline. It produced closely spaced anticlines, synclines and related faults that extend for tens of miles. The second orogeny, apparently confined to northwestern Melville Island, postdates the Moscovian Canyon Fiord Formation, and predates Permian (Guadalupian?) strata. It resulted in gentle refolding of pre-Middle Pennsylvanian structures that had been bevelled by an intervening period of erosion. The Palaeozoic folding apparently was concentric, surficial, and, at least on Bathurst Island, significantly influenced by flowage of Lower Ordovician or older rock salt, which formed the base of the folded layer (Kerr, unpublished manuscript and personal communication; Temple, 1965; Workum, 1965).

The third period of movements affected Permian to Tertiary strata together with the older rocks, and is Tertiary in age, but has not yet been dated precisely. The Permian to Cretaceous strata of northwestern Melville Island form a gentle, northwesterly dipping homocline, with a few superimposed shallow folds that have been outlined by detailed photogeologic studies (J.C. Sproule and Associates Ltd., 1964). The homocline is cut by fractures and faults that commonly trend in northwesterly to northeasterly directions. Northeasterly trends are, perhaps, predominant in the lineaments cutting the homocline, and conform, in part, with such Tertiary structures as the Eglinton Graben, which lies southwest of the present area (see Tozer and Thorsteinsson, 1964, Fig. 12). The sedimentology of the Bjorne Formation (see below) suggests that some northerly and northeasterly trends in the area studied represent basement structures. Tertiary structures parallel with the strike of the homocline are less conspicuous; photogeological interpretation suggests that some faults of this orientation are present on the north side of the Raglan Range, and that others may be concealed by Marie Bay.

PHYSIOGRAPHY IN RELATION TO BEDROCK GEOLOGY

Areas underlain by rocks of the Franklinian miogeosyncline are characterized by predominant east-west trending ridges and valleys, that reflect the fold pattern of the geological province. Topographic highs are formed on carbonates, conglomerates, and indurated sandstones, and topographic lows on poorly consolidated sands and fine clastic sediments.

The area underlain by strata of the Sverdrup Basin is characterized by a step-like series of northwesterly trending escarpments, formed in arenaceous and rudaceous sediments, that are separated by slightly inclined plateau surfaces underlain by argillaceous sediments. Here and there, buttes and mesas rise from the plateau surfaces.

The boundary between the miogeosyncline and the Sverdrup Basin is marked by a valley occupied by rivers, and a marine arm, Marie Bay. The drainage pattern is complicated. Some rectilinear creeks and rivers are probably controlled by bedrock fractures.

In most of the area, the surface is covered by talus representing bedrock weathered in place (felsenmeer) or transported only for short distances. In the central parts, however, east of bitumen deposit 4, considerable glacial drift, derived from pre-Triassic strata to the south, is present.

GENERAL GEOLOGY OF THE BJORNE FORMATION

INTRODUCTION

The Bjorne Formation was named by Tozer (in Fortier et al., 1963, p. 367; see also Tozer, 1961, pp. 9-11, and 1963, pp. 2-3) for quartzose sandstones and local conglomerates lying between Permian strata and the Middle and Upper Triassic Schei Point Formation. Correlation with the Scythian (Lower Triassic) Blind Fiord Formation has been demonstrated clearly at several localities on Ellesmere Island on the basis of physical stratigraphy. At the type section on Bjorne Peninsula, southwestern Ellesmere Island, the formation is about 1,700 feet thick. In the Sawtooth Range of central Ellesmere Island it attains 4,000 feet, which is the greatest thickness recorded. Outcrops of the Bjorne Formation occur on western Ellesmere Island between the head of Tanquary Fiord and Bjorne Peninsula; on Exmouth and Table Islands in Belcher Channel, and, in the northern parts of the Parry Island group, on Cameron Island, Sabine Peninsula of northeastern Melville Island, and northwestern Melville Island (see Fig. 1). On Melville Island, the Bjorne Formation has yielded no diagnostic fossils, and the assignment of these rocks to the Bjorne is based on lithological similarity, and the disconformable stratigraphic position above Late Permian strata. This correlation, however, is weakened by the absence on Melville Island of the Middle and Upper Triassic Schei Point and Heiberg Formations.

SEDIMENTOLOGY

Types of sediments

The Bjorne Formation is composed of sand, sandstone, conglomerate, gravel, clay, and silt, in about that order of abundance. The terms gravel, sand, mud, silt, and clay are used to describe sediments that are persistently unconsolidated in outcrop, in spite of the fact that some diagenesis must have taken place. Some geologists prefer the terms conglomerate, sandstone, mudstone, etc. for such strata.

Sand and sandstone

Composition

The predominant constituents of the sands and sandstones are quartz and chert, with only trace amounts of white mica, feldspar, ironstone fragments, and heavy minerals. A few beds of member A are rich in limonite; calcite is very rare.

Quartz is more abundant than chert, but the latter dominates the coarse and very coarse sand grades. Accordingly, the quartz-chert ratio decreases with increasing grain size. In ten specimens analyzed in thin section (Appendix 3, Table 1) this ratio ranges from 3.3 in a fine grained sandstone to 1.0 in a poorly sorted, very fine to very coarse grained specimen. The average quartz-chert ratio of the ten specimens is 1.9. Most grains are single crystals, but some are semi-composite, and a fraction of these show vein-type structure.

Most chert grains are nearly pure, but some are carbonaceous and argillaceous. A small proportion shows ellipsoidal nodules, about 50 to 200 microns in diameter, that are nearly free from inclusions (Fig. 22-B). Some nodules are quartz, and others radiating chalcedony fibres, but most are ordinary chert. Most nodules probably represent radiolarian tests or other organic structures.

Some grains show an extinction pattern similar to that of the ordinary chert, but are considerably coarser in texture. In a few grains, ordinary chert grades into this type of material, and it is therefore considered to be recrystallized chert. Elsewhere, however, it is difficult to distinguish recrystallized chert from vein quartz.

Calcite was observed in only one out of more than one hundred specimens, and occurred in a laminated, fine- to medium-grained sandstone of unit A3 at section 25. The calcite consists of medium to coarse, subhedral to euhedral crystals that include finer grains of quartz and chert.

Three samples of fine to medium grained sand, one from member B, and two from member A, were analyzed for heavy minerals. The latter comprise less than 0.2 per cent by weight, and consist predominantly of opaque minerals. Several hundred grains of translucent heavy minerals were examined, and more than nine tenths of these are tourmaline and zircon (Fig. 21). The proportion of tourmaline and zircon is variable. The predominant colours of the tourmaline are greenish brown, green, and bluish green, in that order. Zircon crystals vary considerably in shape and rounding, and their habit ranges from stubby to slender prismatic, with the prisms commonly terminated by pyramids. Other non-opaque minerals are present only in very small quantity, and have not been identified with certainty; these include rutile, garnet, and zoisite.

Cement and porosity

Most arenaceous sediments are unconsolidated, but some are weakly to strongly indurated. The cement is either siliceous or ferruginous. Silica-cemented sandstones are generally friable, except for the area just west of bitumen deposit 1, where the rocks are unusually hard. In members B2 and C, the leaching of ironstone clasts has locally resulted in patchy cementation by limonite. At some localities, particularly near the head of Marie Bay, the uppermost few inches of strata beneath the pre-Jurassic erosion surface are indurated by limonite.

Sandstones rich in primary ferruginous cement occur locally in member A. Siderite was not detected in several thin sections examined. An X-ray determination of one specimen by R. N. Delabio indicates that the cementing material is limonite. A chemical analysis of a representative specimen made by J. L. Bouvier indicates 31.6 per cent (by weight) of total iron, present as Fe_2O_3. The volume percentages established by thin section point count analysis (Appendix 3, Table 1, spec. T-56-1) appear to be too high, probably because of surficial coating by limonite.

The apparent pore volume of seven specimens of poorly indurated sandstone was determined by R.G. Draper (Appendix 5). The porosity ranges from 13.6 to 30.0 per cent and averages 19.5 per cent. The porosity of the unconsolidated sands is probably higher than this average.

Roundness and sphericity

Most quartz grains seem to have been well rounded at one time, but the original shape is somewhat obscured by siliceous overgrowths in optical continuity, which are generally more angular. As these overgrowths occur in unconsolidated sands that show no sign of Triassic or post-Triassic silica-cementation, it is probable that most formed in previous sedimentary cycles. The coarse and very coarse chert is commonly well rounded, and the medium and finer grained material more angular, ranging mostly from subrounded to subangular. The sphericity of the chert, particularly of relatively large fragments, is considerably poorer than that of the quartz. The tourmaline ranges from subangular to predominantly well rounded, and the zircon from angular to subrounded. The presence of well rounded zircon and tourmaline in some phenoclasts (Fig. 21, C and D) supports the conclusion that the rounding of these sediments predates the last erosional cycle.

Size and sorting

The grain size of the sands and sandstones ranges from very fine to very coarse, with medium grained sands being most common. The sorting varies considerably, with well-sorted fine and medium grained sands of member A at one end of the spectrum, and poorly sorted conglomeratic sandstones of member C at the other end. A detailed sieve analysis of nine specimens was carried out by G.A. Turnquist (Appendix 4). The samples were chosen, for the purpose of environmental analysis, from fine to medium grained sediments that are nearly free from gravel and mud, and are not representative of the formation as a whole. The sieve analyses in Appendix 6, Table 2, carried out by R.G. Draper on 21 specimens of oil-impregnated sandstones and pebble-conglomerates represent typical sediments of member C, except for the coarse conglomerates. The sorting of these sediments ranges from good to predominantly poor, and most pebbly sandstones and conglomerates are bimodal or negatively skewed.

Conglomerate and gravel

Conglomerate and gravel are abundant in the upper part of the formation and range in phenoclast[1) -size from granules to coarse boulders. They are composed of three major types: chert; quartzose and cherty sandstones and fine conglomerates; and ironstone (see Appendix 3, Table 2).

Chert is represented mainly in the granule and pebble grades, but also forms cobbles. Most chert is very light to very dark grey, but some is reddish or greenish. Dark grey specimens seem to be rich in argillaceous and carbonaceous matter. A light green specimen examined under the petrographic microscope is rich in silt-sized muscovite. Reddish varieties are probably stained by iron oxide.

The phenoclasts composed of quartzose and cherty clastic sediments range from very fine grained sandstone to fine pebble conglomerate. In composition and texture, these roundstones are similar to arenaceous sediments of the Bjorne Formation, however, with the following minor differences:

- the phenoclasts are well indurated by silica
- the quartz/chert ratio varies over a wider range
- a higher proportion of the chert shows radiolarian(?) nodules
- tourmaline and zircon are more abundant, and can be observed in random thin sections, without previous concentration
- muscovite and feldspar are rare, but slightly more abundant than in the Bjorne Formation.

Most phenoclasts of pebble and coarser grade are well rounded and subellipsoidal. At some sections (e.g. No. 5, 6, and 9), however, the fragments, mainly chert, are relatively angular, and the sphericity is poor.

The matrix of most conglomerates and gravels is sand, which is commonly medium grained, but the matrix of some conglomerates and breccias in unit B2 also contains light grey clay. Conglomerates rich in ironstone clasts are partly cemented by limonite, apparently leached from these clasts.

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1) The term phenoclast, is used for sedimentary particles coarser than 2mm, i.e., granules, pebbles, cobbles, and boulders.

Mud

The term mud is used, according to Folk (1964, p. 24), for all unconsolidated sedimentary material finer than 0.0625 mm. Most muds are very light hues of yellowish grey, greenish grey, and pale orange, but a few thin units are dark to moderate reddish brown. According to X-ray identifications by Anne P. Sabina, the predominant clay minerals are kaolinite and illite, with minor chlorite (Appendix 3, Table 3); montmorillonite was not detected. Varying proportions of silt and very fine to fine grained sand, mainly quartz with minor chert and a little feldspar, are associated with the clay.

The organic content of the muds is low. Four light grey and red muds from members A and B, examined by T.P. Chamney contain mainly carbonized wood fragments with well preserved cellular detail, and very few, poorly preserved, questionable ostracods and foraminifera including ?*Glomospirella*.

Stratigraphic units

Three members, informally named A, B, and C have been distinguished within the Bjorne Formation in most parts of the area. These members have locally been divided in two or more subunits. These various stratigraphic units are partly distinguished by extensive marker beds, such as units of red mud, and partly by their weathering profile, which is directly related to the content of admixed and interbedded clay. The study of numerous, closely spaced sections revealed that, regardless of variations in the maximum size of phenoclasts, the clay content of individual units is fairly constant throughout the area, suggesting that the boundaries between the stratigraphic units represent time-surfaces. There are two reasons to assume that diachronism has not occurred in significant measure. 1) The area studied forms a narrow, elongate belt, parallel with depositional strike, so that the effect of the Lower Triassic regression is negligible. 2) It will be shown below that, on northwestern Melville Island, the Bjorne Formation represents a fan-shaped delta. Palaeocurrent and lithofacies studies suggest that during the time represented by members B and C, the centre of the delta shifted laterally only four to five miles. Thus the effect of lateral shifts of facies belts can be ignored. In contrast to the distribution of the clay, pronounced regional variations in the maximum grade of phenoclasts are apparent, and these are the basis for the distinction of lithofacies.

Member A

Member A is characterized by recessive slopes, and a relatively high proportion of clay. Three assemblages of sediment types have been distinguished in the field, and are represented in the columnar sections of Figure 2: red and grey muds; interstratified sand, silt, and grey mud; and ferruginous sandstone.

Two units characterized by red mud have been traced through parts of the outcrop belt of the Bjorne Formation. The beds themselves are poorly exposed, but can be recognized by the presence of red soil. The lower unit is one foot or less thick, and occurs between one and five feet above the base of the member. It is represented in most sections in the western half of the map-area, but is mostly absent in the eastern parts. The upper unit marks the top of the member, and has been recognized in nearly all but the easternmost sections. It consists of thinly interbedded red and grey mud with generally two or more red layers. The thickness of this unit ranges from about two feet to a few inches.

Thinly interstratified sand, silt, and light grey mud constitute the bulk of the member, but are generally very poorly exposed. The sand is light hues of yellow, orange, and grey. It is very fine to medium grained, and generally well sorted. This assemblage appears to be well stratified, very thin bedded to thinly laminated, and shows some planar and scoop cross-stratification. Heavy mineral separations showed a relatively high proportion of microcrystalline, presumably authigenic pyrite. Locally the pyrite is concentrated in nodules.

Ferruginous sandstones with a rich limonite matrix are confined to the eastern half of the area mapped, that is, from about 20 miles east of the head of Marie Bay to the eastern limit of the area. Some sections contain as many as four ferruginous beds, but none seem to be extensive, most of them having a strike length of less than 1,000 feet. Only one ferruginous sandstone was noted in the western part, about ten miles west of the head of Marie Bay, near section 25. A few X-ray determinations (Appendix 3, Table 3) suggest that kaolinite is the predominant component of the light grey clays, with minor illite, and still less chlorite, whereas the red-brown clays are richer in the latter two minerals.

Member B

Member B is intermediate in clay content and steepness of slope. Its base is marked by light grey and red mud of member A, and its top by cliff- or ledge-forming sandstone and conglomerate of member C. Two subunits, B1 and B2, have been distinguished in parts of the area, mainly in the region west of the head of Marie Bay. Elsewhere, the boundary between the two subunits is too vague to be useful as a stratigraphic marker.

Subunit B1, the lower part of the member, consists of two assemblages of sediments: sand with interstratified mud; and conglomeratic sandstone and conglomerate.

Assemblage 1 is generally poorly exposed. It consists mostly of fine to medium grained sand and interbedded mud. The sand appears to be generally thinly stratified, and in part crosslaminated with scoop crosslamination more common than the planar type. In most of the area, this unit is very light grey, but in the central parts (sections 61 to 74), it is yellowish brown. The mud is light grey, and occurs in units that are in the order of one or a few inches thick. Because of the poor exposure, a precise estimate could not be obtained, but it is probable that clay comprises less than 10 per cent of the unit.

Assemblage 2 consists of slightly indurated pebbly sandstone and sandy conglomerate, which typically shows crosslamination of the scoop type. Individual ledges are usually one or a few feet thick, and some appear to extend laterally for a mile or more. The phenoclasts are mainly pebbles, and to minor extent cobbles, and comprise chert, sandstone, and fine, cherty pebble conglomerate. Ironstone phenoclasts are sparse or absent.

The top of B1 is marked at some localities by a relatively thick (up to about 2 feet) layer of light grey mud, and at others by associated red-beds. Patches of red mud were observed at two sections in the western parts (sections 9, and 11). More extensive outcrops of red mud occur in the central parts of the map-area, at sections 62, 63, 64, 73, and 74. These may have a strike length of perhaps a few miles. Red weathering sandstones occur near the top of B1 at several sections in the western parts (8, 15, 28). At some sections in the central eastern parts of the area (75, 90, 95, 97, 98, 99, 102, 103, 104) sandstones believed to be near the top of B1, are intensely stained yellowish brown by limonitic material.

Subunit B2 is richer in mud than B1, but locally contains coarse conglomerates. It is composed of two assemblages: grey mud occurring in thin units that range from less than one inch to perhaps two feet in thickness; and sand, gravel, and conglomerate showing marked lateral changes in grade. The regional variation in the maximum size of the phenoclasts is shown in Figure 3. A coarse conglomerate with boulders up to eleven inches in diameter, occurs north of the head of Marie Bay, and grades laterally, to the northwest and southeast, through cobble- and pebble-conglomerate to pebbly sandstone. The conglomerates are composed of phenoclasts of chert, sandstone, fine pebble conglomerate, and ironstone in a matrix of sand and minor light grey mud. Only coarse conglomerates rich in ironstone clasts are fairly well indurated; the other sediments are weakly indurated to unconsolidated. At some western sections (6, 8, 9), the phenoclasts are poorly rounded, and the sediments extremely poorly sorted.

Member C

Member C, composed of conglomeratic sandstone, sandy conglomerate, and a small proportion of mud, is the most resistant unit of the Bjorne Formation. The lower few tens of feet or less of this member generally form steep ledges; the upper part is slightly more recessive. Measured thicknesses of the unit range up to 140 feet.

In the area north of Marie Bay, two subunits, C1 and C2, have been distinguished (Fig. 4). C2, the upper subunit, contains several thin, but extensive units of light grey mud, which are lacking in C1. The boundary between the two subunits is placed at the base of the lowest, extensive mud, characterized by a conspicuous ledge.

The sandstones of member C range from fine to coarse grained, and many contain varying proportions of very coarse sand, granules, and pebble-size material. The strata are laminated to thin bedded and commonly show crosslamination, mostly of the scoop type, and to lesser extent of the planar type. The degree of induration varies considerably, but is generally poor to fair. Cementation is generally by silica. Limonitic cementation is noticeable in the upper few inches of strata beneath the pre-Jurassic erosion surface. Yellowish brown iron stain was also seen near the top of C1 at several sections in the western part of the area studied (6, 8, 9, 11, 12).

The conglomerates of member C, like those of B2, are composed of fragments of chert, well indurated sandstone, fine pebble conglomerate, and ironstone. The coarsest conglomerate observed contains boulders up to 23 inches in diameter, and occurs about 2 to 3 miles southeast of the head of Marie Bay. These coarse rudites grade laterally, to the northwest and southeast, through cobble-and pebble-conglomerate to pebbly sandstone (see Fig. 5). Individual beds of conglomerate range in thickness from a few to a few tens of feet, and can be traced laterally only for short distances, usually a few hundred feet. The greatest concentration and coarsest grade of conglomerate occurs in the lower part of C1. Conglomeratic beds are less common in C2, which consists mostly of pebbly sandstone and sandstone. The conglomerates are in part weakly cemented by silica, and in part more strongly cemented by limonite leached from ironstone clasts.

Environments of deposition

The Bjorne Formation is composed of only a few suites of sediments, that appear to have recognizable counterparts in Recent and ancient strata from known environments.

The gravelly and sandy sediments of members B and C that show pronounced facies changes over short distances, and abundant high-angle cross-stratification mainly of the scoop type appear to be of fluviatile origin, and associated light grey muds are characteristic of the same environment. The coarsely conglomeratic facies, and perhaps also some associated arenaceous deposits seem to be characteristic of a braided river.

The laminated sandstones of units A3 and B1 showing crosslamination of the scoop type undoubtedly were deposited by currents. Their association, however, with paralic sediments suggests that they could represent tidal channels or estuaries as well as fresh water channels.

The fine lamination, medium to fine grain size, good sorting, and negative skewness of many sands in units B1 and A3 (see Appendix 4, Table 3) suggests that they may be beach deposits. Some sands analyzed fall in the possible range of dunes, but the latter have not been positively identified. The association of those sands that have textural characteristics of beaches with other paralic sediments supports their assignment to that environment.

The limonitic sandstones of member A resemble modern bog iron deposits, and may have been laid down in small lakes, swamps, or sluggish water courses, which are common in the paralic parts of large deltas.

Unit A4, composed of light grey and red mud, is generally less than two feet thick, but extends laterally for tens of miles. The strike length of unit A2, and of the light grey and red muds that locally mark the top of unit B1 is less, but still considerable when compared with their thickness. These extensive, but thin units of mud would seem to have been deposited in relatively large bodies of slowly moving or standing water. Red muds are common in the paralic parts of deltas. According to T. P. Chamney, the organic content of the muds under consideration is more indicative of a fresh and brackish water environment than of a marine environment.

The environments represented by member A probably include: beaches; bogs, swamps, or sluggish water courses; extensive bodies of slowly moving or standing fresh or brackish water; and fluvial, tidal, or estuarine channels. Unit B1 represents mainly beaches and tidal or fluvial channels, alternating with flood plains. In member B2, flood plains become predominant, and in member C, exclusive.

This sequence represents a general shift, with numerous fluctuations, from predominantly paralic to predominantly fluviatile conditions, and thus a typical regressive succession, terminated at the top by a disconformity. The regressive nature of the succession is also demonstrated by the fact that the O-isopachs of members B and C appear to retreat in a northeasterly direction (see Fig. 6). This regression could be attributed either to the prograding of a delta under more or less stable tectonic conditions, or to prograding accompanied by uplift. Possible evidence for uplift in the later part of the Early Triassic are coarse boulder conglomerates in unit C1. These, apparently, were not transported very far, perhaps only a few miles or less, and may have been derived from topographic highs not previously in existence.

As will be pointed out below, northeasterly to northerly plunging sedimentary troughs were important for the localization of oil. These are apparent from southwestward or southward bulges in the isopachs (see Figs. 3 and 5), in which the formation is thicker than in adjacent areas. Wherever complete sections of the formation are available, the thickening is seen to affect all members. As these troughs do not contain coarser sediments, they neither represent pre-existing erosional channels, nor contemporaneous channels, but rather relatively rapidly subsiding areas, continuously filled with sediments from passing currents. It will be recalled that fractures and faults in the area studied commonly trend in northerly to northeasterly directions; it is difficult to explain the troughs under consideration by any other mechanism than by relatively rapidly subsiding segments of a differentially sinking basement, fractured to some extent along northerly to northeasterly striking planes.

