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ABSTRACT

During the Early Cretaceous, rifting began between the paleo-North American and Greenland plates, eventually resulting in the development of the Labrador Sea, Davis Strait, and Baffin Bay regions. Along the western side of the Labrador Sea, the Labrador margin includes the Hopedale Basin and southern portion of the Saglek Basin. The Saglek Basin continues northwards into western Davis Strait, extending along the southeast Baffin Shelf. These depocentres record sedimentation from the Early Cretaceous syn-rift phase, late rift phase in the Late Cretaceous, drift phase or period of seafloor spreading in the latest Cretaceous to earliest Oligocene, and in the post-drift phase from the earliest Oligocene to Pleistocene. A total of 28 wells intersect the Mesozoic–Cenozoic section in these basins and document an important stratigraphic record for the region. Studies of these wells have included lithostratigraphic, biostratigraphic, and paleoenvironmental analyses, some with a regional or semi-regional undertaking. However, more recent studies have provided new understandings of the age and distribution of the eight formations that make up the stratigraphic succession along the margin. The present study focuses on incorporating existing well data to develop comprehensive and consistent paleoenvironmental interpretations for the wells of the Labrador margin and southeast Baffin Shelf. Lithological, well log, fossil content, and core descriptions are presented and interpreted to produce a regional understanding of paleoenvironmental change through time. In addition, lithostratigraphic boundaries and respective type and reference sections are modified to better fit lithological changes, well-log breaks, biostratigraphic hiatuses, and/or abrupt paleoenvironment changes. This revised paleoenvironmental and lithostratigraphic framework will help to serve future basin history studies in the region.

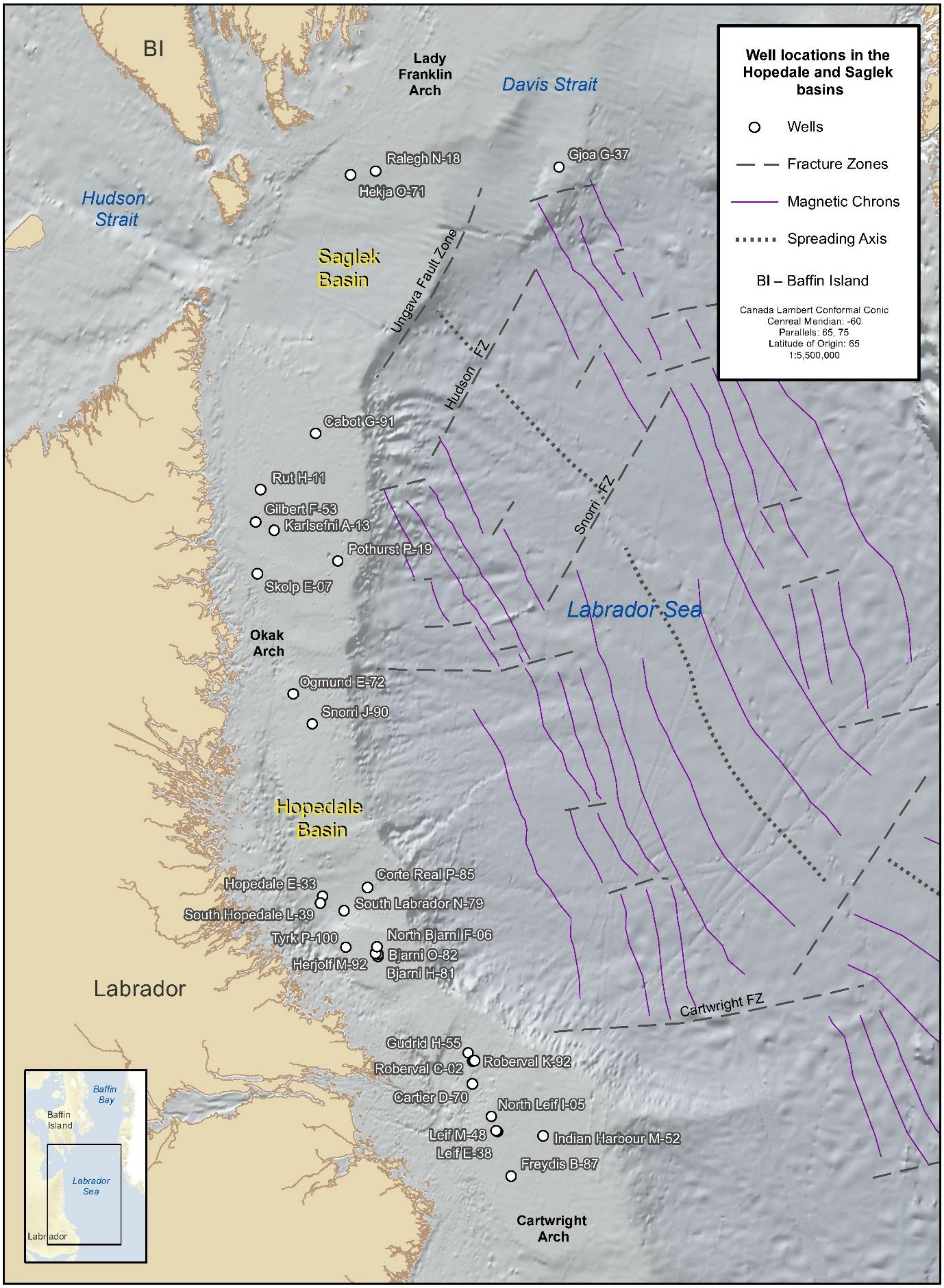
INTRODUCTION

The Labrador–Baffin Seaway, comprising the Labrador Sea, Davis Strait, and Baffin Bay regions, formed as a result of extension and rifting between the paleo-North American and Greenland plates, which began in the Early Cretaceous (Roest and Srivastava, 1989). A key part of this seaway is the offshore Labrador margin (Fig. 1), which has been well studied due to the rich dataset, including exploration wells and multichannel seismic data. Along this margin, extension resulted in the development of grabens and half-grabens below the present-day Labrador Shelf and slope, which infilled with syn-rift volcanic and clastic rocks (Umpleby, 1979; McWhae et al. 1980; Balkwill, 1987; Dickie et al., 2011; Dafoe, Dickie, et al., in press). Subsequently, in the Late Cretaceous, rifting moved farther offshore into the present-day slope region, resulting in sag-basin development along the shelf (Dickie et al., 2011). The onset of seafloor spreading and the final separation of the plates began in the Maastrichtian (chron C31) offshore of central Labrador (Keen et al., 2018a), but seafloor spreading was taking place in the Paleocene (chron C27n) offshore of northern Labrador and more regionally in the Labrador–Baffin Seaway (Keen et al., 2018b; Oakey and Chalmers, 2012). Significant strike-slip motion took place mostly in the Davis Strait region when a change occurred in the opening direction to more northerly between chrons C25n and C24n (Oakey and Chalmers, 2012). Seafloor spreading then ceased near the Eocene–Oligocene boundary, at chron C13 (Oakey and Chalmers, 2012).

The rifting history of the Labrador margin resulted in the development of two major basins (Fig. 1) that sit atop Precambrian and localized Paleozoic basement rock. The Hopedale Basin lies south of the Okak Arch and north of the Cartwright Arch (McMillan, 1980; Balkwill, 1987) and is sampled by 20 industry wells. North of the Okak Arch, the Saglek Basin contains nine wells and extends northwards to the Lady Franklin Arch and along the southeastern Baffin Shelf (Balkwill, 1987), with the Hudson Strait informally subdividing the Saglek Basin into southern and northern segments. The Labrador margin was drilled in the 1970s and 1980s during early hydrocarbon exploration, and a lithostratigraphic framework was developed and refined by several authors (Umpleby, 1979; McWhae et al., 1980; Moir, 1989; Balkwill and McMillan, 1990; Dickie et al., 2011). The eight formations established for the margin are still used today (Fig. 2), with updated interpretations of these units summarized in Dafoe, Dickie et al. (in press); these are the: Lower Cretaceous Alexis Formation basalts and Bjarni Formation sandstones, conglomerates, and shales (Snorri Member); Upper Cretaceous to early Selandian Markland Formation shales with Freydis Member sandstones; late Selandian–lowermost Ypresian Cartwright Formation shales and coeval Gudrid Formation sandstones; lower Ypresian through upper Bartonian Kenamu Formation shales, siltstones, and sandstones (Leif Member); upper Bartonian through Oligocene (and likely younger) mudstones and lesser siltstones and sandstones of the Mokami Formation; and Oligocene through Middle Miocene (and likely younger) sandstones and conglomerates of the Saglek Formation.

Key to understanding the stratigraphy of the region are the depositional paleoenvironments, which have been assessed through well and seismic correlations (Bell, 1989), detailed lithological analyses (Miller and D'Eon, 1987; Dafoe and Williams, 2020a), and numerous biostratigraphic studies (e.g. Bujak Davies Group, 1989a; Nøhr-Hansen et al., 2016; Williams, 1979a–i, 1981, 2007a–f; 2017a–b; Dafoe and Williams, 2020a–b). Despite these detailed studies, discrepancies remain regarding paleoenvironmental interpretations within and between wells, some of which have become more evident with new biostratigraphic constraints (e.g. Nøhr-Hansen et al., 2016) and seismic control (e.g. Dickie et al., 2011; Dafoe, Dickie et al., in press) that suggest revisions are needed to lithostratigraphic boundaries in the wells (e.g. Dafoe and Williams, 2020b). Accordingly, the present study provides a detailed and consistent reassessment of depositional paleoenvironments primarily from a lithological, sedimentological, and paleontological perspective for all of the wells in the Hopedale and Saglek basins. These results take into account other recent work, including a study of conventional core intervals (Dafoe and Williams, 2020a), and resolve discrepancies between previous studies. Many lithostratigraphic boundaries are further revised here to better reflect changes in well logs, lithology, and paleoenvironments, as well as significant unconformities. As a result, many of the type sections established by Umpleby (1979), McWhae et al. (1980), and Moir (1989) are also revised.