Sources of sediments

Palaeocurrent studies (see below) have shown that the main source of the sediments of the Bjorne Formation lay southwest of the present outcrop belt, and the coarse grade of some strata indicates that the source of at least some material was not far from its site of deposition; the pre-Triassic formations of central western Melville Island are, therefore, the most probable source of the Bjorne Formation.

The sand, which makes up the bulk of the Bjorne Formation, appears to have been derived from pre-existing sands or sandstones. This is inferred from the high compositional maturity of the sediments, which consist almost entirely of quartz and chert, and from the good rounding of the quartz. As pointed out above, the roundness dates back to previous cycles. This conclusion is also supported by the heavy mineral composition; heavy minerals are sparse, and the translucent ones represent only the most resistant suite, which leaves little doubt that the present sands are multi-cycle deposits.

The phenoclasts of sandstone, granule conglomerate, and fine pebble conglomerate in the Bjorne Formation are so similar to the sands that they appear to have been derived from the same suite of source rocks. It seems, however, that the sands were derived from poorly cemented strata, whereas the tightly cemented phenoclasts came from well indurated beds.

Possible sources of the arenaceous and rudaceous sediments of the Bjorne Formation are the Middle and Upper Devonian Melville Island Group, the Middle Pennsylvanian Canyon Fiord Formation, and the Permian strata previously assigned to the Assistance Formation, in about that order of importance. The Melville Island Group is considered as most important, because it is thickest, most widely distributed on central Melville Island, and locally deeply truncated by the pre-Triassic erosion surface. Furthermore, specimens from the Hecla Bay or Griper Bay Formations, collected at the foot of the north slope of Raglan Range are indistinguishable, both in hand specimen, and under the petrographic microscope, from certain phenoclasts in the Bjorne Formation. And finally, there is some palaeontological evidence supporting this hypothesis. Plant remains in a limonitic cobble (Fig. 22-A) found by Hills were identified by W.A. Bell as follows:

GSC Loc. 7246 – Member C of Bjorne Formation at north side of creek canyon, about 6.5 miles east of the head of Marie Bay.

"A single specimen apparently of a fossil lycopod, much too decorticated to be identifiable, even generically, but nonetheless, strongly suggesting an Upper Devonian or Mississippian age. The latter is favoured, because the elongate fusiform scars are arranged not only spirally, in oblique rows, but are also aligned nearly vertically like those of much decorticated stems of Lepidodendropsis eg. L. corrugata (Dawson)."

Known occurrences of Mississippian (Viséan) strata in the Arctic Archipelago are confined to northernmost Axel Heiberg and Ellesmere Islands (Kerr and Trettin, 1962). For this reason a Late Devonian assignment is perhaps most probable. However, the possibility cannot be excluded that this cobble has come from Mississippian strata that, in the miogeosyncline, have been completely removed by pre-Triassic erosion.

The iron in the limonitic bog iron deposits of member A could well have been derived by the weathering of ironstones of the Melville Island Group.

A cobble of light grey chert with rusty weathering graptolites (Fig. 22-C) was found in the lower part of member C, not far from the cobble described above, at bitumen deposit 4b, near locality 4b-2. The cobble is about 5 inches in diameter, and fractured. The relatively coarse grade and fragile nature of this roundstone suggest that it is a first-cycle clast, and was not transported very far. The lithology is typical of the Ibbett Bay Formation, and this assignment is supported by graptolites, identified by J.W. Kerr and R. Thorsteinsson as:

Monograptus cf. M. vomerinus (Nicholson)

Monograptus cf. M. priodon (Bronn)

of Late Early or Middle Silurian age. Probably many other cobbles and coarse pebbles of chert in the Bjorne Formation have been derived from the Ibbett Bay Formation. On the other hand, in unit B1 of the Bjorne there are conglomerates composed of nearly spherical, fine pebbles of varicolored, grey, red brown, and greenish chert, which closely resemble fine pebble-conglomerates in the uppermost Permian strata. These roundstones are perhaps multicycle deposits of ultimate Ordovician and Silurian origin that have passed through Upper Palaeozoic formations.

The muds of the Bjorne Formation probably came from the same sources as the coarse clastic sediments, because most Ordovician to Permian formations of western Melville Island contain considerable proportions of argillaceous sediments.

Palaeocurrents

Directional features

Method of Field Study

A total of 663 determinations of directional features, mainly the dip azimuths of foresets in crossbedded strata, and the axes of scoop-shaped troughs were made at 58 stations. Only one reading, or the average of several readings were recorded for an individual set of crossbeds. On the average, about 11 readings per station were taken. Where the exposed section was too thin to obtain a sufficient number of readings, additional determinations were made on stratigraphically equivalent beds separated from the original locality by at least a few hundred feet.

In the area studied, the horizontal component of the earth's magnetic field is weak, so that the direction of the compass needle can be influenced significantly by local lithological anomalies, daily variations, and magnetic storms. The declination, however, is strong enough to permit consistent readings at a given outcrop for a few hours. Therefore, the direction of palaeocurrent indicators was measured by means of the Brunton compass, and the local declination was established by repeated bearings to topographic points marked on air photographs, and subsequently on detailed topographic maps. Most determinations of declination appeared to be reproducible with an accuracy of 2 degrees. However, at some localities, bearings to distant points could not be obtained, and at these stations an areal mean declination was used. With one exception, the declinations obtained lay within a range of 15 degrees, and most within a range of 10 degrees. The error introduced by the uncertainty about the true north direction, therefore, may range up to a maximum of 15 degrees, but is estimated to be generally about five degrees or less.

Summary Description of Features Used

Direction of Scoop Axes. The structures used are shallow, elongate, spoon-shaped sets of crossbedded strata composed of laminated to thin bedded sandstone and conglomeratic sandstone that correspond closely to troughs described by Harms et al. (1963) from the modern Red River of Louisiana. The direction of current flow, as established by observations on Recent sediments, is parallel with the longest dimension of the scoop, and from the blunt to the acute end. It is most easily recognized on bedding planes by a spoon-shaped outline of the scoop; or, in vertical sections that expose the structure at least from two sides, by sighting down the length of the structure, normal to the minimum cross-section (Fig. 7). The axes of the scoops observed on Melville Island range in length from about one foot to more than 10 feet, and are commonly between 3 and 9 feet. In terms of

Allen's (1963) classification the structures are both grouped and solitary; generally of large scale; and commonly with a gradational lower boundary. The bedding planes are more often discordant than concordant with the scoop-shaped enclosing surface, and the beds are both homogenous and heterogenous in lithology. The steepest dips, which occur on the upper rear end of the structures, were commonly more than 20 degrees. Near bitumen deposit 6, however, relatively small structures are common, which are characterized by maximum dips of less than 20 degrees, and concordance with the enclosing surface.

Azimuth of foreset dip of planar and concave crossbeds. Sets of crossbedded strata of this type range from a few inches to about 5 feet, and are commonly between 1 foot and 3 feet thick. In terms of Allen's (1963) classification, the bedding planes are planar or slightly concave in upward direction. The structures are partly grouped, but more often solitary. The lower contact is mostly gradational and the upper contact erosional. The lithology is both homogenous and heterogenous, and consists, in the latter case, usually of conglomerate grading up to sandstone. The dips of the sets used for crossbedding determinations range between 5 and 35 degrees with a mean of about 21 degrees (see Fig. 8d). Crossbeds with dips of about 10 degrees or less, were rarely used.

The planar and slightly concave crossbeds may represent two different types of features: foresets of transverse bars, as described by Ore (1964), and large-scale scoops, as described by Conolly (1965). In modern, braided rivers (Ore, 1964), transverse bars are usually oriented diagonally to the stream bed, so that the foreset dip azimuths form varying angles with the stream direction. However, the overall distribution of the bars is symmetrical with respect to the stream course, so that the average of the foreset dip azimuths lies close to the average current direction. The large-scale scoops described by Conolly (1965) are characterized by widths ranging from about 50 to 1,000 feet, essentially planar lower bounding surfaces, and slightly concave foresets. The dip azimuths of these foresets form intermediate to low angles with the current direction, and their average lies close to the scoop axis.

Bedding plane lineation, and pebble imbrication. Bedding plane lineation and pebble imbrication were recorded only at three stations, and represent less than 1 per cent of the readings taken.

Compilation and presentation of data

The compilation of data given in the present report is preliminary; a more thorough analysis will be made and a trend surface map will be compiled.

In Table 2 of Appendix 2, the arithmetical and vectorial mean, standard deviation, and vector strength of scoop axes, foreset dip azimuths, and imbrications and lineations are listed separately for individual stations and members. The difference between the arithmetical means and the vectorial means is generally less than 3 degrees, and not significant compared with the probable error in determining true north.

In Figure 8a, the arithmetical means of the foreset dip azimuths are plotted as a function of the corresponding arithmetical means of the scoop axes at the same station. The values are scattered approximately symmetrically about a line for which the two parameters are identical.

Figure 8b shows two histograms that illustrate the deviation of the foreset dip azimuths and scoop axes recorded from their respective means. The two histograms are approximately symmetrical about the mean, and show the bell shape characteristic of normal distributions. The histogram of the foresets is somewhat broader and lower than that of the scoop axes, and the standard deviation is accordingly higher; the standard deviation of the foresets is about 32, and that of the scoop axes, 27 degrees.

Figure 8c is a cumulative frequency curve based on the same data, and gives the probability of deviations of various magnitudes from the local mean. It can be seen, for example, that 75 per cent of the scoop axes deviate less than 29 degrees from their respective means, whereas 75 per cent of the foreset dip azimuths deviate less than 36 degrees from their means. In other words, the probability of finding a scoop axis that deviates more than 29 degrees from the local mean, is only 25 per cent.

In Table 3 of Appendix 2, the limits of confidence at the 95 per cent level of confidence for varying numbers of readings of foreset dips and scoop axes are listed, assuming a standard deviation of 32 degrees for the foresets, and of 27 degrees for the scoop axes. It will be recalled that about 11 readings per station were taken. The limits of confidence for 11 foreset dip azimuths, according to this table, are about plus or minus 17 degrees, and those for 11 scoop axes, plus or minus 15 degrees. This table also shows that only 9 determinations of scoop axes would be necessary to achieve the same limits of confidence (plus or minus 17 degrees) as 11 foresets. In other words, in the case of about 11 readings, the scoop axes may be considered as 1.2 times as significant as the foreset dip azimuths.

In order to avoid overcrowding of the map, it was desirable to combine the two types of means, and to represent them by a single arrow. From the foregoing it is clear that it is reasonable to choose the arithmetical mean of all readings for this purpose. If the scoop axes were assigned a slightly greater weight, because of their greater significance, the results would be modified only slightly, by about 2 degrees or less, which is negligible.

Variations in the maximum grade of phenoclasts

Regional variations in the maximum size of clastic particles are generally a useful tool for establishing the direction of sediment transport. In particular, the maximum size of phenoclasts, that is, of fragments more than 2 mm in diameter, is a useful parameter. In the area studied, however, it was found that the maximum grade of the phenoclasts varied so considerably between adjacent sections that this parameter could not be contoured (see Appendix 2, Table 1). It was possible, on the other hand, to show on the map the distribution of three to four broad, and overlapping grade classes (see Fig. 3 and 5).

Summary of results

The means of the directional features form a semicircular radiating pattern. In the extreme northwestern and southeastern parts of the area investigated, the directional features are nearly parallel with the isopach trends, but in the central western parts, near the head of Marie Bay, they are approximately normal to the isopachs. The coarsest conglomerates are found in the same area; these grade laterally into finer grained sediments. The pattern as a whole represents a fan-shaped delta, the apex of which lay, during the time interval represented by member B, a few miles west of the head of Marie Bay, and during the time represented by C, about 5 miles to the southeast. A minor apex for both members is recognizable in the central eastern parts of the area studied, about 10 miles southeast of bitumen deposit 6. It is interesting to note that, although the 0-isopach of the formation coincides roughly with the northern limit of the Canrobert Hills in the west, and the Raglan Range in the east, neither of these two uplands appears to have been in existence during the Early Triassic.

STRUCTURAL GEOLOGY

Structural setting

In the northwestern Melville Island outcrop area, the structure of the Bjorne Formation is homoclinal (see Figs. 17 to 20). The overall strike, with local modifications, is about N 75° W, and the dip is to the northeast. Measured dips generally range between 1 and 4 degrees, but steeper dips may occur adjacent to some faults. Photogrammetric investigations by J. C. Sproule and Associates Ltd. (1964) have outlined two anticlines located about 4.5 miles north, and 7 miles northeast of the head of Marie Bay. These are separated from the area studied by synclines. The Bjorne Formation is transected by several steeply dipping faults. The vertical component of movement of these faults does not exceed a few hundred feet, and is commonly in the order of one hundred feet or less. The faults extend upwards into the Lower Jurassic beds, and probably formed during the Tertiary orogeny.

Contact relationships

Lower contact

The lower contact of the Bjorne Formation is disconformable. In most of the area studied, the Bjorne Formation rests on Permian strata. In the westernmost parts, however, the pre-Triassic erosion surface cuts through the upper Palaeozoic, so that the Bjorne, at some localities, rests on the Moscovian Canyon Fiord Formation, and at others, on the Ordovician to Lower Devonian Ibbett Bay Formation. The discordance between the Permian and the Triassic is generally so low that it can only be detected by regional mapping. At some localities, however, an angular discordance is recognizable on air photographs. Such angular discordances are probably related to local pre-Triassic faulting, rather than to regional folding.

Upper contact

The upper contact of the Bjorne Formation, with the Borden Island and Wilkie Point Formations, is also disconformable, and the corresponding hiatus involves the Middle and Upper Triassic, and, where the Borden Island Formation is absent, the Lower Jurassic. For simplicity, this disconformity is referred to as the pre-Jurassic erosion surface, although this is not a strictly correct designation. In outcrop, the disconformity is made apparent by an abrupt change in lithology from medium to coarse grained, relatively resistant pebbly sandstone, or sandy conglomerate, to recessive mixtures of mud and very fine grained sand. At some localities, particularly north of the uppermost part of Marie Bay, the uppermost strata of the Bjorne Formation are indurated by limonite, apparently produced by the leaching of ironstone clasts on the pre-Jurassic erosion surface. The original thickness of the Bjorne Formation is unknown, and therefore an absolute measure of pre-Jurassic erosion cannot be obtained. A few observations and speculations relating to this problem, however, have been made and are summarized below.

1) Pre-Jurassic erosion is generally confined to member C. Only at the very margin of the basin of deposition, where the Bjorne Formation is ten feet or less thick (sections 53, and 54 at bitumen deposit 4c), does the Jurassic appear to rest directly on member B; and this may be the result of non-deposition, rather than erosion of member C.

2) In the area north of Marie Bay, where C1 and C2 have been distinguished, the relative proportion of these two subunits gives some indication of the topographic relief prior to the deposition of the Jurassic strata. Sections having equal thicknesses of C1 (e.g., sections 16 and 30) differ by as much as 75 feet in the thickness of C2. This may give an indication of the minimum total relief in the area. Much higher figures are obtained if C2 is restored according to the lowest values of C1/C2 observed, and if these restored values are compared with the actual ones. At section 8 this ratio is about 1/6; at 14, about 1/3, and at 4, about 1/2. At section 43, C1 is about 104 feet, and C2 about 20 feet. If C2 originally was six times as thick as C1, then about 600 feet would have been removed by erosion; if it was three times as thick, about 290 feet, and if it was twice as thick, about 190 feet. These figures suggest that the actual relief may have been in the order of several hundred feet.

3) Figure 9 is a contour map, showing areal variations in the ratio C1/C2. Assuming that, at any given locality, the rates of subsidence during the intervals represented by C1 and C2 remained about constant, the following two interpretations are possible.

a) A high value of C1/C2 may indicate a positive area, where relatively strong uplift was followed by erosional levelling. The map shows that, according to this interpretation, the amount of uplift increases to the northeast. However, some distance farther to the northeast, beyond the present area, this hypothetical uplift must die out, because in the axial parts of the Sverdrup Basin the Triassic is complete, and forms a conformable sequence with the Jurassic. This assumption, then, leads to the concept of a tectonically positive area located within the marginal part of the Sverdrup Basin, but at some distance from its outermost margin.

b) High values of C1/C2 could also indicate erosional channels and basins carved into the more or less uniformly uplifted margin of the Sverdrup Basin. In this case, the present contours would have some resemblance to topographic contours, with low elevations represented by high C1/C2 values, and vice versa. This interpretation is considered more probable.

GEOLOGY OF THE BITUMEN DEPOSITS

DESCRIPTION OF THE DEPOSITS

Two minor and four major outcrop areas, or groups of outcrop areas of oil impregnated sandstones and conglomerates are known in the map-area. They have been informally designated as bitumen deposits 1 to 6, and are described below with respect to areal extent, thickness, degree of impregnation, stratigraphic position, reserves, and thickness of overburden. An adequate estimate of reserves could only be obtained by drilling, and many more analyses than the twenty-two obtained. However it is possible on the basis of the present data, to assess, at least the order of magnitude of these deposits. In the analyses obtained, the bitumen content was expressed in per cent by weight of the formation sample, and these weight percentages have been multiplied by 2 to obtain volume percentages. This conversion is based on an approximate specific gravity of the oil of 1, and of the reservoir rocks of 2, as seven specimens of sandstone from members B and C averaged 2.06 in density (see Appendix 5 for specific gravity of rocks).

Deposit 1

Deposit 1 forms a butte in the western part of Marie Bay area, several miles south of the main escarpment of the Bjorne Formation. This butte obviously has resisted erosion because the upper part of the formation here has been cemented by highly viscous oil. On the west, south, and east, the limits of the deposit are erosional; the northern limit appears to be gradational (see Fig. 10). The base of the deposit covers an area of about 600 acres; the area covered by the upper surface is estimated to be about 550 acres. The greatest thickness, ranging up to 65 feet more or less, and the highest concentration of oil, ranging up to more than 14 per cent of bitumen by weight occur at section 8, on the southeast side of the butte. The lowest grade (less than 0.5 per cent) and the lowest thickness (about 18 feet) occur on the northwest side, at section 7. At the intermediate section, number 6, the thickness of the deposit is about 40 feet. There only one analysis has been obtained, with a bitumen content of 3 per cent, but higher concentrations may be represented. Near these three sections, exposure is relatively good; elsewhere it is rather poor. The oil always occurs in the uppermost part of the formation, and dies out downwards. The stratigraphic position of the lower surface of the oil-impregnated zone rises, as the thickness of member C increases. At section 6, the thinnest section, the lower boundary of the impregnated zone is relatively sharp, and coincides with the base of C1. The lower 15 feet are generally impregnated, but strata fairly rich in oil alternate with rather lean ones. At section 8, member C is thicker, and the lower boundary of the impregnated zone coincides approximately with the base of C2. The lower 9 feet here are very lean, and the overlying 11 feet only slightly richer. At section 7, member C is thickest, and the oil confined to the upper part of C2. In the lower 22 feet of the impregnated zone, only a few small oil-stained lenses were observed. In the upper 18 feet impregnation appears to be general, but of very low grade.

Assuming an area of 550 acres, a maximum average thickness of 50 feet, and a maximum average grade of 12 per cent of bitumen by volume, the deposit could contain in the order of 25×10^6 bbl. Assuming the same area, a minimum average thickness of 20 feet, and a minimum average grade of 4 per cent, the deposit would contain about 3×10^6 bbl. Applying the averages of sections 6, 7, and 8, a mean thickness of 35 feet, and a mean grade of 9 per cent, the deposit would contain 13×10^6 bbl. This estimate is judged to be closest, but perhaps slightly high. The reserves of deposit 1 may thus range anywhere from three to twenty-five million barrels, and are perhaps in the order of ten million barrels. Only 50 per cent or less of this deposit would seem to contain more than 6 per cent of bitumen by weight, which is the present lower economic limit for the processing of the Athabasca bituminous sands.

The deposit is locally overlain by Lower Jurassic sandy mud, probably not more than 20 feet thick. The mud has spread, by solifluction, from the outcrop area over the entire upper surface of the deposit.

Deposit 2

Deposit 2 forms an isolated knob (Fig. 17), which apparently owes its resistance to weathering to cementation by oil of the uppermost beds. The deposit covers an area of only a few acres. Its present boundaries are erosional, but it probably did not extend far beyond its present limits. This is inferred from the low thickness of the deposit, and from the observation that stratigraphically equivalent beds exposed about one half mile to the north are barren of oil. At the south end, the deposit is one or two feet thick, and on the east side, about four feet. An analysis from the latter locality indicated 2.8 per cent of bitumen by weight. Some oil occurs in the uppermost bed of member C1, and a higher concentration in the basal bed of C2, the two being separated by a stratum of light grey mud. Member C2 is here only about 2 feet thick, probably because of deep pre-Jurassic erosion. The deposit is estimated to contain only a few thousand barrels of oil. It is overlain by olive grey Lower Jurassic sandy mud.

Deposit 3

Deposit 3 (Fig. 11) occurs in three isolated outcrop areas referred to as 3a, 3b, and 3c.

Deposit 3a

Deposit 3a forms a conspicuous, southwest trending butte north of the central part of Marie Bay. From northwest through south to southeast, the limits of the deposit are erosional. The deposit appears to die out on the northeast, and to be separated from deposit 3c by a barren interval of one quarter of a mile. The maximum thickness observed is 67 feet at section 14. At the south end of the butte, the thicknesses are in the order of thirty feet. The degree of saturation appears to be low, and three analyses average only 1.78 per cent of bitumen by weight. Assuming an area of 150 acres, an average thickness of 35 feet, and an average saturation of 3.5 per cent by volume, the volume of oil contained in this deposit would be in the order of 1.4×10^6 bbl. It is overlain by Lower Jurassic sandy mud and muddy sand, locally exceeding 50 feet in thickness.

Deposit 3b

Deposit 3b comprises a group of scattered outcrops some of which appear to represent remnants of continuous zones, and others original small lenses. Individual outcrops are usually a few feet long, and one or a few feet thick. The degree of saturation appears to be mostly low. The showings occur in the uppermost strata of the Bjorne Formation, generally in unit C2, and are locally overlain by Lower Jurassic sandy mud.

Deposit 3c

Deposit 3c is exposed intermittently along the slopes of a sinuous, southwesterly facing escarpment. On the southeast end, it appears to die out. The southwestern border is erosional. On the northeast, the deposit disappears under the Jurassic cover. Deposit 3c is probably connected with 3b, from which it is separated on the surface by the Jurassic cover. On Figure 11 a tentative interpretation of the extent of the oil impregnated area is given. According to this interpretation, it covers about 700 acres. The maximum thickness observed is at section 17, where about 55 feet of strata are impregnated. The oil occurs both in C1 and C2 and appears to be slightly richer in the lower subunit, which is unusual. It appears to be concentrated in layers that show a pinching and swelling pattern or are composed of individual lenses, a few inches long. The two analyses obtained from this zone average 2.1 per cent of bitumen by weight.

Assuming an area of 700 acres, an average thickness of 15 feet, and an average grade of 4 per cent by volume, this zone would contain about 3×10^6 bbl of oil. None of the oil appears to be present in concentrations of 6 per cent weight or more. The thickness of the Jurassic cover above this deposit locally reaches 150 feet.

Deposit 4

Deposit 4 consists of three groups of showings named 4a, 4b, and 4c, which lie relatively close to each other (Fig. 18).

Deposit 4a

Deposit 4a is intermittently exposed, for some 4,000 feet, on the uppermost levels of a south-facing escarpment near the head of Marie Bay. The deposit seems to die out on the east and west. Northwards, it disappears under the Jurassic cover. Because it is thin, and has not been observed in creek cuts north of the escarpment, it may be presumed to die out a short distance from the outcrop. The thickness of impregnated strata ranges up to about 5 feet. In general the degree of saturation appears to be low, but a relatively rich specimen has yielded a bitumen analysis of 9.8 per cent by weight. The oil occurs in member C2 within the highest strata of the formation, except for the uppermost few inches, which are here strongly iron-cemented and low in porosity. The deposit is estimated to contain only a few thousand barrels of oil. The thickness of the Jurassic overburden is in the order of a few tens of feet and less.

Deposit 4b

Deposit 4b comprises two groups of occurrences of oil-impregnated sandstones and conglomerates. The first includes seven or more isolated outcrops exposed on the southwest-facing escarpment just east of the head of Marie Bay. The thickness of impregnated strata is a few feet or less. Some beds are very lean; a relatively rich specimen, however, contained 5.79 per cent of bitumen by weight. The oil occurs in member C at the top of the preserved section, but the Jurassic cover, and probably also the uppermost beds of the Bjorne Formation have been eroded. It is not known whether these scattered outcrops represent individual lenses, or erosional remnants of a once continuous zone; the general setting suggests the former. The second outcrop area is exposed in a creek canyon parallel with, and about one and one half miles north of the escarpment. The impregnated zone is about 1,000 feet long, and appears to die out on the east and west sides. Northwards, it disappears under the Jurassic cover, and southwards, under Pleistocene till. The thicknesses observed range from a few to about 22 feet, but only the uppermost few feet are fairly well saturated. A sample from this deposit contains 4.5 per cent by weight of bitumen. Stratigraphically, the oil occurs in the uppermost part of member C, at the top of the formation. The Jurassic cover in the north is at least 50 feet thick.

Exposure between the two groups of showings is poor, as the intervening area is covered by till. Minor occurrences of the same type as described above are probably present here.

Deposit 4c

Deposit 4c is exposed on a southwest sloping hillside southeast of the head of Marie Bay (Fig. 12). The escarpment of the Bjorne Formation, which generally parallels the isopachs, and trends in southeasterly direction, here swings south, and cuts through the isopachs. The retreat of the escarpment in this area has undoubtedly been slowed by oil cementation of the sediments.

The oil appears to die out on the northwestern and southeastern sides. The southwestern limit of the deposit is erosional. To the north, the deposit disappears under Jurassic muds. A tentative interpretation of the extent of the base of the zone is given on Figure 12. Its upper surface, according to this interpretation, covers an area of approximately 670 acres. Exposure is generally poor, and at some sections it is not certain whether the oil seen in merely surficial or represents bedrock. The maximum thickness of the deposit could lie anywhere between 100 and 166 feet. It is apparent, however, that the thickness of the deposit, like the thickness of the formation, decreases gently in a southeasterly direction, and that it thins out very abruptly on the northwest end. The bitumen content is relatively rich, ranging from 4.1 per cent to 10.0 per cent by weight, and averaging 7.4 per cent. This is the only deposit in which the oil impregnates both members B and C.

Assuming an areal extent of 670 acres, an average grade of 12 per cent by volume and an average thickness of 50 feet, the deposit would contain about 30 x 10^6 bbl of oil. If the average thickness is assumed to be only 30 feet, the reserves would be in the order of 20 x 10^6 bbl., and if it was 80 feet, in the order of 50 x 10^6 bbl. It is probable, then, that at least a few tens of millions of barrels are present in this area, much of which may be present in concentrations of 6 per cent by weight or more.

The thickness of the Jurassic cover is in the order of 50 feet and less.

Deposit 5

Deposit 5 occurs on a southwest-facing escarpment, along which it has been traced for about 500 feet (Fig. 19). The maximum thickness observed is about 60 feet. The oil occurs in conglomerate and sandstone, presumably of members B and C. The highest outcrops seen are about 10 feet below the present plateau surface, which is covered with sand and gravel, probably bedrock of the Bjorne Formation that has weathered in place. This deposit is significant mainly because it demonstrates a certain continuity of oil occurrences between deposits 4 and 6, which would otherwise be separated by a barren stretch of nearly twenty miles. It also illustrates the relationship between oil occurrences and sedimentary troughs noted in some other deposits. Its oil reserves cannot be assessed at present, but may be presumed to be less than one hundred thousand barrels.

Deposit 6

Deposit 6 is exposed on the upper levels of cliffs that face several branches of Kitson River (Fig. 13). The deposit can be observed to die out to the northwest and southeast. The southern limit is erosional, but it appears that the original southern limit lay not far from the margin of the present outcrop area. In the northwest, the deposit is cut off by an extensive fault. Northwards, it disappears under the Jurassic cover. The deposit forms two main outcrop areas, and several minor patches. The northern outcrop area, exposed on three sides, covers at least 1,000 acres but may actually be twice as large. The southeastern outcrop area covers about 200 acres. The maximum thickness observed is 50 feet, and the average thickness may be 20 to 25 feet. Three analyses range from 1.3 to 10.2 per cent of bitumen by weight and average 4.8 per cent. The oil occurs in member C, at the top of the formation, and generally decreases in grade downwards.

Assuming an areal extent of 1,000 acres for the main outcrop area, an average thickness of 25 feet, and an average grade of 10 per cent by volume, this area would contain 20 x 10^6 bbl. The actual content, however, may be twice as large.

Assuming for the minor, oval zone an areal extent of 200 acres, an average thickness of 20 feet, and an average grade of 10 per cent by volume, this area would contain about 3 x 10^6 bbl. This estimate is probably high, because the actual grade in this part may be considerably less than 10 per cent, so that an estimate of about 1 to 2 x 10^6 bbl would seem to be more realistic.

The known reserves in deposit 6, then, are judged to be about twenty million barrels. Most of this material is present in concentrations of less than 6 per cent by weight.

The southern outcrops are nearly bare of overburden, but on the northern outcrops, the Jurassic cover reaches a thickness of 150 feet.

SUMMARY OF RESERVES AND ECONOMIC CONSIDERATIONS

As stated above, not enough information is available to give a reliable estimate of the reserves; however, enough is known to draw two important conclusions:

1) Considerable quantities of oil impregnated sandstone with more than 6 per cent of bitumen by weight are present only in deposits 1 and

4, and total perhaps around thirty million barrels or less. This reserve would clearly be insufficient for a mining operation of the Athabasca type, which needs volumes twenty times as large to be economic. Furthermore, it is obvious that mining and processing on Melville Island would be much more expensive than in the Athabasca area, so that the minimum requirements as to the grade and volume of the deposits must be considerably higher.

2) The total known reserves are estimated to be, perhaps, seventy million barrels, and, accounting for the covered area north of deposit 6, perhaps one hundred million barrels. Restored to its original size before erosion, the entire belt may have contained as much as two hundred million barrels of oil. The original oil was of a type that is presently produced from conventional wells (see Chapter V). The presence of an exhumed oil field of perhaps two hundred million barrels in this area, then, is encouraging for further petroleum exploration in the Arctic regions, particularly around the margin of the Sverdrup Basin.

CONTROLS

Several factors appear to have been influential in the localization of the oil, and are listed below in the order of importance.

Roof effect of Borden Island and Wilkie Point Formations

The oil is always concentrated in the upper part of the Bjorne Formation, and dies out downwards. It is usually confined to member C; but where the impregnated zone is relatively thick, and the formation relatively thin, as in deposit 4c, the oil extends downwards into member B. This distribution is modified, to a minor extent, by vertical variations in the porosity of the reservoir sediments. No oil has been found in the overlying Borden Island and Wilkie Point Formations, which obviously formed an impermeable barrier to upward migration.

Position within a tilted wedge of permeable sediments, near the up-turned edge of the wedge

The overall shape of the Bjorne Formation is that of an inclined wedge of permeable sediments, the edge of which is tilted upwards. The bitumen occurs within the wedge, at or near its up-turned edge, that is, near the "pinchout" of the formation. All deposits, except for deposit 6, appear to die out to the north or northeast, but have an erosional southern or southwestern margin. The greatest thickness and highest degree of saturation of deposits 1, 3, and 4 occurs at that erosional margin. Furthermore, the greatest thickness and highest degree of saturation in the entire belt occur in those deposits that are closest to the depositional limit of the Bjorne

Formation, deposits 1 and 4c. The southern margin of deposit 1 lies about one half mile north of the O-isopach of Member C, and deposit 4c locally touches it. As stated above, deposit 6 forms an exception to this rule, and possible reasons for this will be discussed below.

Location in sedimentary troughs and embayments of the basin margin

Deposits 1, 3a, 4a, 5, and 6 lie in well defined northerly to north-easterly plunging troughs, which can be recognized by southward or south-westerly bulges in the isopachs. If the O-isopach is drawn parallel with the isopachs based on measured sections, then these troughs are seen to terminate, up-dip, in embayments of the basin margin. Deposit 4c lies in a trough that is only weakly defined. No such structures can be demonstrated for the minor deposits 2 and 4b. It has been pointed out above that these troughs are basement-controlled, and do not represent erosional channels.

Occurrence in porous sediments

The oil is confined to poorly cemented or unconsolidated sand-stones and conglomerates of members B and C that are generally free from or poor in clay. At deposit 4c, some oil also occurs in cobble and boulder conglomerates, but the bitumen content of these sediments is relatively low, particularly where the leaching of ironstone clasts has resulted in limonite cementation. The oil content is also poor in limonite cemented sandstones of deposit 4a that underlie the pre-Jurassic erosion surface. Near the base of some deposits, unsaturated strata alternate with partly impregnated beds. In some instances the distribution of the oil in these strata may be related to grain size, sorting, and related features; in others, no significant difference is visible. It is perhaps not coincidental, however, that the highest analyses obtained were from medium to predominantly fine grained, fairly well to well sorted sandstones (see analyses No. 388, 389, and 402).

Possible effect of thin overburden at time of migration

The thickness of overburden during the time of entrapment of the oil is probably a very important but unfortunately poorly known factor.

Detailed isopachs of the Mesozoic strata of northwestern Melville Island are not available, but the approximate regional trends are given in Douglas et al., 1963, Figures 17 and 18. Generally, the formations thin towards the south and southwest. On Melville Island, Jurassic strata are not preserved south of the present outcrop belt. Furthermore, on south-eastern Melville Island, some sixty miles south of the eastern extension of the present outcrop belt of the Bjorne Formation, isolated outcrops of the

Lower Cretaceous Isachsen Formation rest directly on Devonian strata, thus the Jurassic beds must wedge out somewhere within this sixty-mile interval. In the present area the escarpment of the Bjorne outcrop has receded generally less than one and one half miles from the depositional limit of the formation, and it is probable that in the central and eastern parts the same holds true for the Jurassic beds. Conditions, however, are probably different in the northwesternmost part of the area studied, where the trends for the Triassic and the Jurassic separate, with the former turning northwest and the latter southwest. It is possible, therefore, that at the time of emplacement the thickness of overburden was greater in the northwestern part of the area than in the southeastern portion. Although the mode of migration and entrapment of the oil are not well understood, it is held that a relatively thin cover of overburden at the time of migration might have been a decisive factor in arresting the oil of deposit 6 at some distance from the ultimate trap, that is, from the depositional limit of the Bjorne Formation. It is conceivable, for example, that at a critical depth of overburden the oil flowing in an up-dip direction encountered, and was arrested by, groundwater flowing down-dip.

GEOLOGICAL DISCUSSION OF THE ORIGIN OF THE OIL

The problem of the source of the Melville Island bitumen will probably not be solved in a conclusive manner until a geochemical framework of reference has been established for the syngenetic and epigenetic hydrocarbons of the Arctic Archipelago. However, several possible modes of origin are examined below in the light of the geological evidence presently available, in order to provide a working hypothesis for petroleum exploration.

Origin in argillaceous sediments of the Bjorne Formation, within the northwestern Melville Island outcrop area

It might be suggested that the oil originated within the present outcrop area, in paralic muds of members A and B1, and migrated upwards, until it was trapped beneath the Lower Jurassic seal. This theory, however, is not in agreement with the composition and inferred depositional environment of these sediments. It was found that the argillaceous sediments of the Bjorne Formation are generally poor in organic matter, and that this material consists mainly of carbonized wood and megaspores, substances that are not normally considered to be sources of petroleum. Bituminous matter, if it was present originally, must have been destroyed by oxidation. This conclusion is supported by such indicators of an oxidizing environment as limonitic deposits in member A, and the red colour of some muds in members A and B. Furthermore, the ubiquitous crossbedding in the associated sandstones suggests a shallow and agitated environment that was probably well aerated.

Derivation from lower Palaeozoic reservoirs by migration through fractures

Several geologists, including, in more recent years, M. Y. Williams (1949), J. C. Sproule (Sproule, 1938, 1951; Sproule and Lloyd, 1963), and T. A. Link (1951) have suggested that the oil of the Athabasca deposits came from underlying Devonian carbonate reservoirs, and reached the present reservoirs through fractures. An analogous origin is favoured by J. C. Sproule and his collaborators (Sproule and Lloyd, 1963; J. C. Sproule and Associates Ltd., 1963, 1964) for the Melville Island oil sands, although the possibility of an origin in argillaceous equivalents of the Bjorne Formation is not rejected by them. Sproule and his collaborators suggest that the oil is of lower Palaeozoic origin, was originally trapped in lower Palaeozoic reservoirs comparable to the Raglan Range carbonates, or in Devonian sandstones, and reached the present reservoirs by migration through fractures, perhaps combined with some lateral migration. The following observations may be taken as evidence in favour of this hypothesis; occurrences of fossil oil in the lower Palaeozoic strata of the Parry Islands; the rather local distribution of the present oil, without structural closure or an obvious stratigraphic control; a certain amount of fracturing and faulting near Marie Bay; and a possible relationship with lower Palaeozoic anticlinal structures.

This hypothesis is not rejected by the writers, but is considered less probable than an origin in Triassic shales, as outlined below. The reasons may be summarized as follows:

1) The only part of the area studied where information about the lower Palaeozoic strata directly underlying the bitumen deposits can be obtained, is in the vicinity of deposits 1 and 2, although exposure here is poor (Fig. 17). The main rock unit here is the Lower Ordovician to Lower Devonian Ibbett Bay Formation, with some areas apparently underlain by the Middle Devonian Weatherall Formation. Wherever exposed, the Ordovician and Silurian strata dip steeply. Pre-Pennsylvanian and pre-Triassic erosion have cut deeply into the Palaeozoic sequence, so that locally the Bjorne Formation rests directly on the Ibbett Bay. Any domal structure that may have existed in the Late Devonian would seem to have been truncated by these two periods of erosion, and any oil that may have been present in such structures, would seem to have been removed.

2) Practically nothing is known about the subsurface of the other deposits. With thick sequences of shale and chert present, the structure however, may be assumed to be complicated.

3) No relationship between the occurrence of oil and any of the major fractures and faults visible on the ground, and on air photographs could be detected. The distribution of the oil is decidedly different from fracture-controlled ore deposits, where mineralization can actually be seen

to spread out from fissures. There is, however, at least one minor vertical fracture, leading up to a bitumen deposit (No. 6), which is filled with bitumen. This evidence is, unfortunately, ambiguous; it is not certain whether the oil filled the fracture from above, or ascended in it from below.

Derivation from upper Palaeozoic reservoirs by migration through fractures

The upper Palaeozoic strata of the northwestern Melville Island outcrop belt could be considered as potential intermediate reservoirs that have lost their petroleum to the Bjorne Formation by upward migration in fractures. This theory is attractive because the upper Palaeozoic of northwestern Ellesmere Island, as Thorsteinsson has shown, is characterized by associations of sediments, such as shales and reefs, that are promising for the accumulation of hydrocarbons. However, these facies are not represented in the area studied, which probably lies shoreward from the favourable facies. Furthermore, both the Canyon Fiord Formation, and the Upper Permian rocks have been exposed at the surface for some time prior to the deposition of the Bjorne sands; it is difficult to see how they could have retained their oil during these periods, to lose it at later times, after the Bjorne Formation was deposited. Also, as pointed out in the discussion of the lower Palaeozoic source theory, there is no obvious relationship between the localization of the oil, and of fractures and faults transecting the Bjorne Formation. And finally only trace amounts of oil stain have so far been detected in the upper Palaeozoic formations of northwestern Melville Island. On the other hand, as stated below, it is possible that fluids from upper Palaeozoic shales were channelled into the Bjorne Formation, down-dip from the outcrop belt.

Origin in pre-Middle Jurassic shales of the Sverdrup Basin

The concentration of the oil in the upper part of the Bjorne Formation leaves little doubt that the overlying muddy sediments of the Borden Island and Wilkie Point Formations acted as a seal to further upward migration. Therefore, the migration of the present oil must have occurred after these beds, and a sufficient thickness of overlying strata, were laid down; that is, not before Middle Jurassic time.

The concentration of most oil in sedimentary troughs, and the increase in the degree of saturation towards the up-turned edge of the Bjorne Formation suggests that migration occurred mainly within these troughs, and proceeded from the north or northeast to the south or southwest, that is towards the margin of the Sverdrup Basin.

It is reasonable to suppose that the fluviatile arenites and rudites of Members B and C of the Bjorne Formation grade, on the north and northeast, to paralic and eventually to marine sediments both with a considerable proportion of shale. The argillaceous and silty equivalent of the Bjorne Formation, the Blind Fiord, is exposed only on Axel Heiberg Island and western Ellesmere Island but there can be little doubt that it also underlies the Sverdrup Islands, and other regions.

Heavy, nearly continuous sedimentation occurred in the Sverdrup Basin from Pennsylvanian to Tertiary time, and the total maximum thickness of the sedimentary column in the central parts probably exceeds 40,000 feet (Thorsteinsson and Tozer, 1960, p. 12; Douglas et al., 1963, p. 14). Along with sedimentation, a progressive compaction of the interbedded shales must have taken place in the central as well as the marginal parts of the basin. After an early stage of direct upward movement, the expelled fluids probably escaped laterally, at the basin margins (see Hedberg, 1964, pp. 1780-1783). The main avenues for migration probably were arenaceous units, such as the Bjorne Formation, and, particularly, clastic tongues that have broad contact areas with surrounding shaly strata.

Paralic or marine argillaceous strata, then, interfingering with the Bjorne Formation would seem to be the most obvious potential source of the present oil. However, petroliferous fluids originating in Middle Triassic paralic and marine shales may also have been channelled into the Bjorne Formation. The latter sediments have been assigned to the Blaa Mountain Formation, which includes black shales, and exceeds 8,000 feet on Axel Heiberg Island (see Tozer, 1961, pp. 18-23; 1963, pp. 6-15). A few units of shale also occur in the basin margin equivalent of the Blaa Mountain Formation, the Schei Point Formation (Tozer, 1961, pp. 13-18; 1963, pp. 4-6). Furthermore, the possibility that the remaining units of the pre-Middle Jurassic section of the Sverdrup Basin, namely the Lower Jurassic, Upper Triassic, and Permo-Pennsylvanian formations have contributed oil, cannot be dismissed.

NOTES ON THE CHEMISTRY OF THE BITUMEN

SOME PHYSICAL AND CHEMICAL PROPERTIES OF THE OIL

Twenty-two specimens of oil-impregnated sandstones and conglomerates, representing surficial material, were submitted to D. S. Montgomery of the Mines Branch (Department of Mines and Technical Surveys) under whose supervision several types of analyses were carried out. The results are tabulated in Appendix 6, and the most important data are briefly summarized here. Linear trends and correlation coefficients were calculated by the Departmental Computer, with K. R. Dawson acting as liaison officer.

The bitumen was obtained from the sediments by benzene extraction, and is completely soluble in CS_2.

The specific gravity of the oil was measured at 77° F and converted to the corresponding value at 60° F. In the twenty-two specimens analyzed, it ranged from 1.025 to 1.083, corresponding to the range 6.5° to -0.8° API.

Elemental analysis for C, H, and N was performed on six samples. The compositional range of the ash free bitumen of these samples is as follows:

C	:	79.14	-	82.67%
H	:	9.27	-	10.59%
N	:	0.39	-	0.63%

The percentage by weight of carbon involved in methylene and methyl group of five specimens was determined by infrared spectroscopy, and the molecular weight was measured by thermoelectric osmometry in benzene solution. The fraction of aliphatic carbon atoms, and the total percentage of carbon atoms are essentially the same as those of the Athabasca bitumen. The classification of the organic matter, according to Abraham (1960) is:

Genus:	Bitumen
Species:	Native asphalt
Member:	Associated with mineral matter

The O_2 content of the six specimens mentioned above, obtained by subtraction of the percentages of C, H, N, S, and ash from 100, ranges from 3.67 to 8.24 per cent. The oxygen content of three specimens was determined by neutron activation; after correction for interference by colloidal clay, the samples were found to range in O_2 from 3.4 to 7.1 per cent.

The sulphur content of twenty-one specimens analyzed ranges from 0.88 to 3.08 per cent. The mean sulphur value of the major deposits

(1, 3, 4, and 6) decreases systematically from northwest to southeast (see Fig. 14). At two localities (deposit 1, section 6, analyses 387-389; deposit 3a, section 15, analyses 392-393) consecutive samples were taken. The sulphur content in these sections decreases from base to top by 0.53 per cent and 0.32 per cent respectively.

From these various analyses, the atomic ratios of H/C, N/C, S/C and O/C were calculated.

The nickel content of five specimens analyzed varies from 5 to 20 ppm. These few analyses seem to show the same pattern of regional, and local vertical variation as the sulphur values, the correlation index of sulphur and nickel being 0.98 (see Fig. 15d).

A fraction of the nickel and vanadium of crude oils commonly occurs in porphyrin complexes, and therefore, three specimens of bituminous sandstone were submitted to G. W. Hodgson of the Alberta Research Council for porphyrin analysis. Unfortunately, these specimens were too highly weathered to yield useful results. An earlier study of porphyrins on samples from Melville Island (Hodgson et al., 1963, p. 84) had yielded 0.8 ppm of vanadyl porphyrin; nickel porphyrins were below detection limits, i.e. less than 0.2 ppm.

DISCUSSION

Original Gravity of the Oil

Several observations indicate that the oil in the outcrops sampled is highly altered, and that the present specific gravity is higher than the original one. 1) The oxygen content, ranging up to 8 per cent O_2, is unusually high, and indicates alteration of the oil by exposure to air. 2) The specific gravity of the oil is approximately proportional with the oxygen content, the coefficient of correlation being 0.94 (see Fig. 15e). 3) Crude oils from western Canada commonly show good correlation between sulphur, nickel, and vanadium content on the one hand, and gravity on the other hand (see Fig. 15a and b). The lack of correlation between sulphur and specific gravity in the Melville Island oil (see Fig. 15c) indicates that a change in gravity must have occurred; polymerization concomitant with oxidation seems to be the most ready explanation for this. 4) A high degree of alteration is also apparent from the apparent destruction of the porphyrins.