Figure 1 (next page): *Map of the study region showing the wells in the Hopedale and Saglek basins. FZ=fracture zone.*



Well locations in the Hopedale and Saglek basins
Wells
Fracture Zones
Magnetic Chrons
Spreading Axis
BI – Baffin Island
Canada Lambert Conformal Conic
Cenreal Meridian: -60
Parallels: 65, 75
Latitude of Origin: 65
1:5,500,000
BI
Lady Franklin Arch
Davis Strait
Hudson Strait
Ralegh N-18
Hekja O-71
Gjoa G-37
Saglek Basin
Ungava Fault Zone
Hudson FZ
Snorri FZ
Cabot G-91
Rut H-11
Gilbert F-53
Karlsefni A-13
Pothurst P-19
Skolp E-07
Okak Arch
Labrador Sea
Ogmund E-72
Snorri J-90
Hopedale Basin
Corte Real P-85
Hopedale E-33
South Labrador N-79
South Hopedale L-39
North Bjarni F-06
Tyrk P-100
Bjarni O-82
Herjolf M-92
Bjarni H-81
Labrador
Cartwright FZ
Gudrid H-55
Roberval K-92
Roberval C-02
Cartier D-70
North Leif I-05
Leif M-48
Indian Harbour M-52
Leif E-38
Freydis B-87
Cartwright Arch
Baffin Bay
Baffin Island
Labrador Sea
Labrador

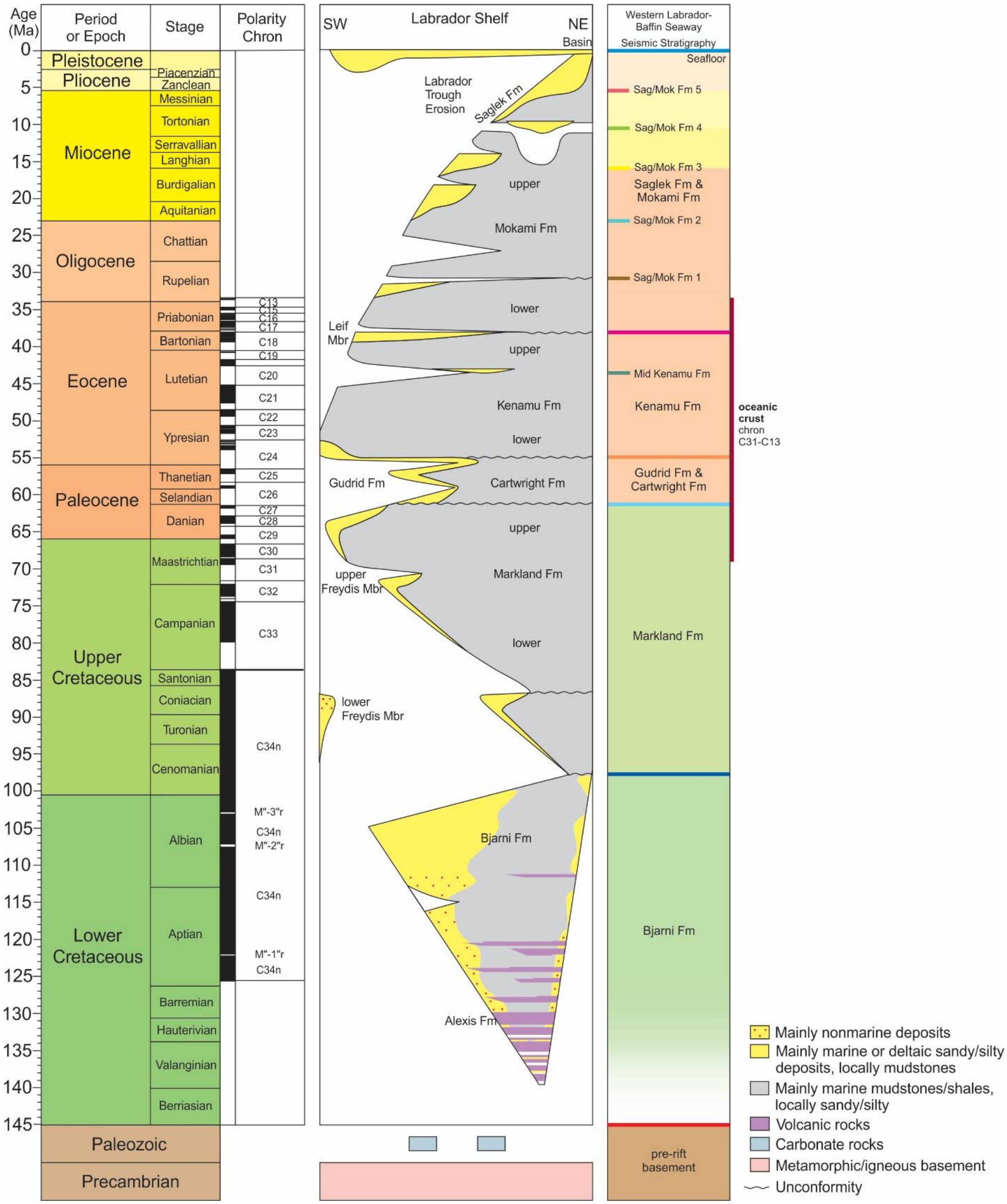


Figure 2: *Lithostratigraphic column for the Labrador Shelf from Dafoe, Dickie et al. (in press) and modified from Dickie et al. (2011) and Nøhr-Hansen et al. (2016) and plotted against the timescale and magnetostratigraphy of Gradstein et al. (2012). The western Labrador–Baffin Seaway seismic stratigraphy is from Dafoe, Dickie et al. (in press) and is based on the Labrador margin. Fm=Formation; Mbr=Member; Mok=Mokami; Sag=Saglek.*

METHODS

For each of the 28 exploration wells, the stratigraphic section was divided into lithologic intervals with similar characteristics. The lithologic data for each interval was compiled from existing well reports and logs, with the available information varying from well to well. All wells include a Canadian Stratigraphic Service Ltd. (Canstrat; www.canstrat.com) well plot with information obtained from cuttings analyses including: lithology, grain size, grain rounding and sorting, rock colour, and general cuttings descriptions, with accessory elements and fossil material noted. In addition to these logs, cuttings descriptions, sidewall core assessments, and analyses of conventional core intervals, data generally found within well history reports, as well as other reports, further include observations on the lithology, grain size, rock colour, fossil content, and accessory elements. The information obtained from both the Canstrat logs and well reports were compiled into the rock descriptions for each interval described in the present study. Individual sources of information for each well are summarized at the beginning of each well section. In addition to lithologic information, the electric well logs provide unique information on grain size, heterogeneity, and composition, as well as indicating the presence of stratigraphic breaks. Pertinent well log descriptions for the gamma-ray, sonic velocity, density, and resistivity logs are further included in the observations for each interval (where applicable), with key stratigraphic breaks noted, especially in relation to lithostratigraphic boundaries. Note that the sonic velocity is the inverse of the transit time shown in the well plots; where transit time increases, the velocity decreases. The Cabot G-91 well location was not completely drilled due to boulders present on the seafloor, icebergs, and strong currents during drilling operations (Plé, 1976), and is not included in the present study. Depths are indicated in metres for all wells, and also in feet for wells that were initially drilled using that metric.

The compiled observations for each lithogic interval are then interpreted in terms of the respective paleoenvironment based on the evidence cited. Paleoenvironmental interpretations follow standard sedimentological interpretations such as those presented in James and Dalrymple (2010) in reference to sedimentary structures, lithology, accessory elements, and well log character. Macrofossils (typically fragmented in cuttings) are also considered important components of the intervals defined in the present study, with the generalization that there is a decrease in diversity and abundance of forms towards the shelf edge and into deeper water, such as described in Clarkson (1998). An exception to this occurs in brackish-water settings in which there is limited fossil diversity, with a low diversity assemblage of bivalves and gastropods typically colonizing those settings (Clarkson, 1998). Microfossils, primarily foraminifera, are further included in the lithological descriptions for most wells (note that foraminifera are included under listings of fossil fragments as indicated in the original well descriptions, but due to their size, they are unlikely fragmented). While foraminifera may colonize terrestrial to deep-sea settings, general trends are utilized: benthonic forms are typically found in the outer shelf to slope; agglutinated forms generally occur in deep-water settings; and planktonic forms are commonly found in water depths equating to the slope and deep water (Armstrong and Brasier, 2005).

In some cases, sedimentological and paleontological observations were insufficient to provide a definitive paleoenvironmental interpretation, and in these instances, previous paleoenvironmental interpretations from lithologic and biostratigraphic studies were considered. Paleoenvironmental terminology follows that of Dafoe and Williams (2020a) based on the sedimentology (Fig. 3): nonmarine, backshore, foreshore, shoreface (upper, middle, lower), inner shelf, outer shelf, and slope and deeper water. In the present study, however, the middle shelf is considered to be a transitional interval equivalent to the distal inner shelf of Dafoe and Williams (2020a). Furthermore, true slope conditions were not established along the Labrador margin until Kenamu Formation time (Early–Middle Eocene; Dickie et al., 2011). Accordingly, 'slope' paleoenvironments prior to this time represent water depths greater than about 200 m and should be considered slope-equivalent settings. Figure 3 further shows the relationship between the terminology used here and that of palynological studies based on dinoflagellate cysts (dinocysts) such as Nøhr-Hansen et al. (2016) and Dafoe and Williams (2020a). For each lithologic interval, the results of the present study are also compared with the paleoenvironments of Miller and D'Eon (1987), a study that also primarily utilized lithology as the basis for interpretation and forms the only other regionally comprehensive paleoenvironmental study of the 28 wells. Other paleoenvironmental studies generally exist for most wells and are based on fossil assemblages, and the most comprehensive for each well is also compared to the present study.

Although the framework of Moir (1987a, b, c, 1989) forms a regional basis for the lithostratigraphic picks within the 28 wells, Dafoe, DesRoches, et al. (in press) further refined the lithostratigraphic assignments for the three wells in the northern part of the Saglek Basin, and Dafoe and Williams (2020b) also provided some revised picks for the North Leif I-05 and Skolp E-07 wells. In the present study, the lithostratigraphic designations are further revised based on new understandings with regard to paleoenvironmental changes, age constraints, and the framework for the margin established by Dafoe, Dickie et al. (in press). Revised picks are shown in the well plots, described in the text, and summarized in tables for each well to indicate divergence from those of Moir (1987a, b, c, 1989), Dafoe, DesRoches et al. (in press), and Dafoe and Williams (2020b). Where wells were initially measured in feet, slight discrepancies can arise between intervals defined in the present study and Moir (1989), as the present study has relied on using feet with conversions to metres to the nearest tenth of a metre rather than rounding to the nearest metre. The lithostratigraphic picks revised here are primarily based on well log, paleoenvironmental, lithologic, and sometimes biostratigraphic revisions to the wells. As a result of these changes, many of the type and reference sections established by Umpleby (1979), McWhae et al. (1980), and Moir (1989) are also modified based on the present study. Revision of type and reference section boundaries is permitted under Article 19 in the North American Stratigraphic Code where the change "will make a unit more natural and useful" (p. 1565, North American Commission on Stratigraphic Nomenclature, 2005). Most of the revisions to type and reference sections are minimal and are documented in the lithostratigraphy tables at the end of each well section. Readers are referred to Dafoe, Dickie et al. (in press) for further discussion on the type and reference sections.

For most wells, there are several biostratigraphic studies by various authors that generally utilize palynomorphs (dinocysts, pollen, and spores) and/or foraminifera to determine age, with some reporting paleoenvironmental results as well. Studies conducted prior to the year 2000 often report the age to only the subepoch level for the Cenozoic, while the Cretaceous is generally reported to the stage level. In more recent studies, from the year 2000 and onwards, ages can be reported to the stage level for both the Mesozoic and Cenozoic. In all instances, the ages are reported as documented in the original studies without simplification or modification (and as they are shown in the well plots, *see* below). For each lithologic interval, there can be similar or contrasting ages, with variation in the age terminology. Accordingly, the age of each lithologic interval is rationalized based on the perceived lithostratigraphic interval that is present, indication of stratigraphic breaks, and alignment with the regional understanding of the lithostratigraphic framework in Dafoe, Dickie et al. (in press). In this latter publication, the authors rationalized ages for the lithostratigraphic units based on the type and reference sections, but also included more modern biostratigraphic studies to refine the work of Umpleby (1979) and McWhae et al. (1980). It is not reasonable to assume that individual sections in different wells from a particular lithostratigraphic unit will present identical ages, thus Dafoe, Dickie et al. (in press) have used the best possible information and averaged between wells to refine the stratigraphic framework for the Labrador margin.

Well plots are provided for each of the 28 wells and show key electric logs where available, lithology, grain size, and rock colour from the Canstrat well plots. The electric logs include gamma ray, sonic transit time (units are inverted from sonic velocity to match the density log character), density, and resistivity. Conventional core intervals and well-log scale changes (casing points) are also shown. Several biostratigraphic studies by various authors exist for most wells, but only the four most relevant studies with ages that best align with the regional framework of Dafoe, Dickie et al. (in press) are shown (often these are more recent studies). Paleoenvironmental interpretations for the present study are shown along with those of Miller and D'Eon (1987) and that of a third, well-specific study to allow for comparisons. The lithostratigraphic picks of Moir (1987a, b, c, 1989) are shown for each well and compared with those of the present study, and some wells show a further third set of picks from other recent work. Reference and type sections are also shown on the plots and include a reference number that is tied to the relevant study, with only the most recently defined intervals plotted (most intervals are from the present study; also see the lithostratigraphy section for each well for more information). A general legend for the well plots is detailed in Appendix A, including abbreviations for the ages and paleoenvironments.

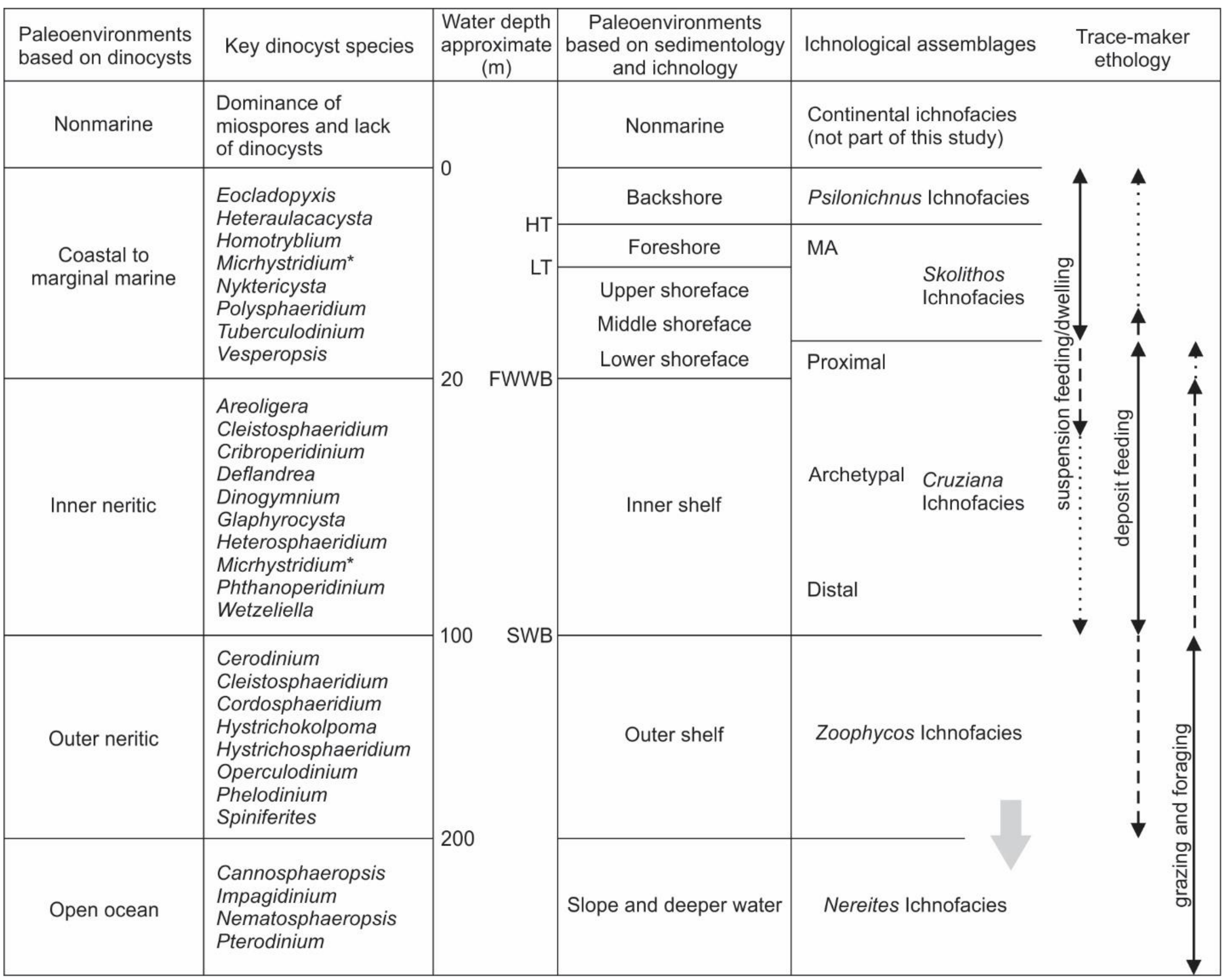


Figure 3: *Paleoenvironmental comparison chart from Dafoe and Williams (2020a). The two columns at left show the paleoenvironments based on dinocysts (palynology) and related key species from Nøhr-Hansen et al. (2016; * indicates acritarch taxa). The water depth is approximate and the high tide (HT), low tide*

(LT), fair-weather wave base (FWWB), and storm wave base (SWB) are also shown. Paleoenvironments based on sedimentology and ichnology from core observations and the related ichnological assemblages and trace-maker ethologies are modified from Pemberton et al. (2001) and shown to the right of the figure with the addition of the Nereites *Ichnofacies. The* Macaronichnus *Assemblage (MA) can colonize the foreshore and the* Zoophycos *Ichnofacies can also be found beyond the shelf (as indicated by the grey arrow). In general, the ichnofacies are not necessarily restricted to the normal marine settings shown, but can also be found in other settings that might have similar environmental conditions such as deltas and restricted embayments.*

RESULTS

BJARNI H-81

The Bjarni H-81 well is located in the central part of the Hopedale Basin (Fig. 1). Detailed lithological descriptions for this well are compiled from several sources. The well history report by Corgnet and McWhae (1973a) includes core, sidewall core, and rock cuttings descriptions. Cuttings descriptions and lithologic details from the Canadian Stratigraphic Service Ltd. Eastcan et al. Bjarni H-81 log (log EC-78) were also used, as well as conventional core descriptions from Dafoe and Williams (2020a). The well plot in Figure 4 includes key well logs, lithology, grain size, rock colour, ages, and paleoenvironmental and lithostratigraphic information. Biostratigraphically determined age assignments used in the present study are those from Williams (1979a). Table 1 provides a summary of the paleoenvironmental interpretations from the present study, and these are compared in the following sections against settings proposed by Bujak et al. (1974) based on micropaleontology and those of Miller and D'Eon (1987). Some lithostratigraphic designations are modified from Moir (1989) as shown in Figure 4 and in Table 2.

Base (m)	Top (m)	Paleoenvironment
2255.5	2208.3	NONMARINE FLUVIAL AND FLOODPLAIN
2208.3	2148.8	DELTA FRONT
2148.8	2133.6	SHELF
2133.6	1706.9	SLOPE
1706.9	1524.0	OUTER SHELF
1524.0	1387.1	MIDDLE SHELF
1387.1	1280.2	OUTER SHELF
1280.2	1130.8	MIDDLE SHELF
1130.8	723.9	INNER SHELF OR PRODELTA
723.9	499.9	DISTAL DELTA FRONT
499.9	381.0	SHOREFACE OR DELTA FRONT

Table 1: Paleoenvironmental determinations for Bjarni H-81 from the present study.

Nonmarine fluvial and floodplain

The interval from 2255.5 to 2208.3 m (7400–7245 ft.) is characterized by white to brown sandstone with grey shale. Sandstones are medium- to coarse-grained, with subangular clasts, common feldspar, scattered quartz and feldspar pebbles, and rare pyrite. Grey shales are silty, fissile, and bituminous, with common lignite and coal stringers.

The abundance of coal in this interval suggests a nonmarine setting, combined with the alternation of shale and sandstone, but the presence of feldspar indicates sediment immaturity and short transport distances. The most likely setting is fluvial with alternating channel and floodplain deposits. This setting closely resembles the fluvial interval of Miller and D'Eon (1987), but Bujak et al. (1974) suggested a more coastal, supralitoral setting.