In order to obtain an estimate of the original gravity, the Melville Island oil was compared with oils from western Canada that have similar sulphur and nickel content. This approach seems reasonable in view of the many geological similarities between western and Arctic Canada, although one cannot be certain about the original composition of the oil until unaltered specimens have been obtained and analyzed. Figure 15b, showing the API gravity of 1,277 crude oils from western Canada as a function of their sulphur content, is based on Table II in Hitchon, 1964. According to this graph, the Melville Island oil would range approximately from 16° to 31° API, with the mean near 26° API. Seven analyses of western Canadian oils with sulphur and nickel values close to those from Melville Island were selected from the sixty-seven analyses presented by Hodgson (1954) (see Fig. 15d). On Figure 15a, the API gravity of the seven oils is plotted as a function of their sulphur content, and the linear trend is shown. According to this regression, the Melville Island oil would range approximately from 19° to 31° API, and would have a mean gravity of about 26° to 27° API.

These comparisons suggest that the specific gravity of the Melville Island oil was originally lower than that of the Athabasca bitumen, and that it falls in the range of heavy crude oils produced from conventional wells. This implies that the original gravity and hence viscosity of the oil are not incompatible with migration over a considerable distance, which was inferred from sedimentological evidence.

Local vertical variations in sulphur and nickel content

If it is assumed that the nickel and sulphur content of the Melville Island oil are proportional to the original specific gravity of the oil, then the upward decrease in these elements noted at two sections, would correspond to an upward decrease in the original specific gravity (or increase in API gravity). Such vertical variation in gravity, within individual pools, is not uncommon, as the amount of dissolved gas may increase in an upward direction. Levorsen, for example (1958, p. 341) reports that the gravity in the Hawkins pool of the Upper Cretaceous Woodbine sand of northeastern Texas ranges from 16° API at the bottom to 31° API at the top.

Regional variation in sulphur and nickel content

Systematic regional variations in the sulphur and nickel content of large pools or groups of pools of the same age, and concomitant variations in gravity are not unusual; well studied examples from western Canada are the Cretaceous Cardium pools of the Pembina field, and the Viking pool of the Joffre field (Hodgson and Baker, 1959), and a well known example from the United States is the Pennsylvanian Seminole sands of Oklahoma (Bonham, 1956).

Changes of this nature have been explained by several theories; e.g. variations in the environment of formation of the oil; differential absorption of heavy and polar constituents during migration; and metamorphic factors.

On northwestern Melville Island, the presumed host rocks are not exposed, and the distances of migration are unknown, and therefore the first two theories cannot be tested. Regarding the third theory, it should be noted that the petrography of the associated sediments indicates rather shallow burial, and thus relatively low pressure and heat. Unfortunately, isopach maps of the overlying formations are not yet available.

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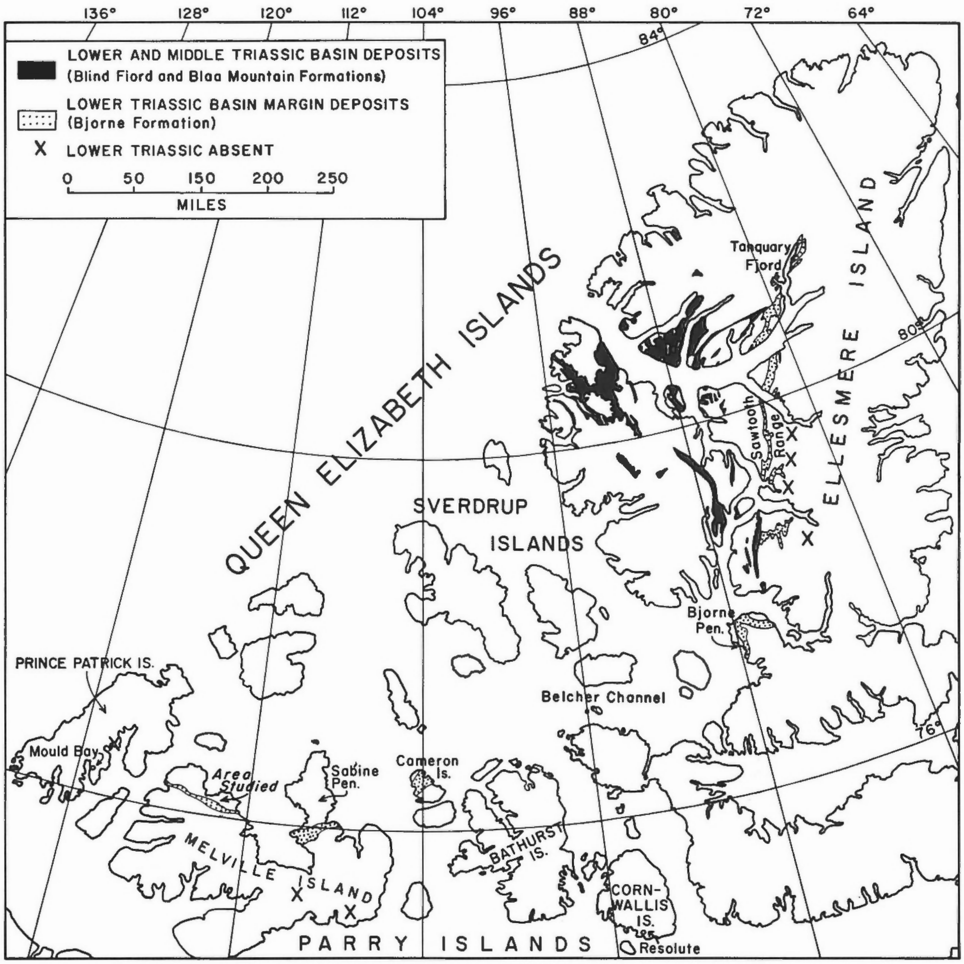


Figure 1. Lower Triassic facies of the Sverdrup Basin, and location of area studied.

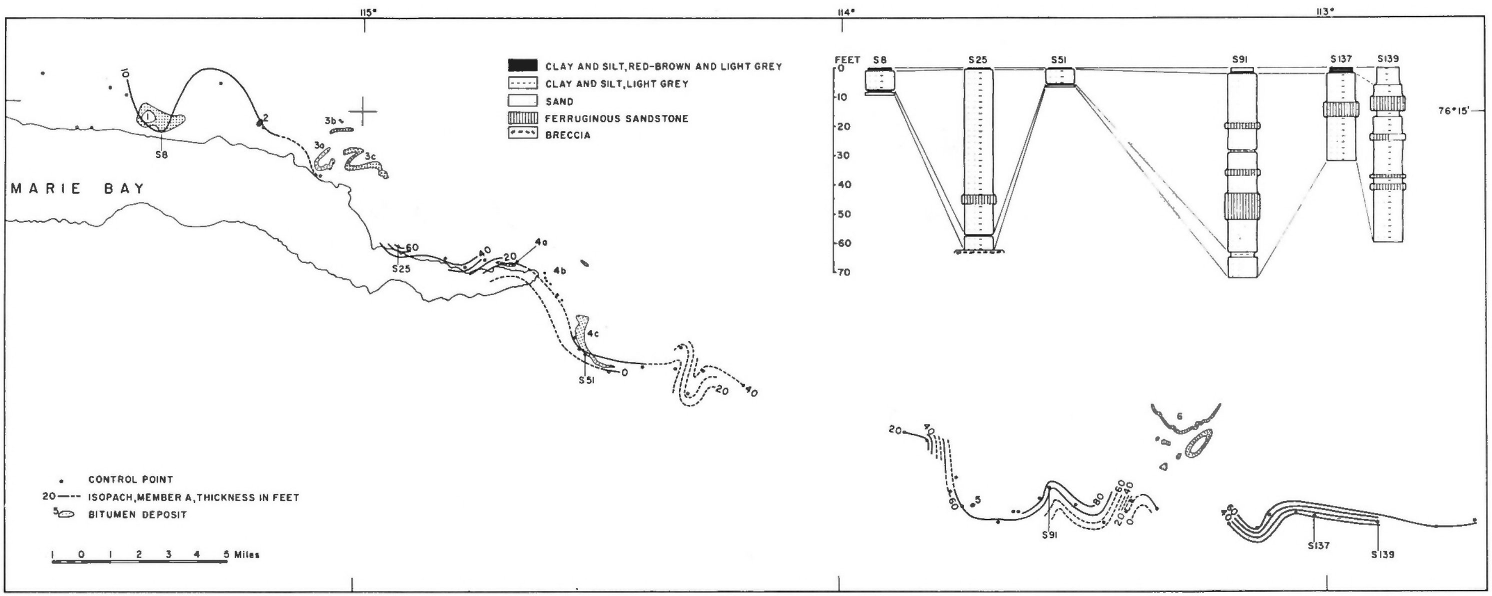


Figure 2. Member A, isopachous map and columnar sections.

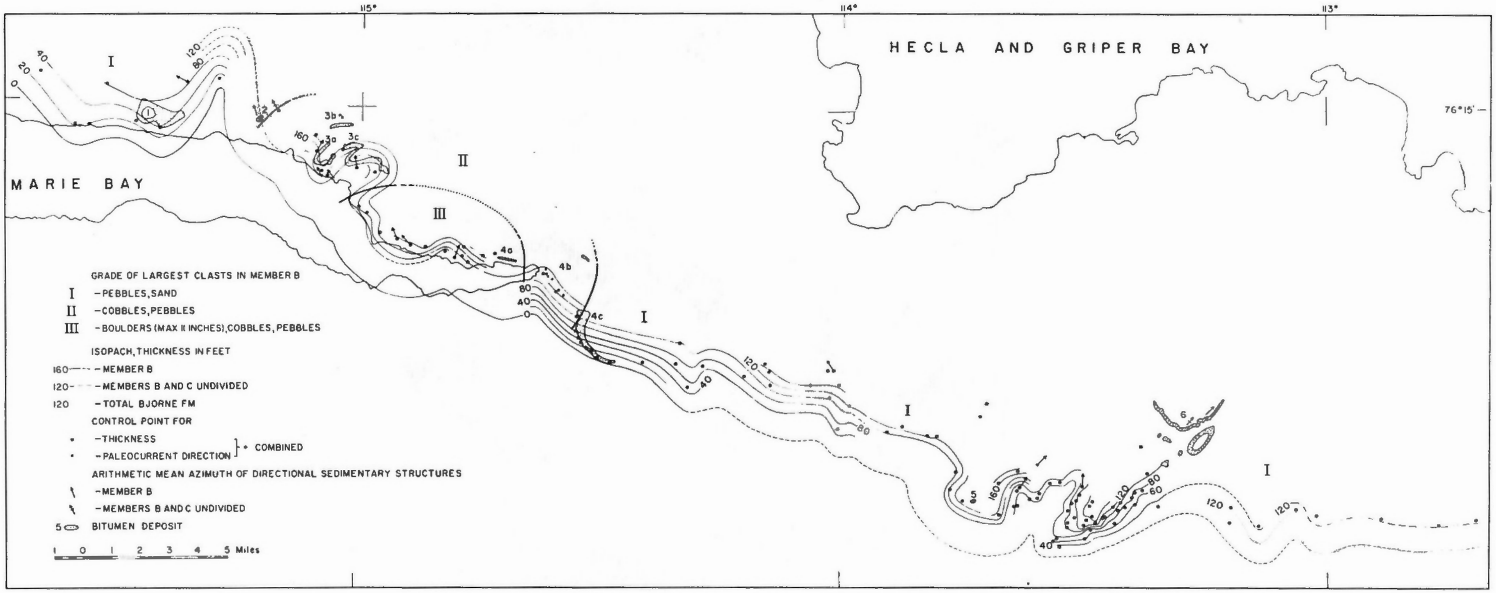


Figure 3. Member B, isopachous, palaeocurrent, and lithofacies map.

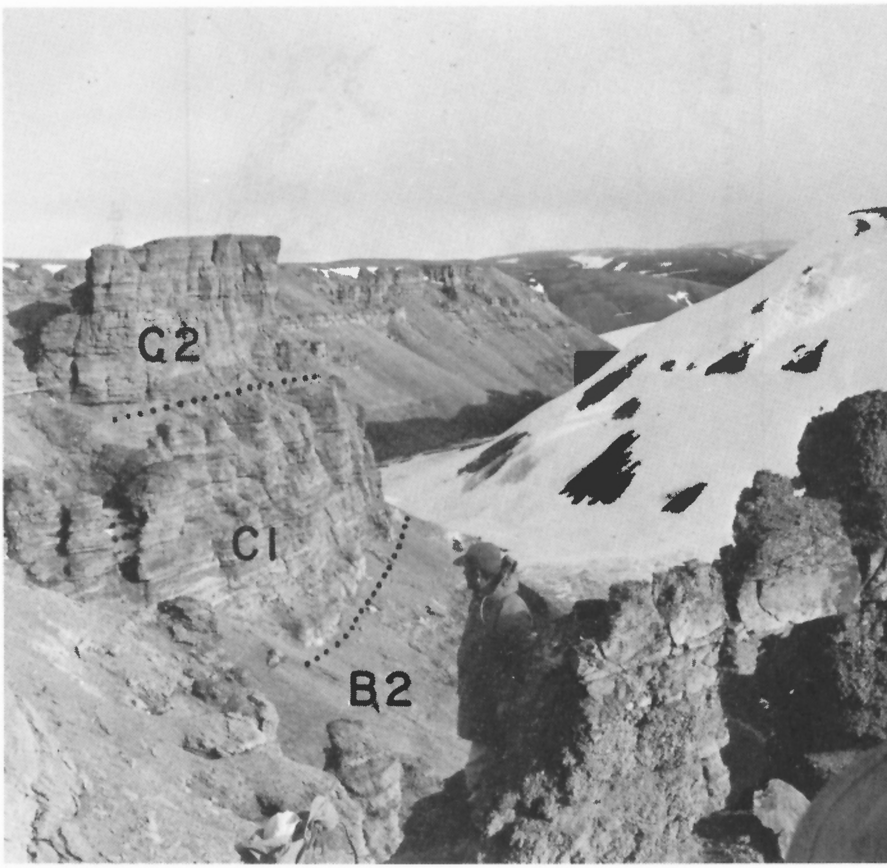


Figure 4. Cross-stratified sandstone and conglomerate of member C at section 39. View is to the south. The plateau on the left coincides approximately with the base of the Jurassic.

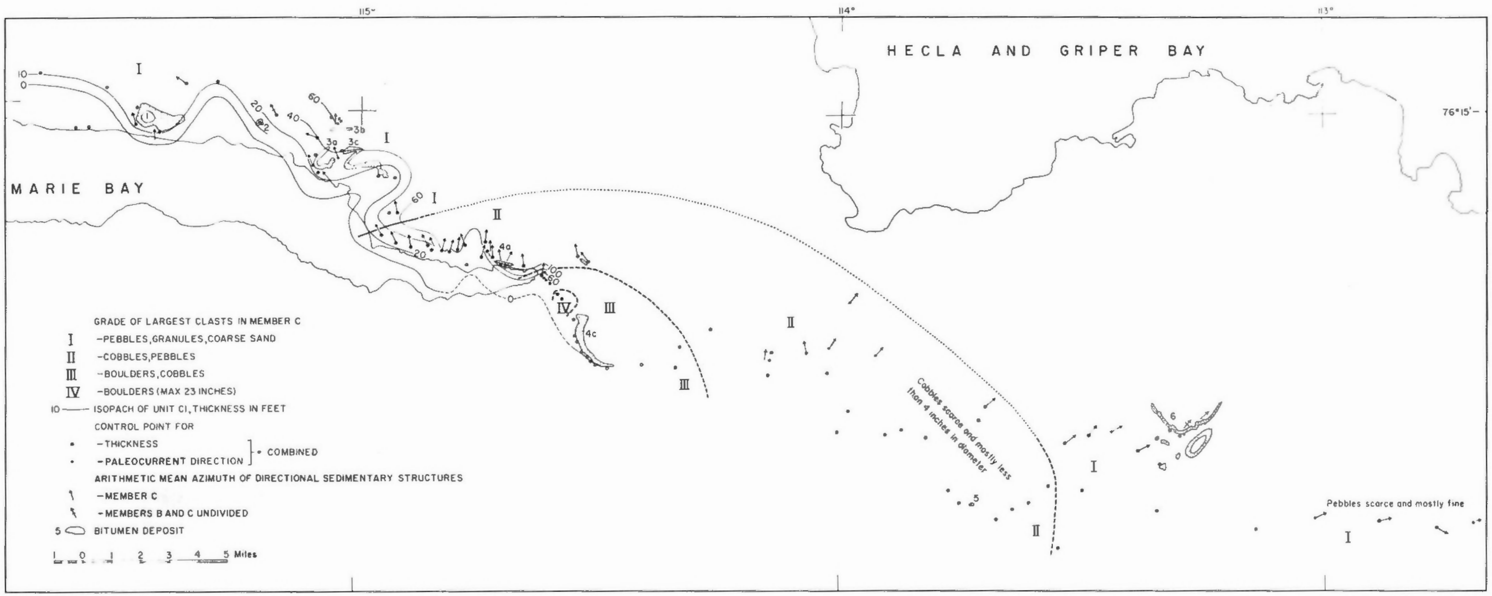


Figure 5. Member C, isopachous, palaeocurrent, and lithofacies map.

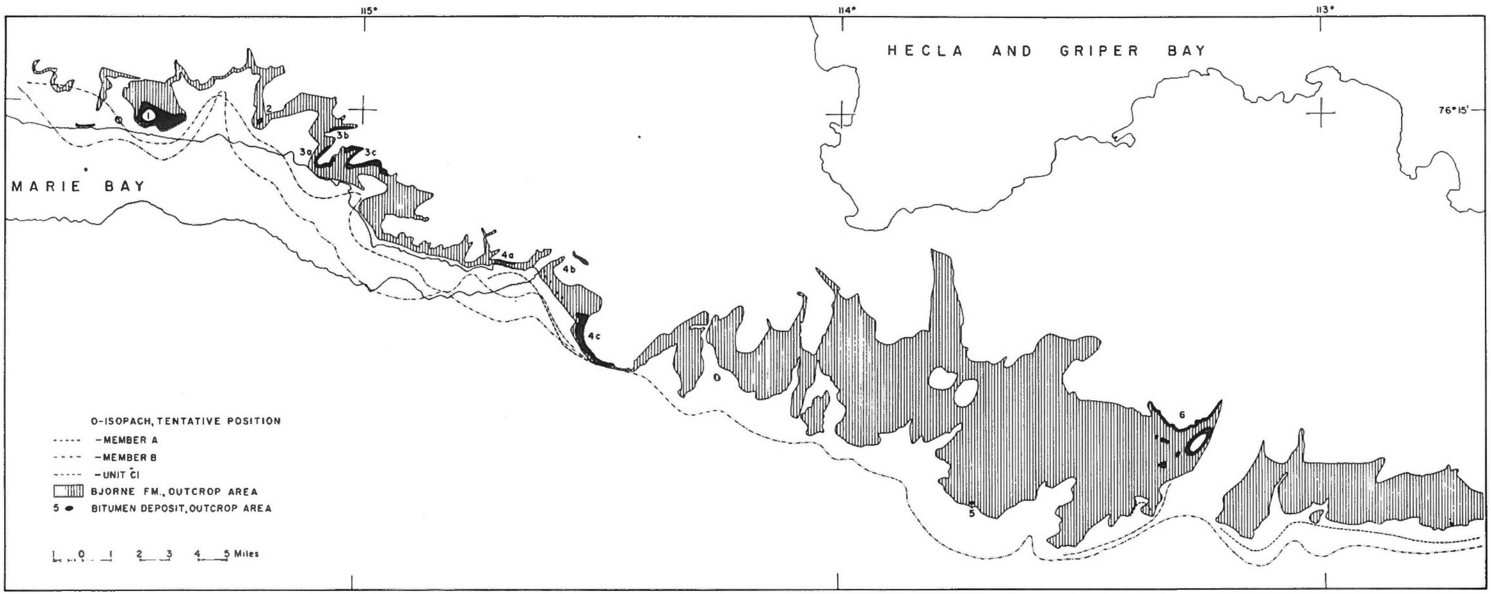
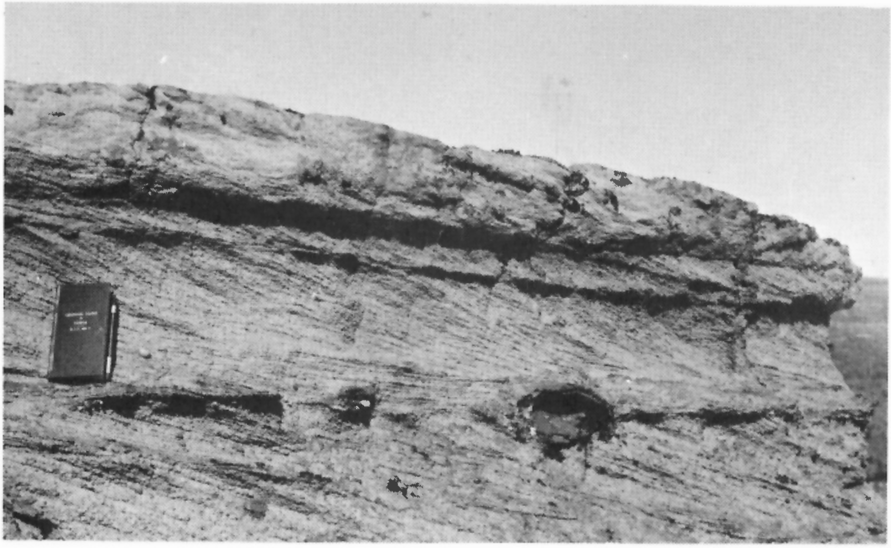


Figure 6. Generalized outcrop area of the Bjorne Formation, and position of O-isopachs of members A, B, C.



A

Figure 7A. Oil impregnated pebbly sandstone of member C at deposit 6 showing several sets of scoop-shaped cross-strata. View to the north, inferred palaeo-current direction to the northwest.

B

Figure 7B. Conglomeratic sandstone of unit C1 near section 40 showing cross-stratification. Above the geological pick, a scoop-shaped set of cross-strata in cross-section. View to the northwest, inferred palaeo-current direction to the north.