This interval is from the Bjarni Formation and is (?)Barremian–Aptian (Williams, 1979a), although an Albian age has been proposed by others (Bujak et al., 1974; Fenton and Pardon, 2007). A basal pick of 2255.5 m for this interval slightly modifies the base of the Bjarni Formation from that of Moir (1989; Table 2). This change also modifies the extent of the underlying Alexis Formation, which thus extends from 2515 m to 2255.5 m, modifying the type section originally defined by Umpleby (1979; Table 2).

Delta front

From 2208.3 m to 2148.8 m (7245–7050 ft.) is white, quartz-rich sandstone with grey shale. Sandstones are fine- to coarse-grained, blocky and weakly coarsening-upward, with subangular to rare subrounded grains. Feldspar is common in the sandstones, as well as pyrite and quartz and feldspar pebbles, with rare glauconite. Crossbedding is also noted, as well as faulting and evidence of slumping. The sandstones are also partly kaolinitic, with carbonaceous fragments present and rare coal fragments. Dark grey silty shales are micaceous, with rare bitumen. The gamma-ray log shows high API values than typical for sandstone (Fig. 4), but this is explained by the highly feldspathic nature (Umpleby, 1979).

Dafoe and Williams (2020a) interpreted core 1 from within this interval (2164.11–2157.1 m) as river-influenced deltaic deposits with significant terrestrial influx. This interpretation, combined with the presence of glauconite and coarsening-upward units suggests a shallow marine, delta-front paleoenvironment for the entire interval. Bujak et al. (1974) proposed a supralitoral setting in general agreement with the present study, but Miller and D'Eon (1987) interpreted a nonmarine setting characterized by fluvial or alluvial fan deposition. The presence of glauconite is, however, a convincing marine indicator.

These sandstone-dominated strata lie at the top of the Bjarni Formation, but the top of this interval (2148.8 m) marks a significant change in the paleoenvironment, as well as a prominent log break, and is taken here to refine the top of the Bjarni Formation and also the reference section previously defined by McWhae et al. (1980), with the revised section now spanning 2255.5–2148.8 m (Table 2). Fenton and Pardon (2007) also noted a major unconformity at about the same depth as the revised top Bjarni Formation (2150.39 m). Williams (1979a) gave a (?)Barremian–Aptian age for this interval, with a younger Albian age possible according to Bujak et al. (1974).

Shelf

Dark grey silty shales with mica grains, rare sand grains, and rare lignite occur between 2148.8 m and 2133.6 m (7050–7000 ft.).

This interval contains limited diagnostic features to indicate a paleoenvironment; however, the overlying interval is deep marine (*see* below), with notably less silt and more calcareous content (Fig. 4). Accordingly, the silt, sand, and lignite within this interval appears to be consistent with a shelfal setting, where coarser clastic detritus and terrigenous influx was marginally significant, but it is uncertain if this interval reflects a more proximal or more distal setting on the shelf. Regardless, this interval represents the onset of marine transgression over the underlying shallow marine sandstones. Previous results determined a shallower, inner sublittoral setting (Bujak et al., 1974) or a deeper, (?)bathyal paleoenvironment (Miller and D'Eon, 1987), further implying an uncertainty in the paleoenvironmental affinity. Lying above the Bjarni Formation, this interval comprises the basal part of the Markland Formation in Bjarni H-81 and is of Maastrichtian age according to Williams (1979a); although a range of ages has been proposed by other studies (Fig. 4).

Slope

The interval from 2133.6 m to 1706.9 m (7000–5600 ft.) encompasses medium to dark grey to brown-grey shale, with siderite nodules, pyrite, and rare mica grains. Brown limestone stringers increase in abundance upward, and rare foraminifera, lignite, and carbonaceous material occur near the top of the overall interval.

The consistent nature of the shale, generally barren of fossils and with increasing limestone and terrigenous material upward, suggests progressive shallowing in a slope-equivalent setting. The persistence of deeper-water conditions throughout such a thick section confirms the distal position of Bjarni H-81 on the shelf relative to the paleoshoreline. Similar to the underlying interval, shallower settings were previously proposed by Bujak et al. (1974), who indicated an inner to outer sublittoral (shelf) setting, but bathyal conditions were interpreted by Miller and D'Eon (1987). The present interpretation generally agrees more closely with that of the latter study.

These slope-equivalent deposits are Maastrichtian through Middle–Late Eocene in age (Williams, 1979a) and include much of the Markland Formation, the entire Cartwright Formation, and the base of the Kenamu Formation. Here, the Markland Formation and respective type section is modified from that of McWhae et al. (1980) at the base to range from 2148.8 m to 1975 m (Table 2). The Cartwright Formation is well defined by a prominent log break at its base in both the gamma-ray and resistivity logs (Fig. 4) and is unchanged from that of Moir (1989), with the type section as defined by McWhae et al. (1980; Table 2). The top of the Cartwright Formation is best demarcated in the sonic and density logs through a change in character.

Outer shelf

Silty and slightly micaceous, brown-grey to dark grey shale between the depths of 1706.9–1524.0 m (5600–5000 ft.) locally grades into siltstone-dominated units. The shale is partly calcareous and includes scattered limestone stringers and nodules and rare pyrite. Fossil material includes foraminifera and bivalve shell fragments, as well as rare scaphopod fragments .

The overall dominance of shale, with silt and minor fossil content is consistent with an outer shelf setting displaying shallowing from the underlying slope succession. Outer sublittoral (outer shelf) to bathyal conditions were interpreted by Miller and D'Eon (1987) and Bujak et al. (1974), roughly in agreement with the present study. Comprising the middle portion of the Kenamu Formation, this interval is Middle–Late Eocene (Williams, 1979a), but a variety of ages have been reported for this part of the well (Fig. 4).

Middle shelf

The interval from 1524.0 m to 1387.1 m (5000–4551 ft.) consists of claystone with siltstone and limestone beds. Claystones are grey-brown to grey, silty throughout, slightly calcareous, and often sandy (very fine-grained). Rare grey limestone nodules and mica grains are present, as well as siltstone stringers. Siltstone units are grey-brown, argillaceous, sandy, and calcareous, and grey-brown limestone contains very fine-grained sand grains, as well as silt.

The degree of silt and very fine-grained sand is consistent with continued shallowing to middle shelf conditions relative to the underlying interval; however, the lack of fossil material is unusual. Like the underlying interval, outer sublittoral (outer shelf) to bathyal conditions were interpreted by Miller and D'Eon (1987) and Bujak et al. (1974), settings that are deeper than interpreted in the present study. Miller and D'Eon (1987) further suggested that the sandy and silty claystones represented turbidite successions; however, the lithology is more homogenized than would be expected for discrete turbidity current deposits.

Defining the top of the Kenamu Formation as interpreted in the present study, this interval is Middle–Late Eocene based on the work of Williams (1979a). Dafoe, Dickie et al. (in press) found the Kenamu Formation to end in the late Bartonian (Middle Eocene). The findings of most studies in this well concur with this age for the top of the Kenamu Formation at 1387.1 m (Fig. 4), in contrast to the top picked at 1334 m by Moir (1989). Furthermore, the overlying deeper-marine setting (*see* below) is consistent with transgression at the base of the overlying Mokami Formation (Balkwill, 1987; Balkwill and McMillan, 1990; Dickie et al., 2011; Dafoe, Dickie et al., in press). The log break between the two formations is, however, not well developed in this well as it is elsewhere in the Hopedale Basin.

Outer shelf

The interval from 1387.1 m to 1280.2 m (4551–4200 ft.) is characterized by grey-brown, silty, slightly micaceous, locally slightly calcareous claystone, with rare siltstone beds, rare, very fine-grained sand, rare pyrite, and rare limestone stringers.

In comparison to the underlying intervals, the reduction in sand content suggests a slight deepening back to outer shelf conditions. This interpretation agrees well with that of Bujak et al. (1974), but is slightly shallower than the bathyal setting of Miller and D'Eon (1987). This interval falls within the Middle–Late Oligocene to Early Miocene according to Williams (1979a), with other studies reporting similar ages (Fig. 4). Based on the modification to the Kenamu–Mokami Formation boundary described above, this interval marks the base of the Mokami Formation and a transgression above the top Kenamu Formation.

Middle shelf

The interval from 1280.2 m to 1130.8 m (4200–3710 ft.) is a brown-grey, silty, micaceous, locally sandy claystone, with scattered limestone stringers, some siltstone beds, and rare pyrite. Incorporation of very fine-grained sand increases towards to the top of the interval, and rare gastropods are also present.

Again, following the logic of underlying intervals, the increase in sand content and presence of fossil material indicates that the paleoenvironment shallowed into a middle shelf setting. This is in good agreement with the outer to inner sublittoral settings interpreted by Bujak et al. (1974) and mid-shelf setting of Miller and D'Eon (1987), but the latter authors further indicated possible outer shelf to bathyal water depths. This interval forms part of the lower Mokami Formation of Early Miocene age (Williams, 1979a), with other biostratigraphic studies reporting similar ages (Fig. 4).

Inner shelf or prodelta

Brown-grey, silty, micaceous claystone occurs between 1130.8 m and 723.9 m (2375–3710 ft.). The claystone further contains very fine-grained sand grains throughout, trace limestone stringers and beds, and siltstone beds increase in abundance upwards (30–50% silt content locally).

The increase in silt, sand, and limestone beds suggests continued shallowing to an inner shelf setting relative to the underlying strata, but the lack of fossils implies that environmental stresses existed during deposition, possibly brackish conditions. Accordingly, an inner shelf or prodelta setting is interpreted for this interval, which approximately agrees with the inner sublittoral (shelf) settings of Bujak et al. (1974) and the middle to inner shelf conditions proposed by Miller and D'Eon (1987), but there is no evidence for turbidity current deposition.

These Lower Miocene to Pliocene (Williams, 1979a) rocks form the upper part of the Mokami Formation in the well, but the ages are younger than expected, such that the Oligocene age of Fenton and Pardon (2007) is more plausible (*see* Dafoe, Dickie et al., in press). Using the upper boundary of this interval (723.9 m), the present study slightly modifies the top of the Mokami Formation from that of Moir (1989), resulting in a new designation of 1387.1–723.9 m for the formation and the reference section, the latter was initially proposed by McWhae et al. (1980; Table 2).