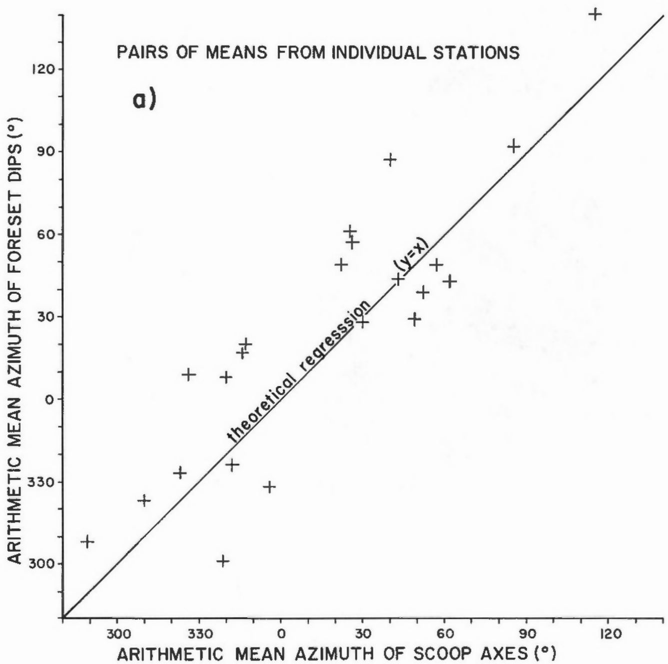


Figure 8a. Scatter diagram, showing arithmetic mean azimuth of foreset dips as a function of arithmetic mean azimuth of scoop axes.

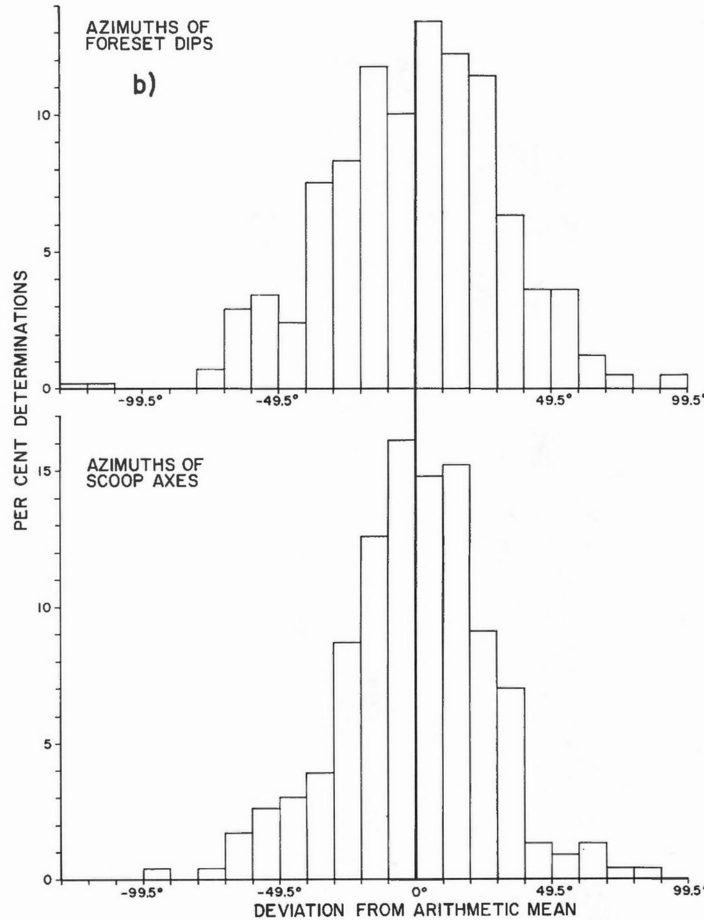


Figure 8b. Histograms, showing deviation from arithmetic mean of scoop axes and foreset dip azimuths.

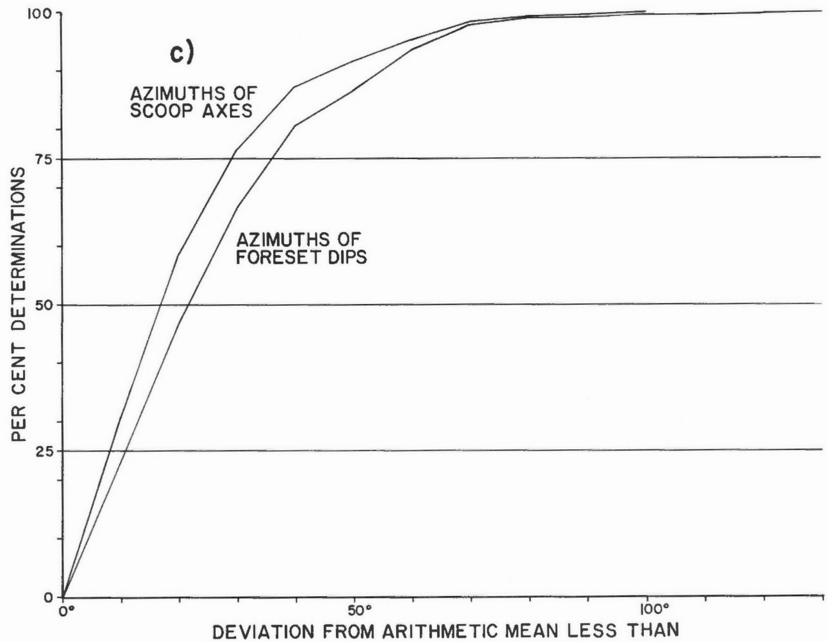


Figure 8c. Cumulative curve, showing deviation from arithmetic mean of scoop axes and foreset dip azimuths.

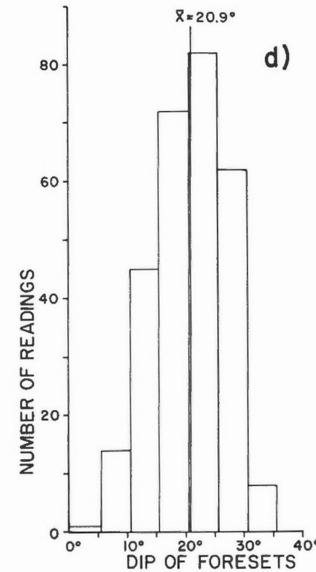


Figure 8d. Histogram, showing frequencies of dips of foresets used for palaeocurrent determinations.

Figure 8. Scatter diagrams, histograms, and cumulative curves, illustrating some statistical characteristics of the palaeocurrent determinations.

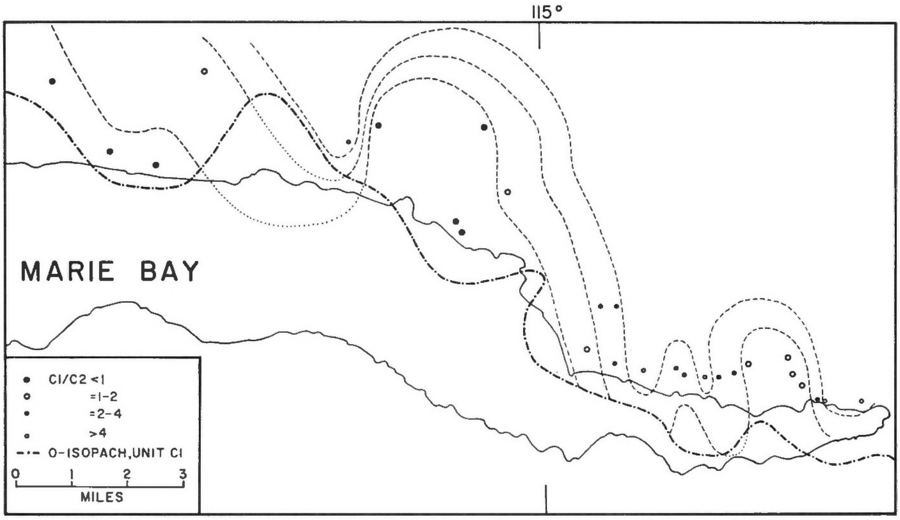


Figure 9. Contoured map, illustrating areal variations in the ratio of: thickness of unit C1/ thickness of unit C2.

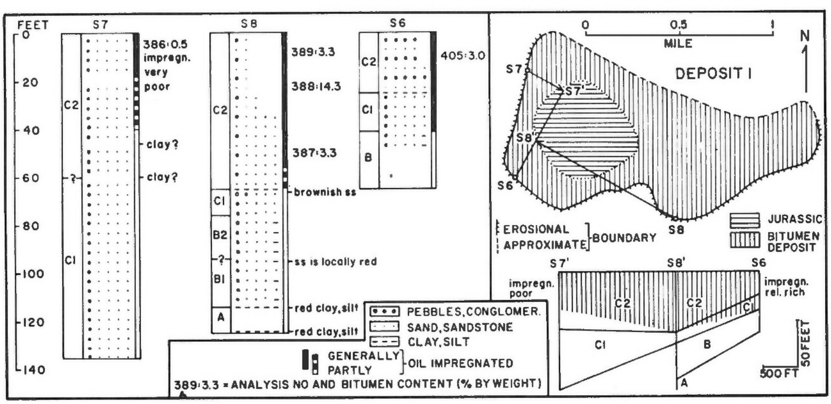


Figure 10. Deposit 1, geological sketch map, columnar sections, and diagrammatic cross-section.

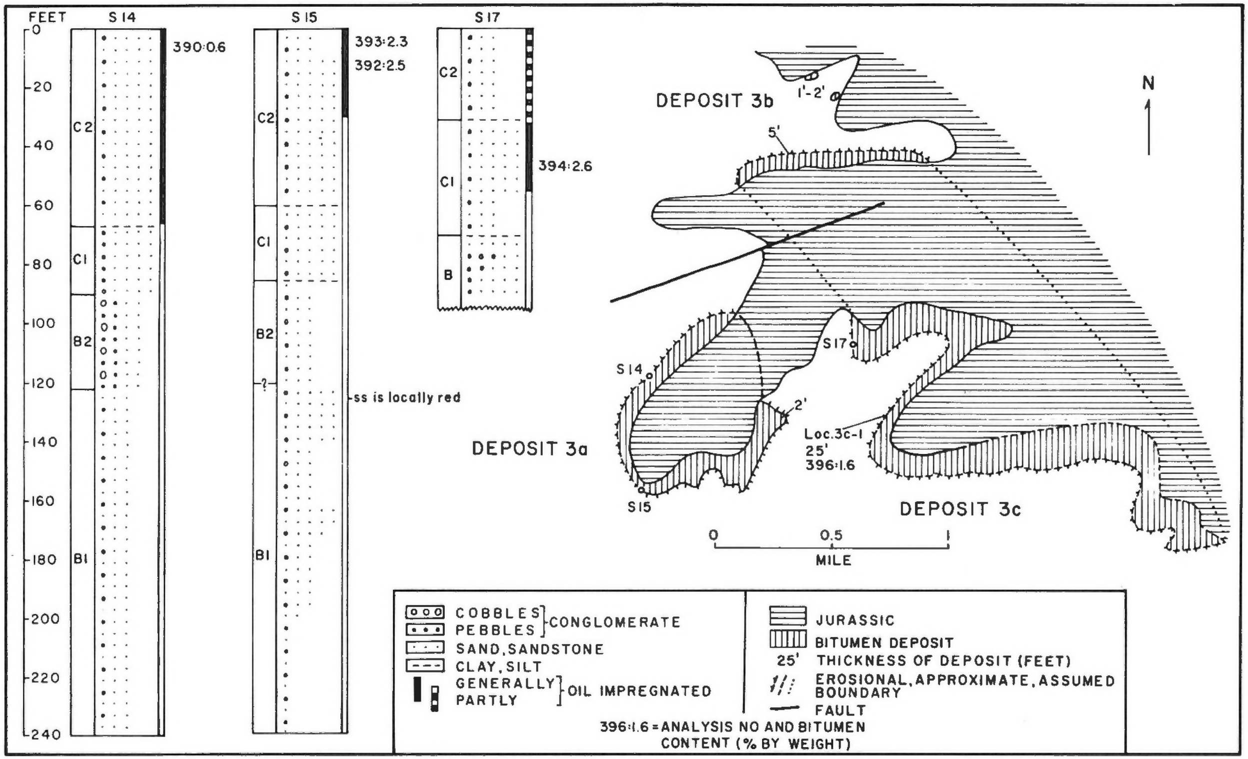


Figure 11. Deposit 3, geological sketch map, and columnar sections.

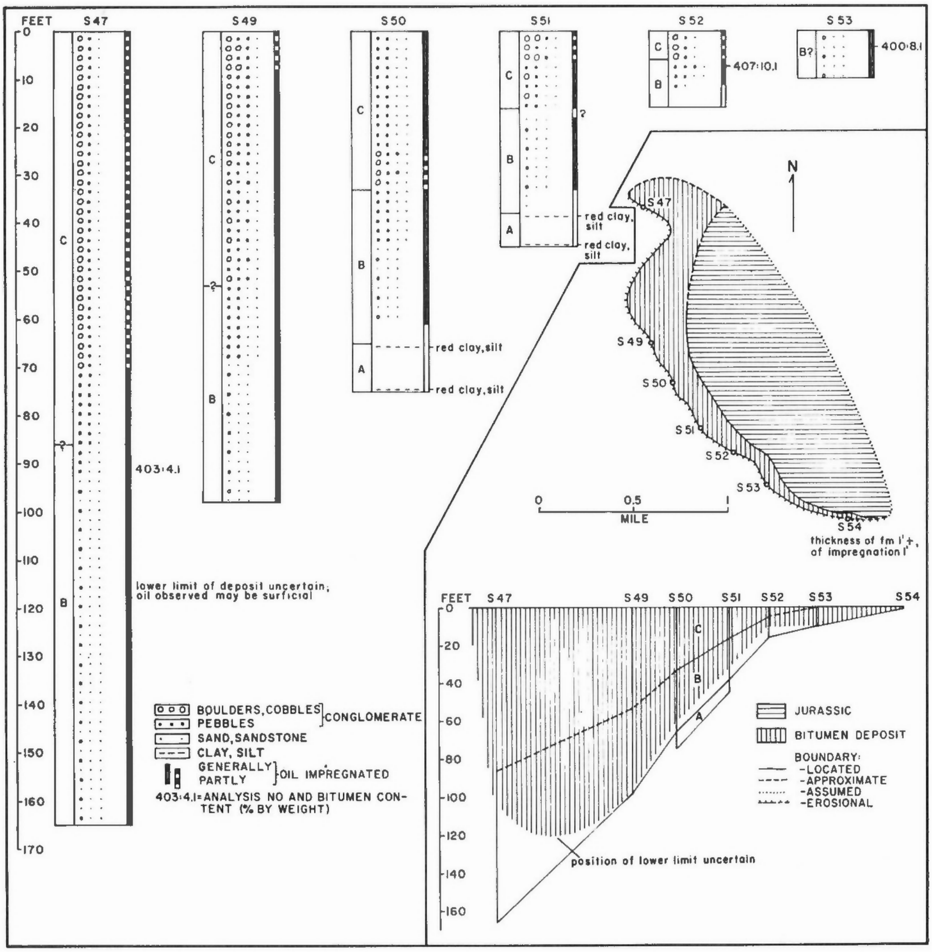


Figure 12. Deposit 4c, geological sketch map, columnar sections, and diagrammatic cross-section.

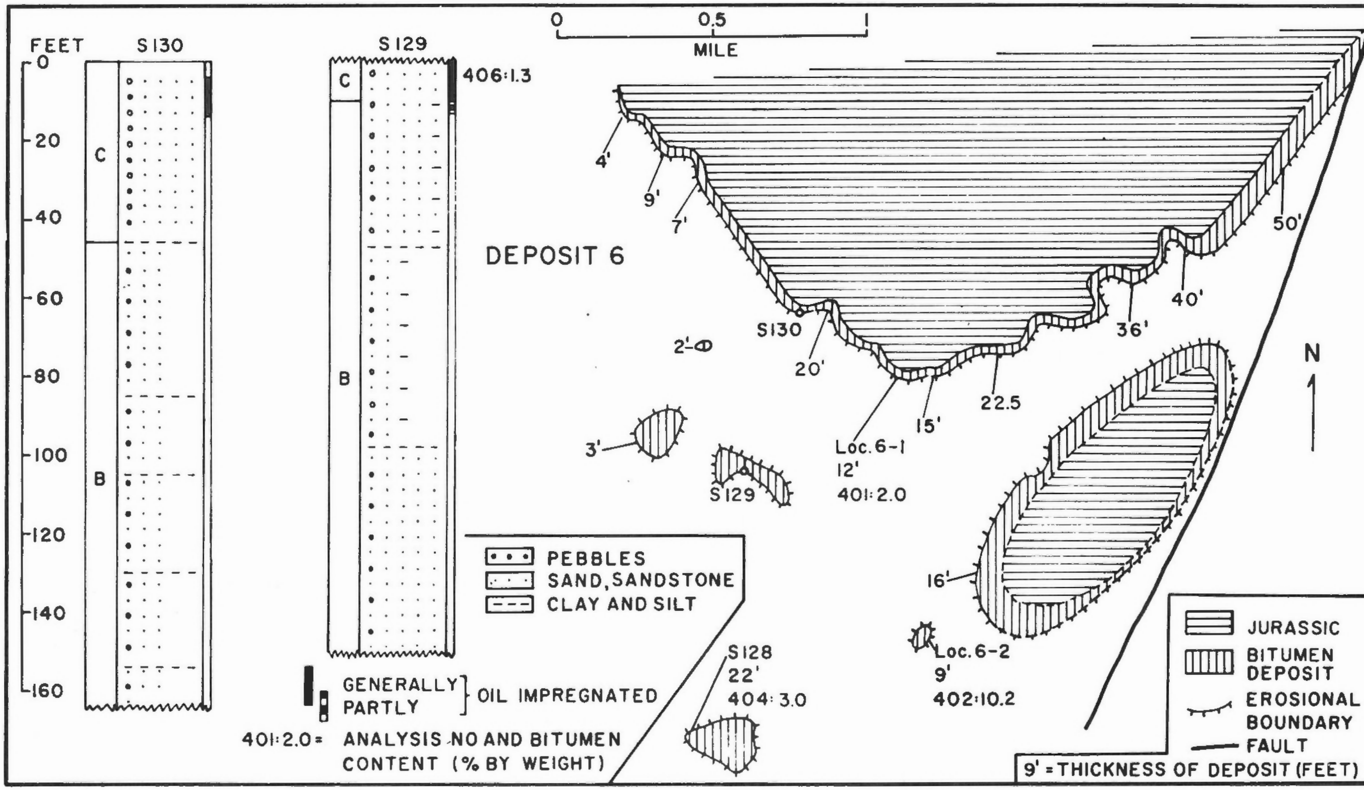


Figure 13. Deposit 6, geological sketch map, and columnar sections.

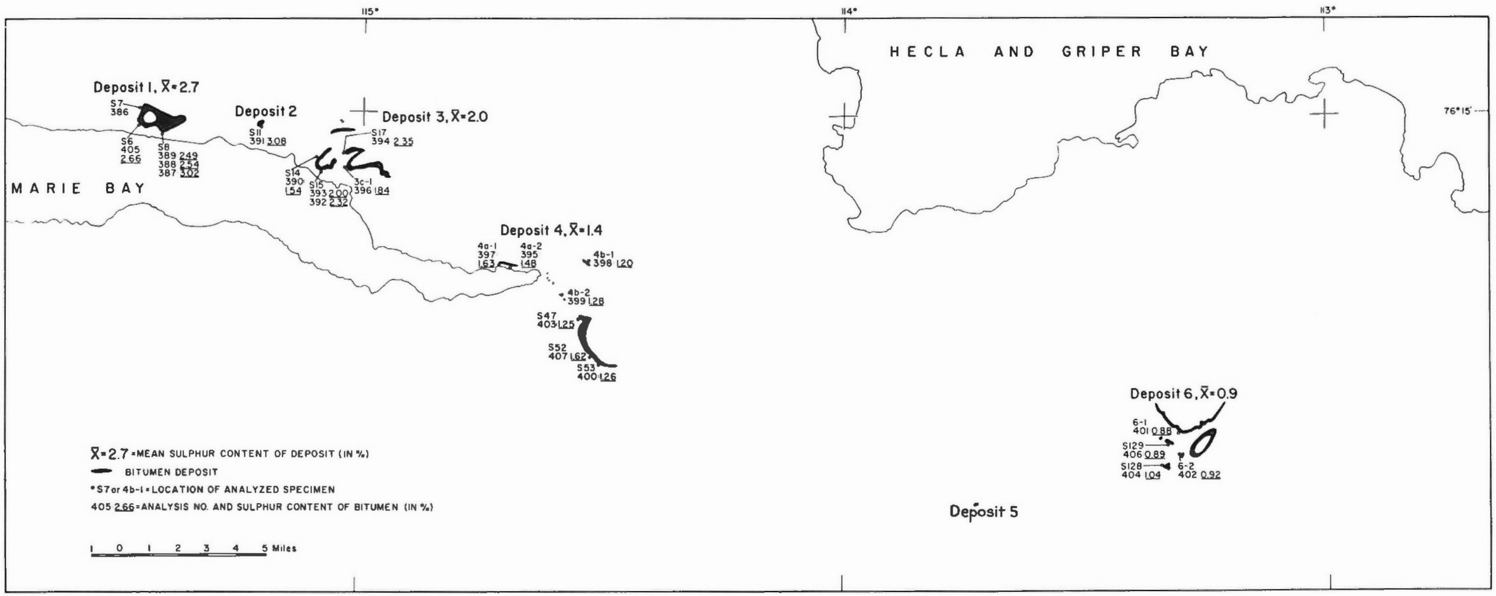
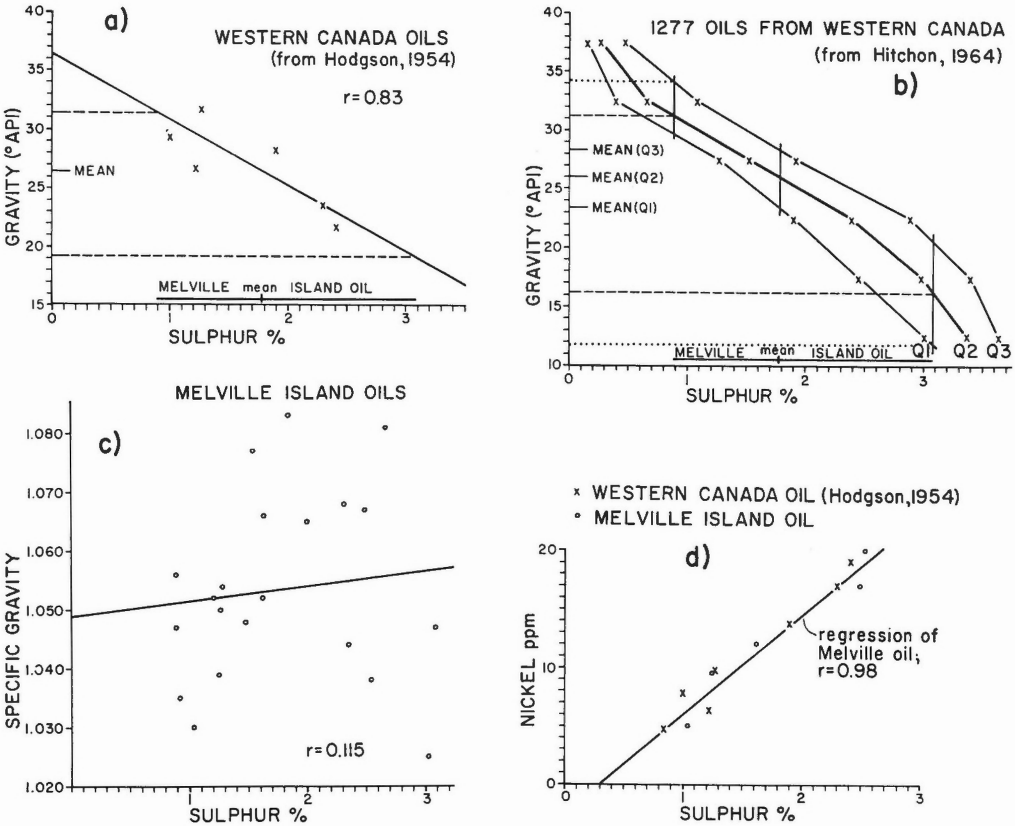
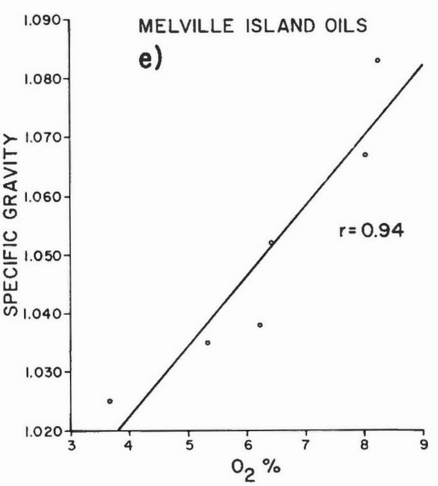


Figure 14. Map showing areal variation in sulphur content of bitumen.





a) API gravity as a function of sulphur content; seven analyses of western Canadian oils from Hodgson, 1954, and position of Melville Island bitumen.

b) API gravity as a function of sulphur content; 1277 analyses of western Canadian oils from Hitchon, 1964, and position of Melville Island bitumen.

c) Specific gravity as a function of sulphur content; 21 analyses of Melville Island bitumen.

d) Nickel content as a function of sulphur content; seven analyses of western Canadian oils, from Hodgson, 1954, and five analyses of Melville Island bitumen.

e) Specific gravity as a function of oxygen content; six analyses of Melville Island bitumen.