Distal delta front

The interval from 723.9 m to 499.9 m (2375–1640 ft.) comprises heterolithic sandstones and shales, but data is lacking from the cuttings between 652.2–591.3 m (2140–1940 ft.). The sandstones are light orange to light yellow, fine- to (mostly) coarse-grained, with subrounded grains, moderate sorting, and a loose consolidation. The sandstones also include abundant quartz pebbles, as well as dark chert grains, feldspar clasts, pyrite, ironstone nodules, wood fragments, rare igneous pebbles, and rare lignite.

Less common brown-grey to green claystones are silty and sandy. The overall gamma-ray log shows a coarsening-upward, but slightly ragged (heterolithic) character (Fig. 4).

The coarse-grained nature of the sediment suggests a relatively high-energy setting, and the presence of lignite and wood fragments indicates terrestrial influence. The heterolithic character is consistent with a deltaic setting and explains the lack of fossil material as a result of environmental stresses associated with brackish conditions. In support of a deltaic interpretation, clinoform development has also been established for these sandstone successions, which comprise the Saglek Formation (Balkwill and McMillan, 1990; Dickie et al., 2011; Dafoe, Dickie et al., in press). The paleoenvironment interpreted from the present study is generally consistent with the inner shelf to marginal marine or littoral settings of Miller and D'Eon (1987) and Bujak et al. (1974), with the former authors also identifying deltaic settings, but also reporting nonmarine conditions not recorded in the present study.

This interval forms the lower part of the Saglek Formation in Bjarni H-81 and is of Pliocene–Pleistocene age according to Williams (1979a). However, other wells in proximity indicate older ages for what is likely equivalent strata (*see* Bjarni O-82, for example) and are based on more recent biostratigraphic assessments (e.g., Nøhr-Hansen et al., 2016).

Shoreface or delta front

Between 499.9 m and 381.0 m (1640–1250 ft.) is an interval comprising blocky, coarsening-upward, coarse-grained sandstone with abundant pebbles, locally becoming conglomeratic. The sandstone is light brown to light orange, light green and white, with abundant quartz pebbles, and lesser igneous pebbles and feldspar clasts. Grains are subrounded, moderately sorted, and loosely consolidated, and included in the sandstone are wood fragments, dark chert clasts, localized pyrite, rare worm tubes, and rare glauconite. A blocky gamma-ray log pattern is noted for this interval (Fig. 4).

The coarse-grained nature of the strata suggests a relatively high-energy setting, and the presence of lignite and wood fragments indicates terrestrial influence. This, with the presence of glauconite and bioturbation suggests a shoreface or delta front setting, with the blocky gamma-ray log character more typical of shoreface strata. The interpretations from previous work (Bujak et al., 1974; Miller and D'Eon, 1987) also indicate a shallow marine setting, with some nonmarine conditions not documented in the present study.

This interval forms the top of the Saglek Formation in Bjarni H-81 as defined in the present study. Moir (1989) took the top of the formation higher in the well, but there is no definitive lithological or log information to confirm this pick. Here, the top of the formation is extended to 369.42 m, which corresponds to the top of the electric logs. Accordingly the reference section is modified from that of McWhae et al. (1980) to 723.9–369.42 m (Table 2). The age is Pliocene–Pleistocene according to Williams (1979a); however, it appears to be older in nearby wells (*see* discussion above for the preceding interval).

Lithostratigraphy

Based on the above discussion around the lithostratigraphic refinements to the framework of Moir (1989) in Bjarni H-81, the lithostratigraphic picks from the present study are summarized in Table 2, with modifications to type and reference sections indicated.

Lithostratigraphic unit	Moir (1989)		The present study		Type or reference section
	Base (m)	Top (m)	Base (m)	Top (m)	
Saglek Fm	725	222	723.9	369.42	Reference section from 725–222 m of McWhae et al. (1980) is modified to 723.9–369.42 m
Mokami Fm	1334	725	1387.1	723.9	Reference section from 1334–725 m of McWhae et al. (1980) is modified to 1387.1–723.9 m
Kenamu Fm	1820	1334	1820	1387.1	None
Cartwright Fm	1975	1820	1975	1820	Type section from 1975–1820 m of McWhae et al. (1980) is retained
Markland Fm	2150	1975	2148.8	1975	Type section from 2150–1975 m of McWhae et al. (1980) is modified to 2148.8–1975 m
Bjarni Fm	2255	2150	2255.5	2148.8	Reference section from 2255–2150 m of McWhae et al. (1980) is modified to 2255.5–2148.8 m
Alexis Fm	2515	2255	2515	2255.5	Type section from 2515–2255 m of Umpleby (1979) is modified to 2515–2255.5 m

Table 2: Lithostratigraphic assignment for Bjarni H-81 from the present study and compared to that of Moir (1989). Fm=Formation.

BJARNI O-82

For the Bjarni O-82 well in the central part of the Hopedale Basin (Fig. 1), the sources of information for the lithologic intervals include the well history report by Total Eastcan Exploration Ltd. (1979a), which contains conventional core, sidewall core, and rock cuttings descriptions. The Canadian Stratigraphic Service Ltd. log for Total Bjarni O-82 (log EC-153) was a further invaluable source of lithological information and detailed rock descriptions. Finally, conventional core descriptions from Dafoe and Williams (2020a) provide control for an interval within the Bjarni Formation. A plot of the well is shown in Figure 5, with key well logs, lithology, grain size, rock colour, ages, and paleoenvironmental and lithostratigraphic information. The age assignments of Nøhr-Hansen et al. (2016) are followed in the present study. Paleoenvironments defined here are summarized below in Table 3 and compared in the below descriptions with those of Miller and D'Eon (1987) and of Williams (2007e), the latter derived from palynological analyses. Moir's (1989) lithostratigraphic assignments are also locally revised in the present study as indicated in Table 4.

Base (m)	Top (m)	Paleoenvironment
2650	2546	NONMARINE TO MARGINAL MARINE
2546	2287	DELTAIC
2287	2235	OUTER SHELF DEEPENING TO SLOPE
2235	2061	SLOPE TO SHELF EDGE
2061	2025	SLOPE
2025	1750	OUTER SHELF
1750	1695	MIDDLE SHELF
1695	1580	OUTER SHELF
1580	1360	MIDDLE SHELF
1360	1312	OUTER SHELF
1312	1110	MIDDLE SHELF
1110	758	INNER SHELF OR PRODELTA
758	410	SHOREFACE OR DELTA FRONT

Table 3: Paleoenvironmental determinations for Bjarni O-82 from the present study.

Nonmarine to marginal marine

At the base of Bjarni O-82, the interval from 2650 m to 2546 m is composed of blocky, 5–10 m thick sandstones with interbedded grey fissile shales containing coal stringers and rare carbonized plant detritus. Sandstones are light grey to pink, fine- to coarse-grained, moderately sorted, rich in feldspar, micaceous, and locally calcareous, with subangular grains, coal stringers and kaolinite throughout, scattered very coarse-grained sand grains, and rare pyrite. As explained by Umpleby (1979), the feldspathic nature of these sandstones results in a relatively high API value on the gamma-ray log, but there is a generally ragged character seen (Fig. 5).

The common occurrence of coal indicates low-lying peat accumulation possibly in a nonmarine, fluvial setting. Biostratigraphic evidence, however, suggests shallow marine incursions within intervals otherwise lacking dinocysts and thus indicating predominantly nonmarine deposition (Williams, 2007e). Miller and D'Eon (1987), however, proposed strictly nonmarine conditions: braided to meandering fluvial settings. Accordingly, the setting may have fluctuated between nonmarine fluvial to coastal or marginal marine conditions. These sandstones form part of the Bjarni Formation in the well and are of Aptian in age according to Nøhr-Hansen et al. (2016). Other studies proposed Barremian ages as well

(Bujak Davies Group, 1987b; Williams, 2007e), but Nøhr-Hansen et al.'s (2016) recent regional study determined a lack of evidence for the Barremian in Labrador Shelf wells.

Deltaic

Between 2546 m and 2287 m, the strata are defined by blocky, 10–25 m thick sandstones, with thin shales and limestone beds in the upper half of the interval. Sandstones are light grey, white to pink, fine- to coarse-grained, and calcareous, with abundant feldspar (orthoclase) and kaolinite, very coarse-grained sand grains present throughout, moderate to poor sorting, subangular grains, rare pebbles, rare glauconite, and rare chlorite. The grey shales contain rare glauconitic sandstone, rare siderite nodules, rare chert near the top of the interval, and sandy limestones that are white to cream. The character of the gamma-ray log is typically ragged, but indicates a subtle coarsening-upward trend (Fig. 5).

The presence of limestone beds and glauconite, with the immature nature of the sandstones (abundance of feldspar and poor sorting), suggests shallow marine conditions prevailed with elevated depositional rates consistent with a deltaic setting and deposition during progradational pulses. The heterolithic sandstones and shales of core 2 (2304–2293 m) were interpreted as delta front deposits, possibly from a river-influenced delta (Dafoe and Williams, 2020a). The adjacent core 1 (2293–2291 m) is, however, composed of interbedded volcanic rocks (glassy and tuffaceous interbeds), likely deposited in a shallow, nearshore setting (Dafoe and Williams, 2020a). This latter lithology is atypical for the Bjarni Formation and does not appear to be representative of the interval from 2546–2287 m. Accordingly, the above evidence suggests a shallow marine, deltaic setting for the entire interval. This interpretation is similar to the marginal marine to inner shelf paleoenvironment of Miller and D'Eon (1987), which also included deltaic deposition, but also some nonmarine units. Similarly, Williams (2007e) postulated marginal marine settings deepening upward to outer neritic to open ocean at the top of the interval. This deep-marine signature may be a function of cavings from the overlying strata, as these settings neither reflect the sandstone-dominated strata described in this interval, nor the core intervals studied by Dafoe and Williams (2020a).