Figure 15. Scatter diagrams, illustrating some chemical and physical characteristics of the bitumen.

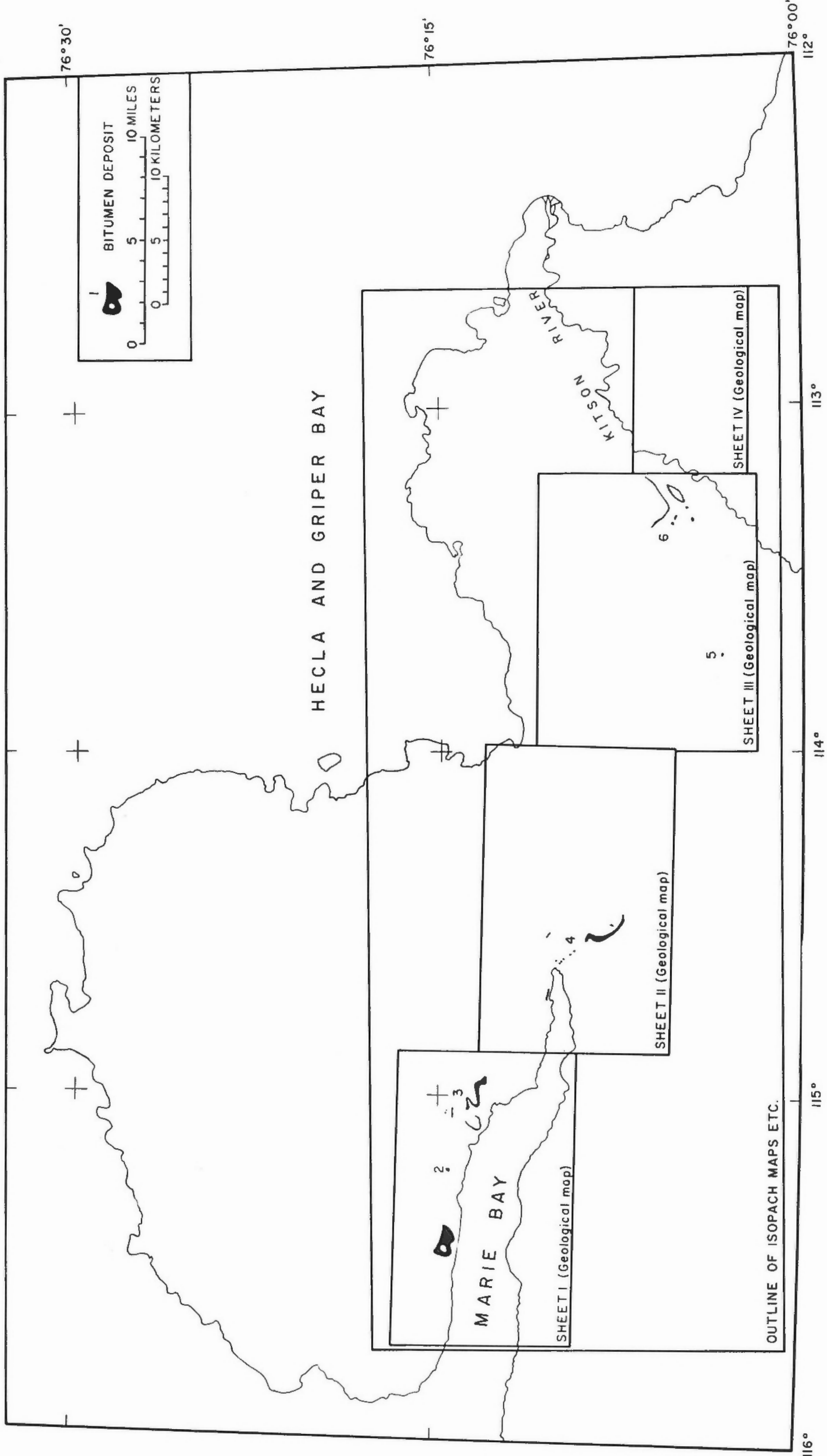


Figure 16. Index Map.

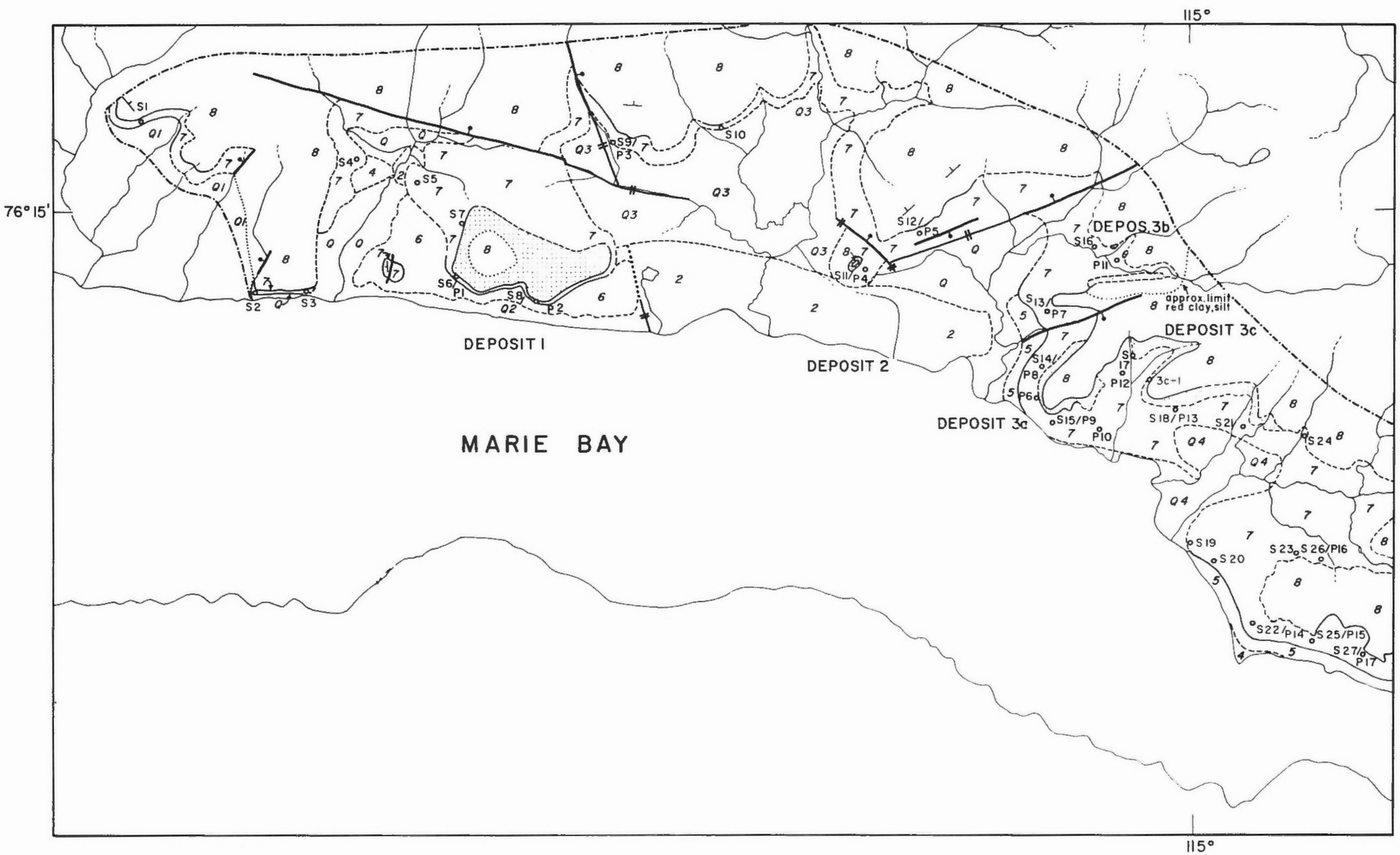


Figure 17. Sheet I.

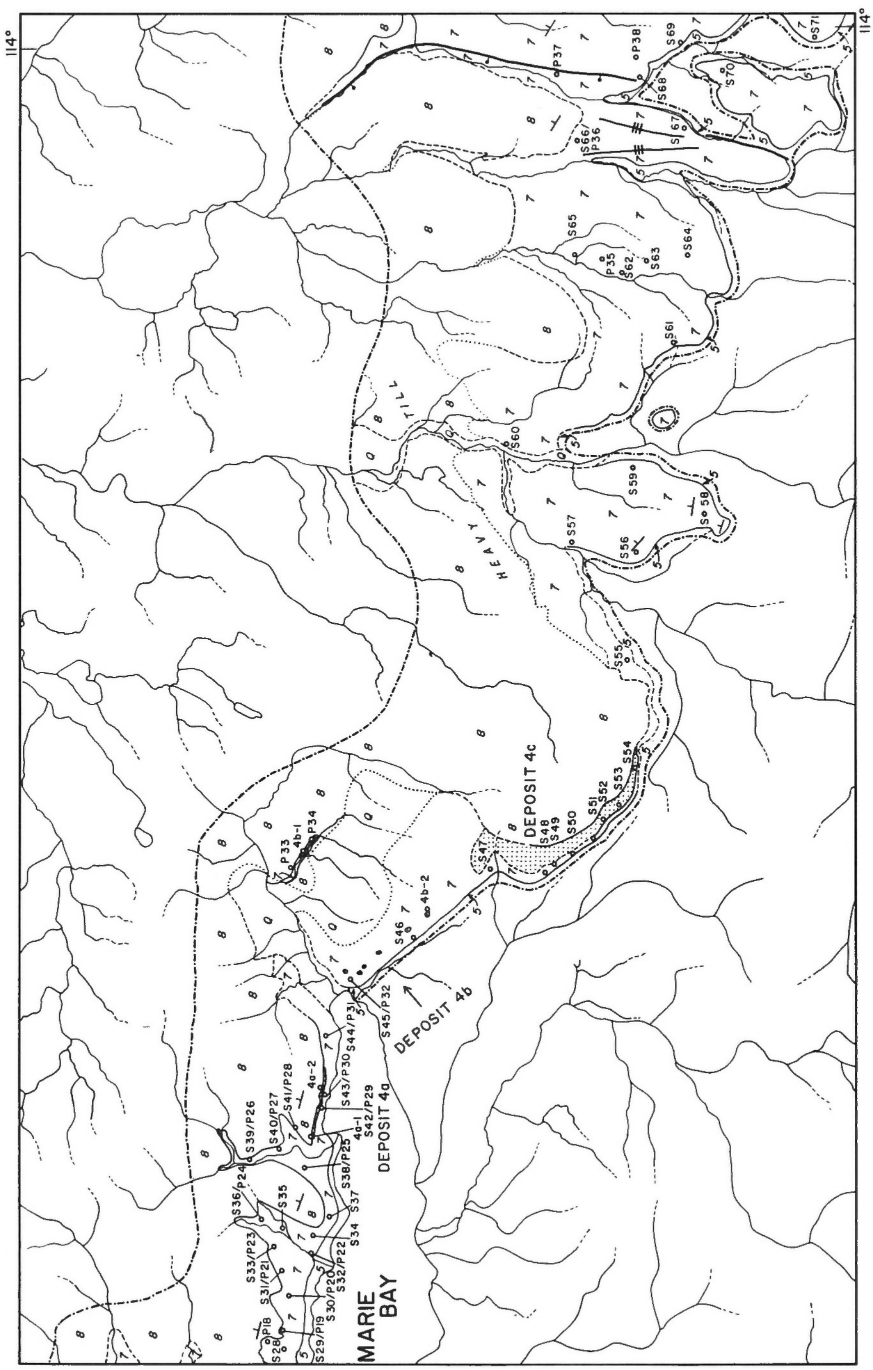


Figure 18. Sheet II.

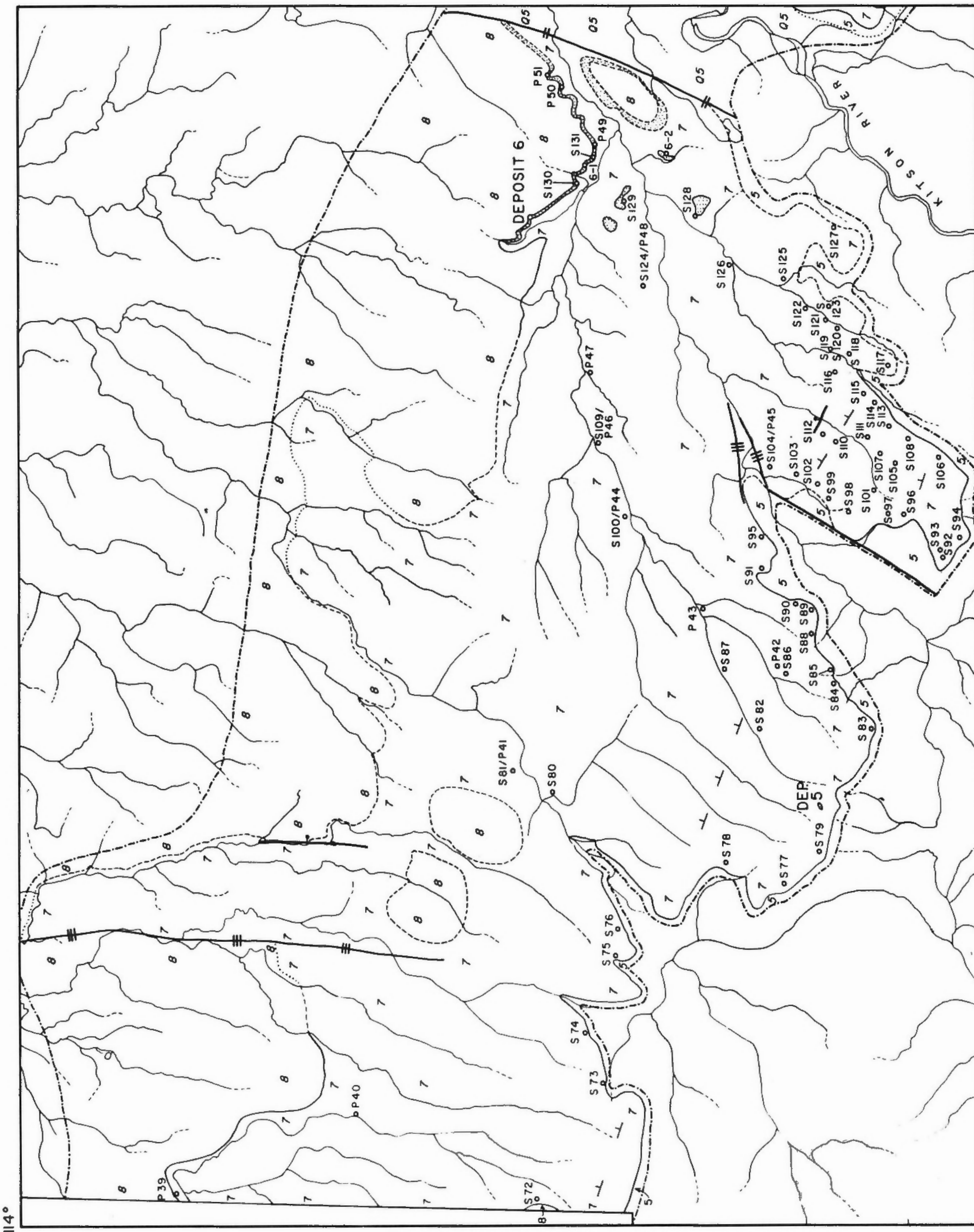


Figure 19. Sheet III.

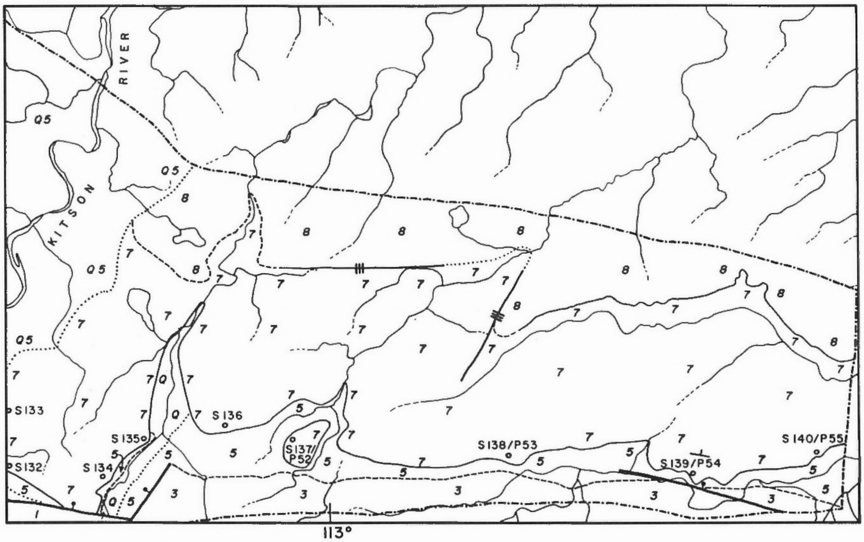
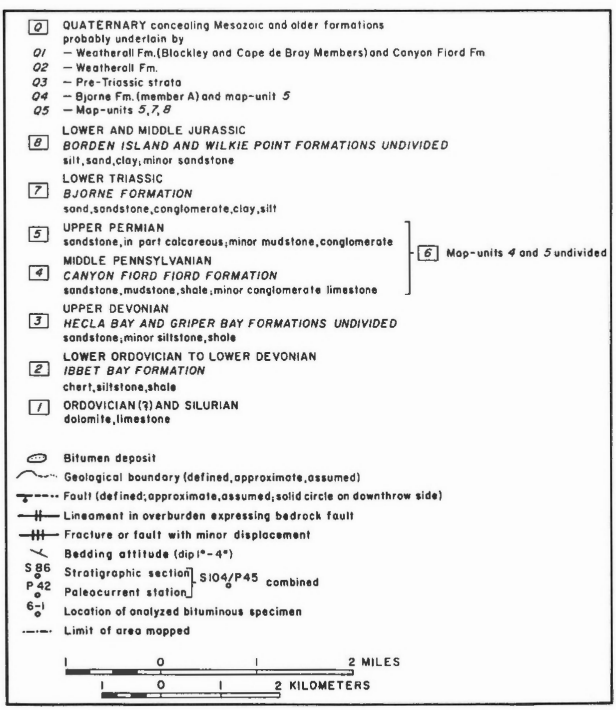


Figure 20. Sheet IV.



Geological map legend, Figures 17-20.

Captions for figures on following pages

Figure 21. Photomicrographs of zircon and tourmaline.

A. Zircon crystals. The relatively little abraded crystals on the left show zoning. Heavy mineral concentrate from sands and sandstones of member A.

B. Tourmaline crystals. Heavy mineral concentrate from sands and sandstones of member A.

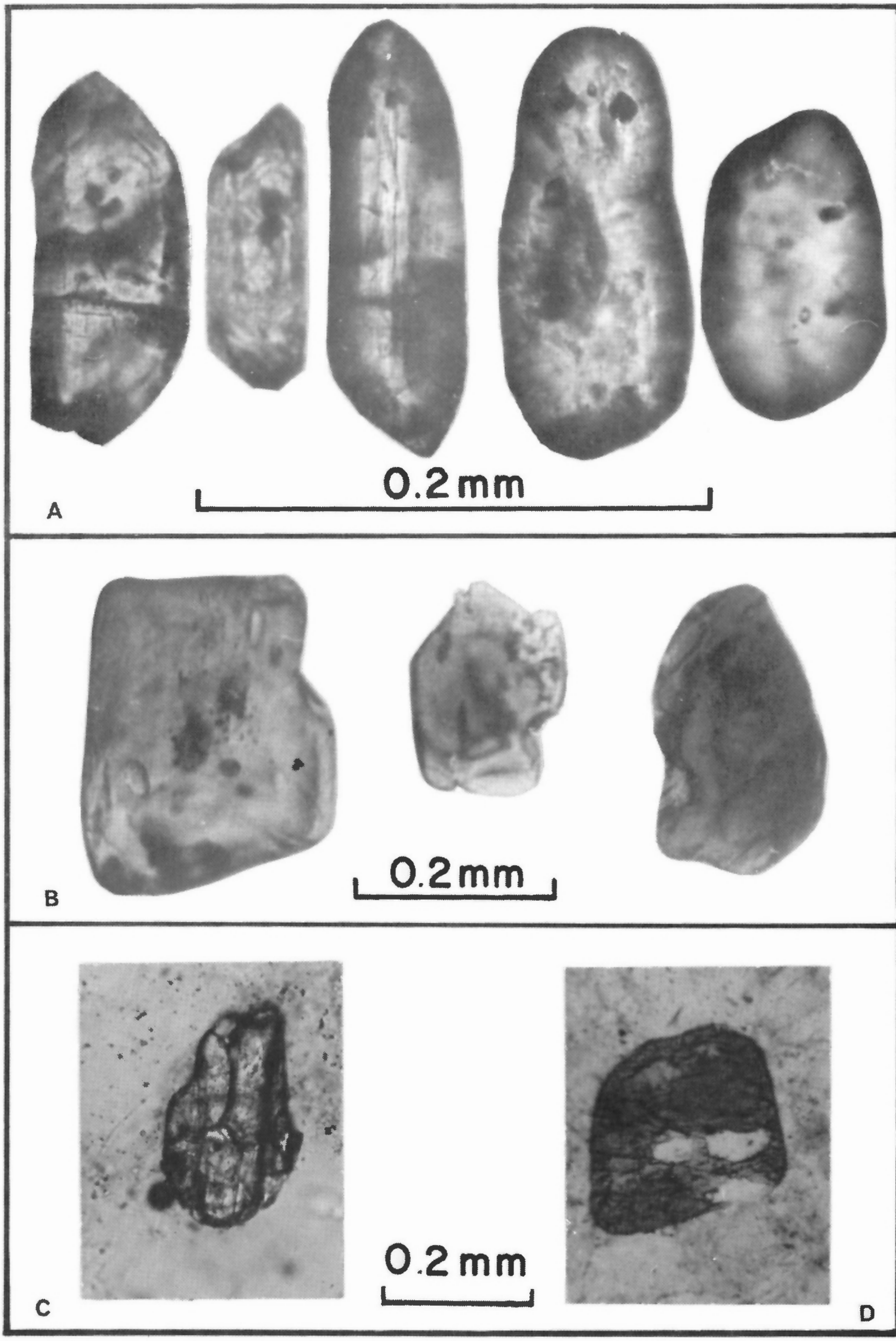
C, D. Rounded zircon (3), and rounded to well rounded tourmaline (4) in orthoquartzite cobble from conglomerate of unit B2 (loc. S 35). This photograph suggests that most of the roundness seen above was acquired prior to the last cycle of erosion and deposition. Thin section photograph, ordinary light.