This interval characterizes the upper portion of the Bjarni Formation in Bjarni O-82, with a top modified to 2287 m based on the paleoenvironmental change noted between this and the overlying interval, as well as the prominent log break most evident in the sonic and resistivity logs (Fig. 5). Aptian, early Albian, (?)Cenomanian, Turonian–Coniacian, and Campanian ages were found by Nøhr-Hansen et al. (2016) for this interval. However, results from the conventional cores from 2304 to 2291 m places the nearly uppermost part of this interval in the middle to late Albian to possibly Cenomanian (Dafoe and Williams, 2020a). The entire interval thus likely ranges in age from Aptian to late Albian, with the Cenomanian age from core 1 at the very top of the interval being more speculative since it is derived from palynomorphs recovered from volcanic rather than sedimentary rocks.

Outer shelf deepening to slope

Glauconitic, grey shales, with pyrite, siderite bands, rare wood fragments, and rare foraminifera are found in the interval from 2287–2235 m.

The presence of foraminifera and glauconite are consistent with a marine setting and the lithology suggests a quiescent environment likely far from the shoreline. The abundance of glauconite is consistent with a marine transgression where sedimentation rates are typically low, allowing for glauconite formation (Amorosi, 2003). Accordingly, an outer shelf setting that deepens upwards into slope-equivalent conditions is interpreted. From cuttings samples partly within this interval, Williams (2007e) indicated open ocean settings, and Miller and D'Eon (1987) suggested a possibly bathyal setting becoming bathyal upwards. Overlying the Bjarni Formation, this shale interval corresponds to the base of the Markland Formation. A Campanian–early Maastrichtian age was given by Nøhr-Hansen et al. (2016), which agrees well with previous studies (Bujak Davies Group, 1989b; Williams, 2007e).

Slope to shelf edge

In the interval from 2235 m to 2061 m, grey, fissile shale becomes silty upward, with siderite stringers, lignite, glauconite, and rare pyrite. Rare sand grains and pebbles are found at 2200 m, and fossil material includes localized rare scaphopod and indeterminate shell fragments.

The fine-grained nature of the sediment and general lack of fossil material and silt and sand content is suggestive of deep-water conditions found along the slope or possibly the shelf edge based on the presence of scaphopods. This setting conforms with that of Williams (2007e), who found alternating open ocean and outer neritic conditions during a period of maximum flooding or condensed deposition, and also with Miller and D'Eon's (1987) bathyal interpretation. This part of the well is attributed to the Markland Formation and is of Maastrichtian to Selandian (Middle Paleocene) age (Nøhr-Hansen et al., 2016). Based on the refinement to the Bjarni–Markland formation boundary, the Markland Formation extends from 2287–2061 m, varying slightly from the designation of Moir (1989; Table 4).

Slope

In the interval from 2061–2025 m, glauconitic, grey shale is present, with siderite and common pyrite nodules, ironstone fragments, and rare foraminifera.

The overall abundance of glauconite, fine-grained nature, and presence of foraminifera is consistent with a condensed sedimentary interval and slope-equivalent water depths. Williams (2007e) proposed a relatively condensed Upper Paleocene section within this interval and indicated the paleoenvironment to be open ocean to outer neritic. The bathyal interpretation of Miller and D'Eon (1987) is also consistent with the present study. The base of the Cartwright Formation is defined by this interval which is latest Paleocene to basal Ypresian (Early Eocene) in age (Williams, 2007e; Nøhr-Hansen et al., 2016).

Outer shelf

Spanning the depths from 2025 m to 1750 m is a silty, fissile grey shale. The shale contains siderite, floating very coarse-grained sand grains, limestone stringers, localized dolostone, rare lignite, and rare pyrite nodules. Fragmented fossil material is scattered throughout and includes gastropod, occasional foraminifera, and indeterminate shell fragments.

The influx of silt, localized coarse-grained sand and relative abundance of fossil fragments implies shallowing relative to the underlying interval to at least the outer shelf. This interpretation matches well with that of Williams (2007e) who recorded outer neritic to open ocean settings based on the presence of the dinocyst *Impagidinium*. This slight shallowing in the paleoenvironment was not noted by Miller and D'Eon (1987) as they reported a continuation of bathyal water depths.

In Bjarni O-82, this interval spans much of the Cartwright Formation and the lower part of the Kenamu Formation. A gamma-ray high and change in the character of the sonic and density logs marks the boundary between the two formations, but there appears to be no discernable lithological change. The Cartwright Formation is unchanged from the designation of Moir (1989; 2061–1880 m; Table 4). The age of these shales is earliest Ypresian to Ypresian (Early Eocene) based on Williams (2007e) and Nøhr-Hansen et al. (2016), with good agreement with the Early Eocene age of Bujak Davies Group (1989b).

Middle shelf

Grey-brown, silty, partly calcareous, sandy shale occurs in the interval from 1750 m to 1695 m, with foraminifera and limestone stringers also present.

The influx of sand compared to the underlying strata is taken to reflect shallowing to middle shelf conditions. This shallowing was not noted by previous authors (Miller and D'Eon, 1987; Williams, 2007e), as they proposed continued outer neritic to open ocean or bathyal conditions. This discrepancy in the paleoenvironment could be explained by the thin nature of this interval and/or sample spacing of the cuttings. This interval forms part of the Kenamu Formation, and was assigned a Ypresian (Early Eocene) age by Williams (2007e) and Nøhr-Hansen et al. (2016), similar to the Early–Middle Eocene interpretation of Bujak Davies Group (1989b).

Outer shelf

Between 1695 m to 1580 m, strata are characterized by grey-brown shale or claystone that is silty, calcareous, and slightly dolomitic. Scattered sand grains are present, as well as scattered fossil fragments (foraminifera, scaphopod, and indeterminate shell material), limestone stringers and beds, and rare lignite.

A reduction in the abundance of sand grains compared to the underlying strata, but presence of marine fossils is interpreted to indicate outer shelf conditions. Open ocean to outer neritic paleoenvironments of Williams (2007e) match well with the present study, but Miller and D'Eon (1987) interpreted a slightly more distal, bathyal paleoenvironment. Also consistent with a deepening at this level in the well is the presence of a condensed Lutetian section (Williams, 2007; Nøhr-Hansen et al., 2016), which Dafoe, Dickie et al. (in press) suggested to be linked to marine flooding. This interval falls within the Kenamu Formation and is Lutetian to Bartonian (Middle Eocene) according to Williams (2007e) and Nøhr-Hansen et al. (2016), similar to the previously reported Middle–Late Eocene age of Bujak Davies Group (1989b).

Middle shelf

A grey-brown, silty and locally sandy claystone comprises the strata between 1580 m and 1360 m. These claystones are also calcareous to slightly dolomitic, with limestone stringers, floating coarse-grained sand grains, rare glauconite, and rare pyrite. Fossils fragments include foraminifera, scaphopod, and indeterminate shell material.

The abundance of fossil material, presence of limestone beds, and sandier character suggests a middle shelf paleoenvironment. This is shallower than the outer neritic to open ocean (Williams, 2007e) and bathyal with turbidite fan interpretations (Miller and D'Eon, 1987) of previous authors. There is no evidence to suggest turbidite deposition, as discrete sandstone intervals were not encountered, and a shallowing at the top of the Kenamu Formation is consistent with previous regional studies involving the formation (Balkwill and McMillan, 1990; Dickie et al., 2011; Dafoe, Dickie et al., in press).

The top of the Kenamu Formation is capped by this claystone interval, which is of Bartonian (Middle Eocene) age (Williams, 2007e; Nøhr-Hansen et al., 2016). Moir (1989) assigned the top of the formation to the Leif Member (Fig. 5; Table 4), but the lithology is inconsistent with the sandstone-dominated strata typical for that member, which reflect shoreline deposition (Umpleby, 1979; McWhae et al., 1980; Balkwill and McMillan, 1990; Dickie et al., 2011; Dafoe, Dickie et al., in press). Accordingly in Bjarni O-82, the Kenamu Formation is here recorded without this member, but its extent (1880–1360 m) is unchanged from that of Moir (1989; Table 4).

Outer shelf

The interval 1360 m to 1312 m consists of brown claystone that is partly silty and locally sandy, with limestone stringers.

There is little information in this interval to derive a comprehensive paleoenvironmental interpretation, other than the fine-grained nature of the sediment that indicates quiescence during deposition. However, the lack of fossil content contrasts with the underlying and overlying units and suggests a marine flooding event and resultant change to at least outer shelf conditions. This interpretation is slightly shallower or more proximal than that of Williams (2007e) and Miller and D'Eon

(1987), but similarly marks an end to deeper-water deposition around the base of the Mokami Formation. Flooding above the Kenamu Formation is well established during early Mokami Formation deposition (McWhae et al., 1980; Dickie et al., 2011; Dafoe, Dickie et al., in press). Above the top of the Kenamu Formation, this interval marks the base of the Mokami Formation of latest Bartonian (Middle Eocene) age based on Williams (2007e) and Nøhr-Hansen et al. (2016), with Bujak Davies Group (1989b) giving a similar Middle–Late Eocene age.

Middle shelf

Between 1312 m and 1110 m, claystone is present, with rare limestone beds. The claystone is brown, silty, locally sandy, partly calcareous, and micro-micaceous, and contains limestone stringers, scattered medium- to coarse-grained sand, and rare fossil fragments (foraminifera and indeterminate shell material). Intermittent limestone beds are brown-black to grey, argillaceous, and silty.

Similar to underlying units, a return to silty and sandy claystone suggests increased proximity to the shoreline, but the dominance of claystone indicates that a middle shelf setting is most likely. In contrast to underlying intervals, however, there is a lack of fossil fragments within this interval. The setting proposed in the present study lies between the inner and outer shelf settings proposed by previous authors (Miller and D'Eon, 1987; Williams, 2007e). Of latest Bartonian (Middle Eocene) through earliest Rupelian (Early Oligocene) age (Williams, 2007e; Nøhr-Hansen et al., 2016), this interval forms part of the lower Mokami Formation in Bjarni O-82.

Inner shelf or prodelta

From 1110 m to 758 m, strata comprise brown claystone with scattered limestone beds. The claystones are silty and sandy, with scattered medium- to coarse-grained sand grains, sandstone beds developed near top of the interval, siderite, and coal fragments. Scattered fossil fragments include foraminifera, rare gastropod, and indeterminate shell material.

The overall silty and sandy nature of the claystone suggests shallowing from the underlying middle shelf interval to inner shelf conditions. A low diversity and abundance of fossil material could, however, indicate brackish water deposition in a more prodeltaic setting. In their study of the lithology, Miller and D'Eon (1987) also postulated an inner shelf setting with a possible brackish character. However, they interpreted turbidite deposits, for which there is no evidence in the present study. Williams (2007e) suggested an inner neritic paleoenvironment, but also ranging into nonmarine conditions, shallower than the evidence above would suggest, but possibly explained by the paucity of dinocysts observed in that study (Fig. 3). This interval reflects the upper part of the Mokami Formation intersected in the well and was found to be of Rupelian (Early Oligocene) age by Nøhr-Hansen et al. (2016). The boundaries for this formation are the same as reported in Moir (1989; Table 4; 1360–758 m).

Shoreface or delta front

The top of the well is defined by a distinctive pebbly sandstone from 758 to 410 m. The sandstone is medium- to very coarse-grained (mostly coarse-grained), moderately to poorly sorted, unconsolidated, locally conglomeratic, locally argillaceous, and light grey, yellow to white. Sand grains are subrounded to rounded and the sandstone also contains dark chert grains and pebbles, granitic pebbles, scattered pyrite nodules, scattered feldspar, rare pyrite, and rare siderite. Rare thin shale and claystone stringers with wood fragments and plant detritus and very rare, unidentified fossil fragments are also observed. Overall, the gamma-ray log character shows a blocky, somewhat coarsening-upward sandstone interval (Fig. 5).

The interval is sharply based, and rounded clasts suggest a mature sediment and a high-energy setting, with wood and plant material indicating terrestrial influx. In addition, the coarsening-upward and blocky nature of the interval is consistent with a shoreface or possibly wave-dominated delta-front setting. This interpretation aligns wells with the inner neritic to marginal marine paleoenvironments determined by Williams (2007e), but this author's interpretation of nonmarine conditions is not represented in the current study and is likely explained by low dinocyst recovery (Fig. 3). Miller and D'Eon (1987) also found inner shelf, marginal marine, and nonmarine settings including beach, shoreface, delta front, distributary bars and channels, and fluvial deposits. Again a nonmarine setting is inconsistent with the present study and with previous descriptions of the clinoform development for the Saglek formation, as described above for Bjarni H-81.

This interval forms part of the Saglek Formation and includes Rupelian (Early Oligocene) and Chattian (Late Oligocene), Early Miocene, Serravallian (Middle Miocene) and Plio-Pleistocene ages (Williams, 2007e; Nøhr-Hansen et al., 2016). There is no lithological evidence to suggest a break in section between the Middle Miocene and Plio-Pleistocene (Fig. 5), so perhaps reworking has confused the age assignments at the top of the well. While Moir (1989) assigned the top of the Saglek Formation to a depth higher in the well, it is defined here at 410 m, at the top of electric log and lithological information, and thus ranges from 748–410 m (Table 4).

Lithostratigraphy

Based on the above discussion around lithostratigraphic refinements to the framework of Moir (1989) in Bjarni O-82, the lithostratigraphic picks from the present study are summarized in Table 4. No reference or type sections are described from this well.

Lithostratigraphic unit	Moir (1989)		The present study		Type or reference section
	Base (m)	Top (m)	Base (m)	Top (m)	
Saglek Fm	758	262	758	410	None
Mokami Fm	1360	758	1360	758	None
Kenamu Fm	1880	1360	1880	1360	None
Leif Mb	1386	1360	--	--	None
Cartwright Fm	2061	1880	2061	1880	None
Markland Fm	2285	2061	2287	2061	None
Bjarni Fm	2650	2285	2650	2287	None

Table 4: Lithostratigraphic assignment for Bjarni O-82 from the present study and compared to that of Moir (1989). Fm=Formation; Mb=Member.

CARTIER D-70

The Cartier D-70 well is in the southern part of the Hopedale Basin in a relatively proximal position on the shelf (Fig. 1). The well history report for this well includes sidewall core and rock cuttings descriptions (Ferrero, J. and Plé, C., 1976), which were used in the present study. The Canadian Stratigraphic Service Ltd. Eastcan Cartier D-70 (log EC-108) log provides further lithological, grain size, grain rounding and sample descriptions for the well. Information in Umpleby (1975a) was also used for auxiliary sidewall core descriptions. The Cartier D-70 well plot is shown in Figure 6, and includes key well logs, lithology, grain size, rock colour, ages, and paleoenvironmental and lithostratigraphic information. The age assignments used in the present study are from Williams (1979b), but Fenton and Pardon (2007) presented further age assignments to the age/stage level that are useful. Miller and D'Eon (1987) reported the only set of existing paleoenvironmental interpretations; those from the present work are summarized in Table 5 and compared with the existing study in the descriptions below. The lithostratigraphy from both Moir (1989) and the present study are also shown in Figure 6 and compared in Table 6.

The interval from 1927.0 m to 1909.9 m at the base of Cartier D-70 is defined by a thin, unnamed Precambrian basement interval (Table 6).

Base (m)	Top (m)	Paleoenvironment
1909.9	1900.8	NONMARINE (WEATHERED BASEMENT)
1900.8	1856.9	(?)SLOPE
1856.9	1795.8	DELTA FRONT
1795.8	1755.7	PRODELTA
1755.7	1713.0	DELTA FRONT
1713.0	1670.3	SHELF
1670.3	1606.3	SLOPE
1606.3	1450.9	OUTER SHELF
1450.9	1280.2	MIDDLE TO INNER SHELF
1280.2	1173.5	UPPER SLOPE TO OUTER SHELF
1173.5	1024.8	MIDDLE SHELF
1024.8	591.3	INNER SHELF OR PRODELTA

Table 5: Paleoenvironmental determinations for Cartier D-70 from the present study.

Nonmarine (weathered basement)

Lying above the Precambrian basement at the base of Cartier D-70 is a thin interval from 1909.9–1900.8 m (6266–6236 ft.) comprising coarse-grained sandstone and shale with fragments of metamorphic basement incorporated as pebbles. The shale is red-brown and grey and may contain oxidized glauconite; and the sidewall core at 1909.9 m (6266 ft.) comprises what was indicated in Umpleby (1975a) as red-brown lateritic soil.

The presence of lateritic soil and inclusion of obvious clasts of basement rock into the sandstone and shale interval is consistent with a subaerially exposed setting in which weathering of basement rock was taking place. Miller and D'Eon (1987) suggested a possible bathyal setting, but this is not in agreement with the observations noted above, and likely reflects cavings from the overlying interval (*see* below). This interval forms the base of the Markland Formation in Cartier D-70 and is possibly Maastrichtian (Williams, 1979b), but the nature of the sediment could indicate that the age is derived from cavings, as others noted a younger, Paleocene age (Ferrero, J. and Plé, C., 1976; Gradstein, 1976b).

(?)Slope

Grey to dark grey, partly fissile shale, with pyrite and rare silt is encountered between 1908.8 m and 1856.9 m (6262–6092 ft.).

Overall, the shale is rather characterless and contains minimal silt content and a complete lack of fossil or terrigenous detritus, suggestive of a distal marine setting. Accordingly, the interval is assigned a possible slope-equivalent water depth, which shows good accord with the bathyal setting of Miller and D'Eon (1987). This interval contrasts with the underlying weathered basement section, but covers the remaining portion of the Markland Formation in Cartier D-70. These strata are Maastrichtian to earliest Late Paleocene based on analyses by Williams (1979b); however, Fenton and Pardon (2007) suggested that only the Danian (Early Paleocene) and not Middle or Late Paleocene are present in this interval. The Markland Formation has been interpreted to include both the Danian and early part of the Selandian (Middle Paleocene; Dafoe, Dickie et al., in press), but could also be incomplete in this well. The Markland Formation thus ranges from 1909.9 m to 1856.9 m, slightly modified from that of Moir (1989; Table 6).

Delta front

In contrast to the underlying strata, the interval from 1856.9 to 1795.8 m (6092–5892 ft.) is composed of three distinct sandstone packages, with intervening thin shales. The sandstones are medium- to coarse-grained, moderately sorted, unconsolidated, argillaceous, white and partly light green. Clasts are rounded to subrounded, with very coarse-grained sand grains and quartz pebbles found throughout. In addition, locally common siderite, bivalve shell fragments, rare glauconite, rare feldspar grains, and rare pyrite are also present. The thin, grey, silty, and sandy shales contain siderite stringers. Overall, the interval is glauconitic at the top and has both a sharp base and top. The gamma-ray log confirms three, roughly coarsening-upward packages within the interval, with somewhat ragged character (Fig. 6).

The slightly heterolithic and coarsening-upward nature, presence of glauconite and siderite, and lack of fossils suggests delta front deposition with three main pulses of progradation. The sandy nature of these strata was, however, interpreted as turbidite fans in a bathyal setting by Miller and D'Eon (1987). There is no evidence of the fining-upward character typical of turbidite fan deposits, and the presence of glauconite and pebbles is not consistent with such a deep-water setting combined with rapid turbidite deposition. Furthermore, seismic interpretation of the Gudrid Formation confirms that it is a shoreline clinoform succession (Balkwill and McMillan, 1990; Dickie et al., 2011; Dafoe, Dickie et al., in press).

This interval aligns with the lower part of the Gudrid Formation and is of Late Paleocene age according to Williams (1979b), although Fenton and Pardon (2007) suggested that it is at least partly Selandian (Middle Paleocene). The top of the Gudrid Formation is slightly modified here to match this interval and the log breaks seen in the gamma-ray, sonic, and resistivity logs at 1795.8 m. Accordingly, this modifies the reference section that was originally proposed by McWhae et al. (1980) to 1856.9–1795.8 m (Table 6).

Prodelta

The interval from 1795.8 m to 1755.7 m (5892–5760 ft.) comprises dark grey to brown-grey shale. The shale is partly silty and includes rare quartz grains and rare pyrite. Near the top of the interval, dark brown, argillaceous, sandy limestone is also present.

The shale is sandier upwards, lacks fossils, and is associated with the deltaic units both below and above (*see* below). As a result, the interval is consistent with prodeltaic deposition where brackish conditions hampered marine faunal colonization, resulting in a lack of fossil remains. Again, a bathyal interpretation was given by Miller and D'Eon (1987), but considering the nature of the under- and overlying sandstones, this is not likely.