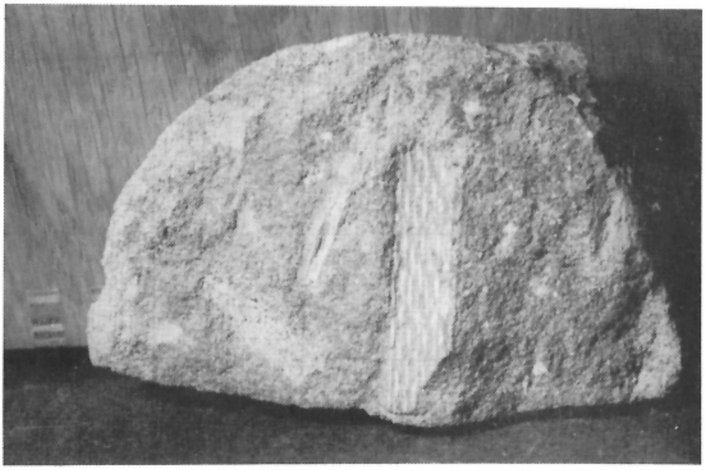
Figure 22. Fossiliferous phenoclasts.

A. Cobble from member C composed of quartz-chert sandstone with siderite-limonite matrix, containing Lepidodendropsis-type stems.
From near loc. 4b-1, x 0.7.

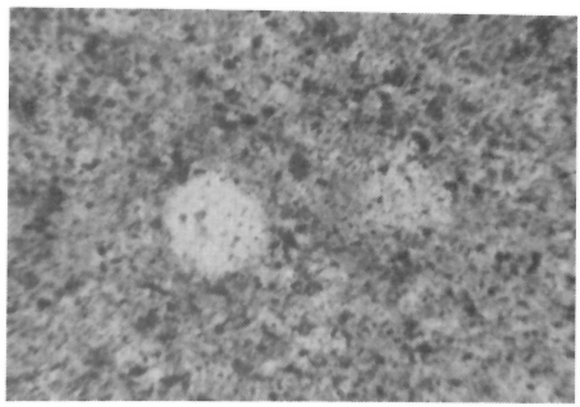
B. Chert with radiolarian (?) nodules, which are characterized by a lower concentration of impurities. The diameter of the left nodule is about 0.15 mm. Pebble from unit B1, loc. S 32. Thin section photograph, ordinary light.

C. Cobble from member C composed of very light grey chert with Silurian graptolites. From near loc. S 45, x 0.7.


0.2 mm
A
0.2 mm
B
0.2 mm
C
D



A



B

C

APPENDIX 1

STRATIGRAPHIC THICKNESSES MEASURED

Abbreviations:
ib = incomplete section, base not exposed
it = incomplete section, top missing
pe = poorly exposed section
cog= unit B2 marked by conglomerate with ironstone clasts
rcl= unit B2 marked by basal red clay and silt

Combined thicknesses of B and C are listed only where these two units could not be distinguished.

	Thickness of Units in Feet								
Sect #	A	B1	B2	B	C1	C2	C	B&C	Total Fm.
S 1	0?pe			30			15		45
S 2	0?pe			23			0?pe		23?pe
S 3	0?pe			20			0?pe		20?pe
S 4	0?pe			61	14pe	33pe	47pe		108pe
S 5	5-10pe								
S 6				24	16	25	41		

Sect. #	A	B1	B2	B	C1	C2	C	B&C	Total Fm.
S 7					75?	60?	135		
S 8	10			38	11	65	76		
S 9		37+?ib	22rcl	59+?ib	46	29	75		
S 10									25pe
S 11	10pe	81	39rcl	120	17	4	21		151
S 12					23	29	52		
S 13		138	47cog	185			89		
S 14		118	32cog	150	23	67	90		
S 15	0-20? pe	119	35cog	154	25?	60?	85		239-259 pe
S 16					60	80	140		
S 17			25+it, cog		39	31	70		
S 18		75	15cog	90					

Sect. #	A	B1	B2	B	C1	C2	C	B&C	Total Fm
S 19		122	18+?it	140?it					
S 20		120	cog						
S 21		85	25cog	110			15+?it		
S 22		148	17cog	165	27	18	45		
S 23					55	20	75		
S 24							20pe		
S 25	63	161	17cog	178	29	8	37		278
S 26					54	20	74		
S 27		153	21cog	174	30	0	30		
S 28		164-184	10-20cog	184	31	10	41		
S 29					31	12	43		
S 30	46	97	cog		61	4	65		

Sect. #	A	B1	B2	B	C1	C2	C	B&C	Total Fm
S 31					55	25	80		
S 32		108	cog						
S 33					69-78	23	92-101		
S 34		100	cog						
S 35			51cog						
S 36					47	36	83		
S 37	36+? ib	100	40cog	140pe			40?pe		216
S 38	25?pe	76	128cog	204			48?pe		277
S 39			51?cog		76	48	124		
S 40			80cog		80	63	143		
S 41			77+?ib, cog		81	58	139		

Sect. #	A	B1	B2	B	C1	C2	C	B&C	Total Fm
S 42			70cog		88	33	121		
S 43			57 ib, cog		104	20	124		
S 44					136	28	164		
S 45		105	20cog	125			55+?it		
S 46		111							
S 47		80-82	16-24cog	96-106			70+?it		
S 48	12			38?pe			92		142
S 49				45-70 pe			28-63		
S 50	10			32			33		75
S 51	6			20-23			16-18		45
S 52				11			5		

Sect. #	A	B1	B2	B	C1	C2	C	B&C	Total Fm
S 53							0-5		10?pe
S 54							0?		1-2?pe
S 55	5?pe			30?pe			18?pe		53
S 56	13?pe			67					
S 57	14			100			25+?it		139+?it
S 58	35pe			50-60					
S 59	35pe			65-69					
S 60							95		
S 61	41			84+?it					
S 62		66-86pe	92rcl	148-168 pe					
S 63		68	61rcl	129			15it		

Sect. #	A	B1	B2	B	C1	C2	C	B&C	Total Fm
S 64		56	56+?it, rcl	112+? it					
S 65							74+?it		
S 66							120+? it		
S 67				141?					
S 68				152-172 pe			55+?it		
S 69				144			34+?it		
S 70				100+?it					
S 71				73+?pe					
S 72				120			21+?it		
S 73		26?pe	76rcl	102?pe			9+?it		

Sect. #	A	B1	B2	B	C1	C2	C	B&C	Total Fm
S 74	20?pe	32	100rcl	132			20+?it		172+?it
S 75	21?pe			122			65+?it		208+?it
S 76				120-150 pe					
S 77	58			122			33+?it		213+?it
S 78	76			97+?it					
S 79	70			154			32+?it		256+?it
S 80				182			30+?it		
S 81							71+?it		
S 82				165					
S 83	67			129			28+?it		224+?it
S 84	100 ? pe			72+?pe					

Sect. #	A	B1	B2	B	C1	C2	C	B&C	Total Fm.
S 85	76?pe			85?pe			12+?it		172+?it
S 86				80-90					
S 87				177pe					
S 88				78pe			25+?it		
S 89				87-97					
S 90	85?pe			90-95pe					
S 91	72			82			25+?it		179+?it
S 92	45			63					
S 93				76					
S 94				36			22+?it		
S 95				91					

Sect. #	A	B1	B2	B	C1	C2	C	B&C	Total Fm
S 96				100					
S 97				115					
S 98				96					
S 99				104					
S 100							72		
S 101				115					
S 102	75			118					
S 103				123					
S 104				107			90+?it		
S 105				132					
S 106				60?pe					

Sect. #	A	B1	B2	B	C1	C2	C	B&C	Total Fm.
S 107				130					
S 108				75					
S 109							72+?it		
S 110				152?pe					
S 111				147					
S 112				143					
S 113				128-138					
S 114				117?pe					
S 115	55			110Pe					
S 116				120					
S 117				65-70					

Sect. #	A	B1	B2	B	C1	C2	C	B&C	Total Fm.
S 118				95?pe					
S 119				100?pe					
S 120	19?pe			76					
S 121				90					
S 122	15?pe			68-73pe					
S 123				60pe					
S 124				88+ib			77+?it		
S 125				75?pe					
S 126				110+?ib					
S 127	10?pe			35?pe			5?pe		50?pe
S 128				100+?ib			0-10?it		

Sect. #	A	B1	B2	B	C1	C2	C	B&C	Total Fm.
S 129				140+?ib			10+?it		
S 130				120+ib			45		
S 131							46		
S 132	30?pe							80?pe	
S 133									130pe
S 134	60			44?			54?	98	158
S 135	55-58								
S 136	30?pe							95	125
S 137	31							174	205
S 138	33			68			54	122	155
S 139	54-61							122	180
S 140	65							123	188

APPENDIX 2
PALAEOCURRENT DETERMINATIONS
Table 1

Grade of Largest Phenoclasts in Member C and Unit B2

Sect. or Loc.	B2	C	Sect. or Loc.	B2	C	Sect. or Loc.	B2	C
S 1	-	p	S 15	c(3)	p	S 29	-	c(8)
S 2	p(2.5)	-	S 16	-	p	S 30	s?	c
S 3	c(5)	-	S 17	c(4)	p	S 31	s?	-
S 4	p	p	S 18	c(8)	p	S 35	c(9)	-
S 6	p	p	S 19	b(11)	-	S 36	-	c
S 7	-	p	S 20	c(10)	-	S 37	-	c(9)
S 8	-	p	S 21	c(3)	p	S 39	c(10)	p
S 9	s	p	S 23	-	p	S 40	c(7)	c
S 11	p	p	S 25	c	c(8)	S 41	-	c
S 12	c(5)	p	S 26	p(2.5)	p	S 42	c(10)	p
S 13	p(2.5)	-	S 27	b(11)	c	S 43	c(9)	c(6)
S 14	c(5)	p	S 28	p	-	S 44	c	p

Sect. or Loc.	B2	C	Sect. or Loc.	B2	C	Sect. or Loc.	B2	C
S 45	c(4)	b(16)	S 64	c	-	S 80	p	-
4b-2	-	b(23)	S 65	-	c(9)?	S 81	c	c
S 47	c(4)	c	S 66	-	b(12)?	S 82	p	c(4)
S 48	p	c	S 67	c	c(10)?	S 83	p	c(4)
S 49	p	b(13)	S 68	p	c(9)	S 86	p	-
S 50	c(3)	b(12)	S 69	p	c(8)	S 91	p	c(4)
S 51	p	c(7)	S 70	p	-	S 92	-	p
S 52	p	c(6)	S 71	p	-	S 93	-	p
S 53	p	-	S 72	p	c(4)	S 94	-	p
S 55	p	b(12)?	S 74	p	c?	S 97	-	p
S 56	-	b(11)?	S 75	-	p	S 100	-	p
S 57	p	b(11)?	S 76	p	p	S 102	p	p
S 60	-	c(9)	S 77	p	c(4)	S 103	p?	p
S 62	p	c	S 78	p	-	S 104	p	p
S 63	-	c	S 79	p	c(4)	S 106	-	p

Sect. or Loc.	B2	C	Sect. or Loc.	B2	C	Sect. or Loc.	B2	C
S 109	-	p	S 124	-	p	S 134	s	p
S 110	p	-	S 128	p	p	S 138	-	p(1)
S 117	-	c(3)	S 130	-	p	S 139	s	p(1)
S 118	p	-	S 131	-	p	S 140	p	p(1)

Abbreviations for grade of largest phenoclasts:

s = sand
p = pebble
c = cobbler
b = boulder
(4) = diameter in inches

The question mark designates phenoclasts on the plateau surface, which are from member C, but partly represent lag gravel, and partly, perhaps, glacial deposits, transported for short distances.

APPENDIX 2
Table 2

Statistical Parameters of Directional Features
Computer program by F.P. Agterberg

Sta = Station
Feat.= Feature
Sc = Azimuths of scoop axes
Fs = Azimuths of foreset dips
N = Number of readings
AM° = Arithmetic mean in degrees azimuth
S° = Standard deviation in degrees
VM° = Vector mean in degrees azimuth
VS = Vector strength
Rge = Range

Members B and C undifferentiated

Sta #	Feat.	N	AM°	S°	VM°	VS	Combined		
							N	Rge	AM
P5	Sc	5	323	18	323	0.96	12	99	329
	Fs	7	333	31	333	0.88			
P49	Fs	12	41	38	43	0.82	12	116	41

Member B

Sta #	Feat.	N	AM°	S°	VM°	VS	Combined N	Combined Rge	Combined AM°
P3	Sc	6	289	58	294	0.62	8	132	295
	Fs	2	308	35	308	0.91			
P4	Sc	10	342	12	342	0.98	13	54	341
	Fs	3	336	28	336	0.92			
P8	Fs	3	29	37	30	0.87	3	65	29
P9	Fs	5	332	11	332	0.99	5	28	332
P10	Fs	9	321	30	321	0.88	9	113	321
P13	Sc	6	349	23	349	0.93	7	50	351
	Fs	1	(9)		(9)				
P15	Sc	3	356	47	358	0.79	12	125	336
	Fs	9	328	39	328	0.81			
P17	Sc	4	310	9	310	0.99	8	77	316
	Fs	4	323	40	323	0.83			
P22	Sc	3	347	30	347	0.91	32	130	17
	Fs	29	20	39	19	0.80			
P38	Sc	5	330	14	330	0.98	6	40	326
	Fs	1	(308)		(308)				

Member B (cont'd)

Sta #	Feat.	N	AM°	S°	VM°	VS	Combined		
							N	Rge	AM°
P42	Sc	4	49	6	49	1.00	12	53	35
	Fs	8	29	19	29	0.95			
P43	Sc	3	43	23	43	0.95	12	70	44
	Fs	9	44	28	45	0.90			
P45	Sc	5	14	23	13	0.94	6	115	0
	Fs	1	(295)		(295)				
P51	Sc	3	22	23	22	0.95	12	149	44
	Fs	9	49	47	46	0.74			

Member C

Sta #	Feat.	N	AM°	S°	VM°	VS	Combined N	Combined Rge°	Combined AM°
P21	Fs	13	16	25	16	0.92	13	90	16
P23	Fs	17	7	47	12	0.71	17	170	7
P24	Fs	16	339	36	339	0.82	17	95	339
	I	1	(348)		(348)				
P25	Sc	7	15	13	15	0.98	14	63	15
	Fs	7	15	20	15	0.95			
P26	Fs	14	5	23	5	0.93	14	60	5
P27	Sc	3	359	6	359	1.00	23	90	356
	Fs	20	355	29	356	0.88			
P28	Sc	12	357	31	356	0.87	17	98	358
	Fs	5	2	34	0	0.87			
P29	Sc	1	(300)		(300)		15	130	351
	Fs	14	355	36	357	0.84			
P30	Sc	2	30	41	30	0.88	5	60	29
	Fs	3	28	23	27	0.91			
P31	Sc	8	340	45	337	0.75	15	125	353
	Fs	7	8	27	7	0.91			

Member C

Sta #	Feat.	N	AM°	S°	VM°	VS	Combined N	Combined Rge°	Combined AM°
P32	Sc	2	346	7	346	1.00	7	55	8
	Fs	5	17	23	18	0.94			
P33	Sc	1	(301)		(301)		7	73	348
	Fs	6	356	17	358	0.95			
P34	Sc	7	339	44	335	0.77	12	154	323
	Fs	5	301	57	299	0.63			
P35	Fs	12	8	21	8	0.94	12	78	8
P36	Sc	5	326	16	327	0.97	10	86	347
	Fs	5	9	27	9	0.91			
P37	Sc	9	25	10	25	0.99	12	53	34
	Fs	3	61	7	61	0.99			
P39	Sc	5	26	45	26	0.77	14	120	39
	Fs	9	57	24	58	0.93			
P40	Sc	2	52	47	52	0.84	10	66	42
	Fs	8	39	18	39	0.96			
P41	Sc	10	40	33	40	0.86	12	92	48
	Fs	2	87	0	87	1.00			

Member C

Sta #	Feat.	N	AM°	S°	VM°	VS	Combined N	Combined Rge°	Combined AM°
P44	Sc	6	62	32	62	0.87	11	90	53
	Fs	5	43	34	41	0.87			
P46	Sc	11	36	35	40	0.86	12	132	39
	Fs	1	(74)		(74)				
P47	Sc	13	61	27	61	0.90	13	102	61
P48	Sc	10	64	20	64	0.94	11	68	64
	L	1	(67)		(67)				
P50	Sc	3	57	17	57	0.95	12	102	50
	Fs	9	49	35	51	0.71			
P52	Sc	6	68	20	69	0.95	8	63	67
	Fs	1	(92)		(92)				
	L	1	(36)		(36)				
P53	Sc	4	77	19	77	0.96	5	37	79
	Fs	1	(86)		(86)				
P54	Sc	7	115	16	115	0.97	9	55	120
	Fs	2	140	20	140	0.97			
P55	Sc	8	85	34	86	0.86	13	92	88
	Fs	5	92	15	92	0.97			

APPENDIX 2

Table 3

Confidence Limits of Arithmetic Mean Azimuths of Directional Features

Based on Student's t-test, using p=0.05, S (foreset dip azimuths) = 32°, and S (scoop axes) =27°

Number of Readings	Limits of Confidence (p = 0.05)	
	Foresets	Scoop Axes
2	143	121
3	54	46
4	38	32
5	31	26
6	26	22
7	23	20
8	21	18
9	20	17
10	19	16
11	17 (+)	15
12	17 (-)	14
13	16	13 (+)
14	15 (+)	13 (-)
15	15 (-)	12
20	12	10
30	10	8

APPENDIX 3

MINERALOGICAL AND PETROGRAPHIC ANALYSES
Table 1

Thin-Section Modal Analyses of Specimens of Sandstone
(about 400 points per section counted)

Section #	25	91	25	134	8	11	79	109	12	5
Spec. #	T-14-2	T-56-1	T-14-5	T-86-1	T-34-4b	T-27-1a	H-26-2	H-34	T-28-5	T-33-1a
Unit	A1	A1	A3	A	B	B2	B2	C1	C2	C
Quartz, single crystals	64 %	36 %	66 %	76 %	49 %	53 %	59 %	62 %	61 %	58 %
Quartz, semicomp. and composite	2	2	1	tr	1	1	1	1	2	1
Chert	26	15	25	20	45	40	37	35	35	36
Chert, recry-stallized	3	tr	2	3	5	6	3	2	2	5
Calcite	-	-	3	-	-	-	-	-	-	-
Feldspar	-	-	tr	-	-	-	tr	-	-	-
Ironstone clasts	-	-	-	-	-	-	-	-	-	-
Limonitic matrix	5	47	3	1	-	-	-	-	-	-

Table 1 (cont'd)

Spec. #	T-14-2	T-56-1	T-14-5	T-86-1	T-34-4b	T-27-1a	H-26-2	H-34	T-28-5	T-33-1a
Sorting	mod	good	mod	good	poor	(bi-modal)	mod	mod	mod	(bi-modal)
Grade	m-cs	m	f-m	f-m	vf-vcs	m-vcs	m-cs	m-cs	m-cs	m. with granules
%Quartz/%Chert	2.3	2.5	2.5	3.3	1.0	1.2	1.5	1.7	1.7	1.4

APPENDIX 3

Table 2

Thin-Section Modal Analyses of Phenoclasts from Members B and C

(about 400 points per section counted)

Section #	32	35	35	36
Spec. #	T-1-B	T-4-8b	T-4-8c	T-5-18
Unit	B1	B2	B2	C1
Quartz	72 %	99 %	40 %	13 %
Chert	28	1	6	55
Limonitic matrix	tr		-	32
Sideritic-limonitic matrix	-		54	-
Sorting	good	poor	good	poor
Grade	f	m	vf	cs
Quartz/chert ratio	2.7	99	6.7	0.24

Abbreviations used on Tables 1 and 2:

mod = moderate
m = medium grained
f = fine grained
cs = coarse grained
v = very
f-m = medium - to predominantly fine grained

APPENDIX 3
Table 3

Semiquantitative X-Ray Diffraction Analyses of Clay Minerals in Specimens of Mud from the Bjorne, Borden Island, and Wilkie Point Formations

by A. Sabina

Sple No.	Sect. No.	Stratigraphic Position	Color	Kaoli-nite	Illite	Chlorite
T-13-4	Near S25	Bjorne Fm, Unit A1	l. grey	82 %	11 %	7 %
T-14-3	S25	Bjorne Fm, Unit A2	red-brown	47	35	18
T-1-3	S32	Bjorne Fm, Unit A3	l. grey	74	17	9
T-1-6	S32	Bjorne Fm, Unit A4	red-brown	48	33	19
H-16-2a	S62	Bjorne Fm, top of Unit B1	red-brown	63	28	9
H-16-2b	S62	Bjorne Fm, top of Unit B1	l. grey	53	29	18
T-15-1	S22	Bjorne Fm, base of Unit C2	l. grey	63	28	9
BW-O	Near S12	About 2' above top of Bjorne Fm	l. grey	70	24	6
BW-A	Near S12	About 5' above top of Bjorne Fm	red-brown	65	20	15
BW-B	Near S12	About 35'-40' above top of Bjorne Fm	olive grey	40	40	20
BW-C	Near S12	About 40'-45' above top of Bjorne Fm	olive grey	44	40	16
BW-D	Near S12	About 70'-75' above top of Bjorne Fm	olive grey	40	40	20

APPENDIX 4
SIZE ANALYSES OF SAMPLES OF SAND FROM MEMBERS A AND B
by G.R. Turnquist
Table 1

Sieve Analyses

Current #	1	2	3	4	5	6	7	8	9	10
Section #	134	134	32	32	32	32	28	35	13	12
Spec #	T-86-1a	T-86-1	T-1-2	T-1-7	T-1-8	T-1-10	T-11-1	T-4-7	H-11-1	T-28-2
Unit	A	A	A3	B1	B1	B1	B1	B2	B2	B2
Weight of sple: (grams)	101.24	109.52	52.80	106.40	94.61	98.71	90.09	109.80	125.92	117.91
% Loss	1.2	1.0	2.8	1.4	0.6	2.2	0.9	2.6	0.5	1.3
Held on										
mesh ϕ	%	%	%	%	%	%	%	%	%	%
6 -1.75	-	2.50			0.96	2.18	0.20	0.13		-
7 -1.50	-	2.04			0.34	0.15	-	0.13		-
8 -1.25	-	1.31			0.17	0.52	0.05	0.12		-

Table 1 (continued)

		Current # and weight per cent									
mesh	ϕ	1	2	3	4	5	6	7	8	9	10
10	-1.00	-	0.93	0.10	0.44	0.06	0.44	0.14	0.10	0.07	-
12	-0.75	-	6.97			0.05	0.90	0.16	0.22		-
14	-0.50	-	7.38			0.12	1.17	0.13	0.17		-
16	-0.25	-	6.90	0.43	0.32	0.08	1.69	0.18	0.18	0.15	0.05
18	-0.00	-	8.81			0.11	2.32	0.16	0.17		
20	0.25	-	17.63	0.57	0.22	0.14	2.43	0.15	0.18	0.19	0.15
25	0.50	-	12.89	0.65	0.16	0.19	4.37	0.09	0.23	0.18	0.43
30	0.75	-	11.94	0.95	0.22	0.45	6.86	0.13	0.28	0.25	0.36
40	1.25	0.01	9.82	4.07	1.35	4.85	19.80	0.56	1.46	4.34	8.93
50	1.75	0.25	1.73	14.00	8.01	22.33	10.32	5.28	5.66	16.91	17.76
60	2.00	1.39	2.20	22.44	14.62	17.26	7.34	14.81	10.79	21.21	18.66

Table 1 (continued)

		Current # and Weight per cent									
mesh	ϕ	1	2	3	4	5	6	7	8	9	10
70	2.25	12.64	0.60	26.17	25.69	19.10	8.00	31.41	27.19	25.84	16.90
80	2.50	11.04	0.65	12.02	8.76	6.11	7.76	14.50	15.48	6.95	5.22
100	2.75	32.19		4.12	20.25	5.34	5.65	18.93	20.62	6.65	6.20
120	3.00	19.56		0.75	7.39	1.32	1.89	5.74	5.76	1.79	5.59
140	3.25	18.09		1.16	5.49	1.83	1.72	3.33	5.10	1.32	2.49
170	3.50	1.44		0.10	0.24	0.25	0.43	0.35	0.95	0.22	0.19
200	3.75	0.79		0.22	1.08	0.20	0.38	0.44	0.74	0.22	0.17
230	4.00	0.84		0.14	0.89	0.15	0.47	0.26	0.69	0.23	0.24
270	4.25	0.23	0.37	0.02	0.15	0.03	0.17	0.09	0.31	0.05	0.46
Remainder		0.47	0.16	0.04	0.50	0.05	0.50	0.18	1.50	0.18	1.00

APPENDIX 4

Table 2

Statistical Parameters of Size Distribution

Current #	1	2	3	4	5	6	7	8	9	10
$\overline{X}_\phi$ (Friedman)	2.68	0.91	1.89	2.23	1.81	1.29	2.51	2.25	1.90	1.87
σ_ϕ (Friedman)	0.38	0.90	0.50	0.56	0.46	1.00	0.63	0.61	0.48	0.59
$\alpha_{3\phi}$ (Friedman)	0.19	-0.75	-0.85	-0.06	-1.32	-1.63	-2.82	-1.31	-0.12	0.54
$\alpha_{4\phi}$ (Friedman)	3.36	4.54	6.35	5.87	25.07	9.53	20.22	12.75	5.38	4.22
M_z (Folk)	2.67	0.97	1.89	2.27	1.81	1.42	2.27	1.97	1.87	1.91
σ_I (Folk)	0.37	0.55	0.44	0.49	0.45	0.99	0.41	0.47	0.44	0.56
Sk_I (Folk)	-0.12	-0.29	-0.13	0.19	0.15	-0.06	0.17	1.85	-0.06	0.24
K_G (Folk)	0.94	1.18	1.26	1.19	1.06	0.93	1.19	1.21	1.09	1.18

APPENDIX 4

Table 3

Environmental Interpretation According to Friedman, 1961

Current #	1	2	3	4	5	6	7	8	9	10
Unit	A	A	A3	B1	B1	B1	B1	B2	B2	B2
Environment from Plot 1	D	B	B	D	B	B	B	B	D	B
Plot 2	R	B	B	B	B	B	B	B	B	R
Plot 3	B	R	B	B	B	R	B	B	B	R
Plot 4	D	0	0	0	0	0	0	0	0	0

B = beach
D = dune
R = river
0 = overlap

APPENDIX 5

POROSITY AND SPECIFIC GRAVITY OF SPECIMENS OF SANDSTONE FROM MEMBERS B AND C

by R.G. Draper

Lab #	Sple #	Loc.	Mbr.	D_T	D_A	Apparent pore volume %	Hand specimen or thin-section
139-65	T-27-1	S11	B2	2.596 2.573 } 2.584	1.948 1.887 } 1.918	24.96 26.66 } 25.8	ss, m gd, pebbly
140-65	T-33-1b	S7	C	2.606 2.625 } 2.616	2.167 2.106 } 2.136	16.85 19.77 } 18.3	ss,m-cs gd,pebbly
141-65	T-5-2	S36	C1	2.703 2.751 } 2.727	2.278 2.371 } 2.324	15.72 13.81 } 14.8	ss, m gd,pebbly
142-65	H-34	S109	C1	2.625 2.641 } 2.633	2.036 2.137 } 2.086	22.44 19.08 } 20.8	ss, cs gd
143-65	H-16-4	S45	B or C	2.610 2.590 } 2.600	1.839 1.825 1.799 } 1.821	29.54 30.08 30.54 } 30.0	ss, m gd,pebbly

APPENDIX 5, (continued)

Lab #	Sple #	Loc.	Mbr.	D_T	D_A	Apparent pore volume %	Hand specimen or thin-section
144-65	T-27-1a	S11	B2	2.591 2.611 } 2.601	1.898 1.886 1.926 } 1.903	26.75 27.21 26.23 } 26.8	ss, m-v cs gd [1]
145-65	T-34-5	S8	B2	2.618 2.626 } 2.622	2.255 2.277 } 2.266	13.87 13.29 } 13.6	ss, m-g,pebbly

V_T = true volume of sample in cm^3

V_A = apparent volume of sample (volume enclosed by its outer surface and excluding its open pores)

D_T = true density in $grams/cm^3$

D_A = apparent density in $grams/cm^3$

Apparent pore volume = $\frac{1-D_A}{D_T}$

Legend for lithology on Table 1, Appendix 6

1) See Appendix 3, Table 1, No. 11

APPENDIX 6
PHYSICAL AND CHEMICAL ANALYSES OF BITUMINOUS SPECIMENS
Table 1

Bitumen Content
by R.G. Draper; description of specimens based on Table 2b

Lab #	Deposit #	Station #	Strati-graphic position	Bitumen % (weight)	Mineral Matter %	Loss [1]	Grade of Sediment	Sorting
405	1	S6		3.0	96.9	0.1	f gd ss	good
386	1	S7		0.5	99.5		f gd ss	good
389	1	S8	high	13.3	86.8	[0.1]	f gd ss	good
388	1	S8	interm.	14.3	85.0	0.7	f gd ss	good
387	1	S8	low	3.3	96.5	0.2	f gd ss	fair
391	2	S11		2.3	97.7	[2]	m gd ss	good
390	3a	S14		0.6	99.1	0.3	granule cogl, pebbly, sandy	poor
393	3a	S15	high	2.3	97.6	0.1	m gd ss, pebbly	poor
392	3a	S15	low	2.5	97.4	0.1	cs gd ss, pebbly	poor
394	3c	S17		2.6	97.5	[0.1]	m gd ss	poor
396	3c	3c-1		1.6	98.3	0.1	m-cs gd ss	poor
397	4a	4a-1		2.0	98.0		pebble cogl,sandy	poor
395	4a	4a-2		9.8	90.1	0.1	m gd ss, pebbly	poor

Table 1 (continued)

Lab #	Deposit #	Station #	Strati-graphic position	Bitumen % (weight)	Mineral Matter %	Loss[1]	Grade of Sediment	Sorting
398	4b	4b-1		5.4	94.4	0.2	v cs gd ss,pebbly	poor
399	4b	4b-2		5.8	94.4	[0.2]	v cs gd ss,pebbly	poor
403	4c	S47		4.1	95.4	0.5	pebble cogl,sandy	poor
407	4c	S52		10.1	89.9	[2]	m gd ss, pebbly	poor
400	4c	S53		8.1	92.2	[0.3]	m gd ss	poor
401	6	6-1		2.0	98.0		cs gd ss,pebbly	poor
402	6	6-2		10.2	89.9	[0.1]	f gd ss	fair
404	6	S128		3.0	96.8	0.2	m gd ss,pebbly	fair to poor
406	6	S129		1.3	98.7		pebble cogl,sandy	poor

1) bracketted results represent gain in weight

2) weighing error in mineral matter - % mineral matter corrected

Abbreviations:

ss = sandstone m = medium
gd = grained cs = coarse
f = fine v = very

APPENDIX 6
Table 2a

Sieve Analyses of Mineral Matter
by R.G. Draper

Lab #	20 %	40 %	60 %	80 %	100 %	150 %	200 %	-200 %
405	0.2	4.3	25.5	50.9	9.5	6.2	1.6	1.8
386	2.5	1.2	16.2	45.6	16.2	15.4	1.6	1.3
389	0.1	0.6	15.3	62.0	11.4	6.3	1.5	2.8
388	0.1	0.3	2.7	36.0	24.1	27.1	4.2	5.6
387	6.2	0.8	26.9	45.0	9.4	8.3	2.1	1.4
391	0.5	11.3	43.3	37.2	4.1	2.0	0.5	1.1
390	62.2	13.8	8.6	6.8	2.7	3.0	0.9	2.0
393	12.8	14.3	32.3	24.0	6.4	6.6	1.5	2.0
392	56.8	21.2	10.3	6.9	1.3	1.5	0.6	1.5
394	19.6	24.7	35.1	15.2	2.0	1.7	0.6	1.1
396	26.8	23.5	32.9	11.3	1.9	2.1	0.6	0.7
397	28.7	8.1	13.1	19.5	11.1	16.3	1.9	1.3
395	18.0	23.8	32.4	17.6	2.1	1.8	1.0	3.3
398	68.6	16.1	3.5	3.3	1.0	2.1	1.3	4.0
399	57.2	21.3	11.1	6.3	0.5	1.1	0.5	1.9
403	69.1	8.8	7.6	4.4	1.6	3.1	2.1	3.4
407	13.1	10.7	30.0	27.9	8.5	5.9	1.9	2.0
400	25.9	11.8	27.9	14.7	11.0	5.6	1.2	1.9

Table 2 a (continued)

Lab #	20 %	40 %	60 %	80 %	100 %	150 %	200 %	-200 %
401	54.2	23.5	8.0	5.5	2.2	4.5	0.8	1.3
402	0.3	0.3	5.6	26.0	18.8	24.8	13.3	10.8
404	13.3	27.9	35.3	14.6	4.0	3.3	0.5	1.0
406	72.0	9.2	7.9	6.3	1.4	2.1	0.3	0.8

APPENDIX 6
Table 2b

Statistical Parameters of Size Distribution
Calculated by G.R. Turnquist

Lab #	Mz φ	Md φ	σ_I φ
405	2.17	2.17	0.48
386	2.37	2.37	0.47
389	2.28	2.25	0.23
388	2.99	2.60	0.48
387	2.18	2.15	0.77
391	1.89	1.95	0.34
390		-0.50	
393	1.67	1.87	1.14
392		0.0	
394	1.16	1.40	1.13
396	0.89	1.25	1.67
397	0.88	2.00	
395	1.23	1.50	1.23
398		-0.35	
399		-0.10	
403		-1.50	
407	1.70	1.96	1.16
400	1.00	1.60	

Table 2b (continued)

Lab #	Mz ϕ	Md ϕ	σ_I ϕ
401		0.10	
402	2.87	2.72	0.62
404	1.36	1.45	0.96
406		-2.70	

APPENDIX 6
Table 3

Specific Gravity, and Content of O_2, S, and N

by R.G. Draper, D.S. Montgomery, *et al.*

Lab #	Spec.[1] gravity	S[1] %	Ni[1] ppm	O_2[2] %
405	1.081	2.66		
389	1.067	2.49	17	7.1
388	1.038	2.54	20	3.4
387	1.025	3.02		
391	1.047	3.08		
390	1.077	1.54		
393	1.065	2.00		
392	1.068	2.32		
394	1.044	2.35		
396	1.083	1.84		
397	1.066	1.63		
395	1.048	1.48		
398	1.052	1.20		
399	1.054	1.28		
403	1.039	1.25	9	
407	1.052	1.62	12	5.9
400	1.050	1.26		

Table 3 (cont'd)

Lab #	Spec.[1] gravity	S[1] %	Ni[1] ppm	O[2] %
401	1.056	0.88		
402	1.035	0.92		
404	1.030	1.04	5	
406	1.047	0.89		

1) Determination by R.G. Draper

2) Oxygen content from neutron activation determination, after clay correlation; by D.S. Montgomery et. al.

APPENDIX 6
Table 4a

<u>Elemental Analysis of C, H, N, S and O</u>

by Micro-Tech Laboratories and R.G. Draper

	Elemental Analysis as Received: Weight %					Elemental Analysis Ash Free: Weight %					Elemental Analysis Ash, S and N free: Atom %		
Lab #	C %	H %	N %	S[1] %	Ash %	C %	H %	N %	S %	O[2] %2	C %	H %	O %
387	81.63	10.15	0.57	3.02	1.00	82.45	10.25	0.58	3.05	3.67	39.76	58.91	1.33
389	78.04	9.73	0.45	2.49	1.39	79.14	9.87	0.46	2.52	8.01	39.04	57.99	2.97
388	79.44	10.08	0.38	2.54	1.44	80.60	10.23	0.39	2.58	6.21	38.92	58.83	2.25
396	78.83	9.11	0.40	1.84	1.72	80.21	9.27	0.41	1.87	8.24	40.76	56.10	3.14
407	80.02	9.96	0.62	1.62	1.46	81.21	10.11	0.63	1.64	6.41	39.33	58.34	2.33
402	81.30	10.41	0.48	0.92	1.66	82.67	10.59	0.49	0.94	5.32	38.85	59.28	1.87

APPENDIX 6
Table 4b

Atomic Ratios

by Micro-Tech Laboratories and R.G. Draper

Atom Ratios				
Lab #	H/C	N/C	S/C	O/C
387	1.48	0.006	0.014	0.033
389	1.49	0.005	0.012	0.076
388	1.51	0.004	0.012	0.058
396	1.38	0.004	0.009	0.077
407	1.48	0.007	0.008	0.084
402	1.53	0.005	0.004	0.041

APPENDIX 6
Table 5

Weight Percentages of Methylene and Methyl Groups, and Molecular Weights

by H.A. Barber, F.E. Goodspeed, and M.F. Millson

Lab. #	Percentage by Weight of Carbon in Groups				Molecular Weight
	CH_2	CH_3	CH_2 & CH_3	Column 2&3	
389	31.3	8.53	40.0	39.8	774
388	32.9	10.0	43.8	42.9	690
395	29.5	9.13	40.4	38.6	1071
407	32.9	8.0	44.7	40.9	751
402	34.8	9.53	46.8	44.3	717

APPENDIX 6
Table 6

Analyses of Western Canadian Oils from Hodgson (1954) Used for Comparison with Melville Island Oil

Oil Field	Producing Formation	Age	Gravity °API	Sulphur %	Nickel ppm
Bantry	Sunburst sand	Lower Cret.	21.7	2.41	19.1
Wapella	Shaunavon	Jurassic	23.6	2.30	17.0
Chamberlain	Basal Cretaceous	Lower Cret.	25.7	1.22	8.64
Stettler	Leduc	Devonian	28.2	1.90	13.8
Wagner	Basal Quartz	Lower Cret.	29.3	1.00	7.86
Drumheller	Basal Quartz	Lower Cret.	31.7	1.27	9.59
Campbell	Basal Quartz	Lower Cret.	33.4	0.83	4.91

ADDENDUM

October 1, 1966

SULPHUR ISOTOPE DETERMINATIONS

Analytical Results

Cadmium sulphide extracted by D.S. Montgomery and his colleagues from four bituminous specimens was analyzed by R.K. Wanless for its S^{34}/S^{32} ratio. The results, expressed with respect to the Canon Diablo troilite standard as δS^{34}, are tabulated below.

Deposit No.	Locality No.	Stratigraphic Position	Analysis No.	δS^{34} (per mil)
1	S 8	high	389	-1.56
1	S 8	intermed.	388	0.22
1	S 8	low	387	4.67
4c	S 52		407	-1.56

Discussion

In view of the wide range of the present analyses, and the many uncertainties surrounding the subject in general, only tentative conclusions can be drawn from these data. However, the information published up to date permits some inferences as to the age and environment of formation of the Melville Island oil, which are in agreement with the geological conclusions drawn in this report.

Age. A large number of sulphur isotope analyses on evaporites indicates that the ratio of S^{34}/S^{32} in the oceans has changed, in the course of geological time, on a world wide scale (Thode and Monster, 1965; Nielsen, 1966; Holser and Kaplan, 1966). A considerably smaller number of published analyses suggests that the time trend of petroleums parallels that of the contemporaneous evaporites, with the former being depleted in S^{34} by about 15 per mil (Thode and Monster, 1965).

The most remarkable characteristics of these curves are the presence of a high of δS^{34} in the lower Palaeozoic and Devonian, and a decline in the upper Palaeozoic, with an all-time minimum near the Permo-Triassic boundary. The δS^{34} values of the Melville Island bitumen are all significantly lower than those recorded for Ordovician, Silurian and

Devonian oils. On the other hand, they lie within the ranges of published analyses on Cretaceous, Triassic, Permian, and Carboniferous oils (Fig. 1); and within the possible ranges for most Jurassic, and some Tertiary and Devonian petroleums (see Fig. 2). As Mississippian strata are absent in this region, a Mississippian source can be ruled out; and, for stratigraphic and structural reasons, a Cretaceous source is not probable. Thus the present isotope analyses, taken at their face value, suggest that the Melville Island oil was derived from a source, or sources, ranging in age from Pennsylvanian to Jurassic; but a specific assignment within that interval cannot be made.

Environment of Formation. A study of Triassic to Tertiary petroleums of the Uinta Basin suggested to Thode, Monster, and Dunford (1958) that the oils from inland basins have anomalously high δS^{34} values, particularly in the late stages of their development. It is interesting to note that the Melville Island oil does not show these characteristics.

Variation in Isotope Ratios. The range of the present δS^{34} values in the bitumen in this deposit is greater than that reported by Thode for any single formation within an individual oil field. The reasons for this are unknown, and the problem merits further research. Dr. Montgomery (pers. comm.) points out that the upward decrease in δS^{34} at locality S 8 is approximately proportional to the sulphur and nickel content, and inversely proportional to the oxygen content, the present specific gravity, and inferred original gravity. It is difficult to see, at the present time, how the sulphur isotope ratio or the nickel content would be influenced by the weathering of the samples. It seems more probable that the variations in these properties reflect genuine differences in the petroleum, and do not reflect the effect of weathering. The variation in sulphur isotope ratio with the oxygen content is interesting, and should be followed up by much more detailed studies. The variation in the values of δS^{34} in the three samples is far greater than analytical error, so that this may be ruled out. To give an indication of the differences in δS^{34} between different laboratories, Abasand bituminous sand was reported by Thode to be +5.7, while the value obtained by R.K. Wanless on a sample of Abasand bitumen analyzed with the group of samples above was +4.8.

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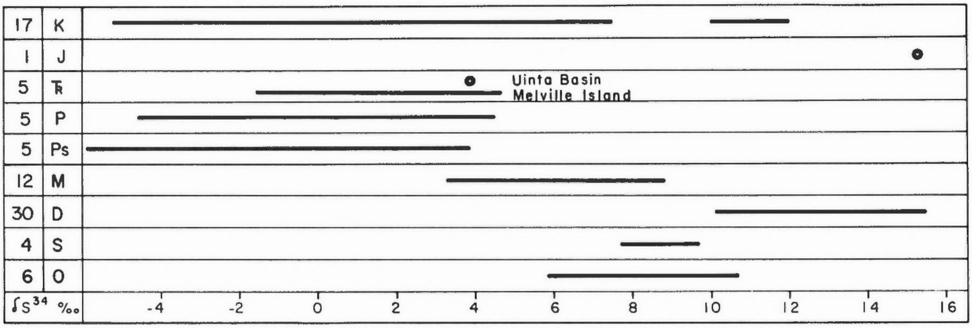

Figure 1. Ranges of the δS^{34} values of Ordovician to Cretaceous petroleums. The ages shown are those of the host formations, and not necessarily of the source beds. The left column indicates the total number of analyses, including those from Melville Island. The single Jurassic analysis is from the Uinta Basin. Based on Thode et al., 1958.

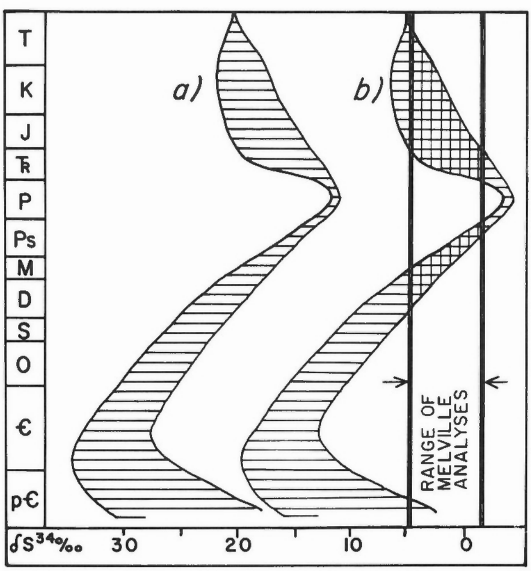

Figure 2. (a) The δS^{34} values of Precambrian to Recent oceans plotted against Kulp's 1959 time scale. The time trend probably lies within the area outlined. but the exact means, confidence limits, or ranges for given instants of time cannot be stated as yet. Based on Nielsen, 1966, Fig. 4.

(b) Hypothetical δS^{34} values of marine petroleums, assuming that they are depleted in S^{34} with respect to the contemporaneous seas by about 15 per mil.