This thin shale interval was assigned to the Cartwright Formation and part of the upper Gudrid Formation by Moir (1989). His boundary between the Cartwright and Gudrid formations appears to correlate to a log break associated with the limestone unit at the top of this prodelta interval rather than a change from the shale to overlying sandstone. Accordingly, the top of the Cartwright Formation is placed here at 1755.7 m (5760 ft.), rather than at 1763 m (5784 ft.; Table 6). Williams (1979b) determined that this interval falls within the Late Paleocene to Early Eocene, but Fenton and Pardon (2007) considered it to be restricted to the Thanetian (Late Paleocene). In either case, the ages are consistent with the stratigraphic framework presented in Dafoe, Dickie et al. (in press).

Delta front

There is a return to a sandstone-dominated succession from 1755.7 m to 1713.0 m (5760–5620 ft.). The sandstone is cream, light grey to brown, very fine-grained, argillaceous, silty, glauconitic, micaceous, friable, and well sorted, with subrounded clasts and rare siderite. Although poor recovery of cuttings was reported for this interval, sidewall core indicates medium- to fine-grained sandstone, with unknown dark clasts (possibly organic, mudstone rip-up clasts) and glauconite. At the very top of the interval is a sandy, glauconitic limestone and a highly glauconitic, medium-grained, poorly sorted sandstone, with subangular clasts. The interval shows a slightly coarsening-upward profile in the gamma-ray log (Fig. 6).

A delta front setting is interpreted based on the lithology, lack of fossils, and presence of glauconite typical in shallow marine settings, as well as possible evidence of detritus or mudstone rip-up clasts. The top of the interval is highly glauconitic, typical of a transgressed surface in which there is limited sedimentation during relative sea-level rise (Amorosi, 2003). Like the underlying lower Gudrid Formation, Miller and D'Eon (1987) indicated bathyal conditions with turbidite fan deposition, but this is inconsistent with the sedimentological and seismic morphological evidence (*see* Dafoe, Dickie et al., in press).

Taking into account the revised lithostratigraphic assignment for the underlying Cartwright Formation, the section from 1755.7–1713.0 m in Cartier D-70 forms the upper Gudrid Formation of Ypresian (Early Eocene) age (Williams, 1979b; Fenton and Pardon, 2007), and represents a modification to the original reference section of McWhae et al. (1980; Table 6).

Shelf

The interval from 1713.0 m to 1670.3 m (5620–5480 ft.) consists of shale with coal stringers and limestone. The shale is medium to dark grey and slightly micaceous, and the limestone is dark grey-brown and argillaceous, with a partly chalky texture.

The juxtaposition of coal and chalky limestone suggests a mixture of marine conditions with terrigenous influx. Alternatively, the interval may reflect transgressive flooding and reworking of the underlying nearshore marine strata, accounting for the incorporation of coaly detritus. A shelf setting is postulated for this interval, but a proximal or distal setting cannot be confirmed. Flooding at the base of the Kenamu Formation is well established (Dickie et al., 2011; Dafoe, Dickie, et al., in press) and consistent with the present study. Miller and D'Eon (1987) found this section of the well to reflect bathyal deposition, but this is inconsistent with the lithological evidence presented above. At the base of the Kenamu Formation, this interval was found to be Middle Eocene by Williams (1979b), but within the Ypresian (Early Eocene) by Fenton and Pardon (2007), with the latter age aligning more closely with the stratigraphic framework outlined in Dafoe, Dickie et al. (in press).

Slope

The section from 1670.3 m to 1606.3 m (5480–5270 ft.) consists of brown-grey to medium grey, slightly micaceous shale, with rare silt and rare dark grey-brown limestone stringers. One brown to white, silty, chalky limestone bed, with indistinct fossil fragments and shale stringers is also observed.

The fine-grained nature of the sediment and lack of silt, sand, and fossil material, combined with chalky limestone suggests a setting far from shore, or a slope-equivalent paleoenvironment. Miller and D'Eon (1987) reported a similar, bathyal setting. Within the Kenamu Formation, this interval is thought to be Middle Eocene (Williams, 1979b), or Ypresian (Early Eocene) to Middle Eocene in age (Fenton and Pardon, 2007), with preference for the latter age.

Outer shelf

Brown-grey shale occurs between 1606.3 m and 1450.9 m (5270–4760 ft.). The shale is silty, with limestone nodules and fossil material, including foraminifera and indeterminate shell fragments.

An increase in silt content and the presence of some fossil material indicates a shallowing relative to the underlying slope-equivalent setting to outer shelf conditions. This shallowing was not noted previously, as Miller and D'Eon (1987) interpreted this interval as representing bathyal water depths with turbidite fan accumulations. The interval lies within the Kenamu Formation and ranges from Middle to Late Eocene according to Williams (1979b), but is more likely confined to the Middle Eocene as indicated by Fenton and Pardon (2007).

Middle to inner shelf

The interval from 1450.9 m to 1280.2 m (4760–4200 ft.) consists of shale with thin sandstones that thicken and clean (become sandier) upwards, forming three major coarsening-upward intervals seen in the gamma-ray log (Fig. 6). The grey to grey-brown, silty, locally sandy, and slightly micaceous shale contains rare indeterminate shell fragments. Sandstones are brown, very fine- to fine-grained, silty, argillaceous, friable, and well sorted. Clasts in the sandstones are subrounded to subangular, and the rocks contains shale stringers, rare limestone stringers, rare pyrite, and rare foraminifera; although, poor recovery was noted from the sandstone portions of this interval.

The increased silt and sand content compared to the underlying interval, with coarsening-upwards nature suggests progressive shallowing from the underlying outer shelf to middle then inner shelf conditions. The sandstones appear to represent progradational pulses within the inner shelf, perhaps equating to three distal shoreline regressions. In contrast, Miller and D'Eon (1987) indicated a bathyal setting and explained the presence of sandstones as related to turbidite fan accumulations. The intermixing of lithologies and coarsening- rather than fining-upward intervals does not agree with such a distal-marine setting.

This shale and sandstone interval encompasses the top of the Kenamu Formation, including the Leif Member (Fig. 6; Table 6). Moir (1989) also placed a thin interval of Kenamu Formation rocks above the Leif Member, which is not followed in the present study. The prominent log change at 1280.2 m at the top of this middle to inner shelf interval in the well also marks a clear transition between the Kenamu and Mokami formations, especially in the gamma-ray and porosity logs. It is unclear why Moir (1989) assigned a thin interval of Kenamu Formation up to 1275 m, but in the present study the Kenamu Formation (and top Leif Member) are interpreted to end at 1280.2 m, thus modifying the reference section for the Kenamu Formation of McWhae et al. (1980; Table 6). Accordingly, this upper part of the Kenamu Formation is Late Eocene (Williams, 1979b) or Middle–Late Eocene (Fenton and Pardon, 2007), with a preference for the latter age. Based on the framework described by Dafoe, Dickie et al. (in press), the top Kenamu Formation is well established to be within the late Bartonian (late Middle Eocene; Dickie et al., 2011; Dafoe, Dickie et al., in press).

Upper slope to outer shelf

Lying above the shallow-water strata at 1280.2 m is an interval from 1280.2 m to 1173.5 m (4200–3850 ft.) of slightly silty, micro-micaceous, grey-brown shale. The shale includes rare sand grains at the base, rare quartz pebbles, and rare limestone nodules.

These silty shales that lack evidence of terrigenous influx and fossil material are suggestive of an upper slope-equivalent to outer shelf setting. The base of the interval is also significant as the inclusion of a sandy lag indicates transgressive reworking consistent with the onset of the Mokami Formation (Dickie et al., 2011; Dafoe, Dickie et al., in press). Miller and D'Eon (1987) also interpreted a bathyal setting for this interval, in good agreement with the present study.

Considering the lithostratigraphy of the underlying interval in Cartier D-70, this interval forms the base of the Mokami Formation. It was dated as middle to Late Oligocene to Early Miocene by Williams (1979b). However, Fenton and Pardon (2007), Ferrero and Plé (1976) and Gradstein (1976b), suggested older Late Eocene to Oligocene ages, which better fit the lithostratigraphic model proposed by Dafoe, Dickie et al. (in press) and are preferred in this study.

Middle shelf

The strata from 1173.5 m to 1024.8 m (3850–3362 ft.) encompass grey-brown, silty, slightly micaceous claystone, with 10–20% very fine- to fine-grained sand, limestone stringers, rare fossil fragments (scaphopod and indeterminate shell material), and rare coarse-grained sand grains.

The sandy nature of the claystone and fossil forms imply a middle shelf paleoenvironment. In contrast, Miller and D'Eon (1987) indicated that this interval reflected continued bathyal depositional conditions. This interval is found near the base of the Mokami Formation and is of Early to Late Miocene age according to Williams (1979b). This age, however, is younger than expected as described in the framework for the Mokami Formation where it is intersected in the wells (*see* Dafoe, Dickie et al., in press).

Inner shelf or prodelta

Heterolithic claystone, sandstone, siltstone and rare limestone characterize the upper part of Cartier D-70 from 1024.8 to 591.3 m (3362–1940 ft.). The interval is sandier at the base, becoming more clayey near the top. Sandstones are very fine-grained (lesser fine-grained), well sorted, brown or white, silty, and argillaceous. These rocks are also composed of subangular grains, with rare glauconite, rare calcareous components, rare coal, and rare quartz pebbles. The claystones are grey-brown, sandy (very fine-grained), and silty, with scattered fossil fragments (bivalve and indeterminate shell material), rare quartz pebbles, and rare coal fragments. Siltstones are brown-grey, sandy (very fine-grained), very argillaceous, and friable, and contain shale stringers. The log signatures for this part of the well depict a heterolithic and ragged character throughout, with some subtle coarsening-upward units (Fig. 6).

The sandy, but claystone-dominated nature suggests inner shelf conditions. The overall lack of fossil material, however, may indicate reduced salinity associated with brackish conditions and prodeltaic deposition. Miller and D'Eon (1987) resolved similar middle to inner shelf paleoenvironments, but suggested turbidites (presumably related to deltaic or fluvial discharge) associated with storm action. This uppermost interval in the well forms the upper part of the Mokami Formation, and is of Middle–Late Miocene age according Williams (1979b), again younger than expected for the Mokami Formation as seen in other Labrador Shelf wells (Dafoe, Dickie et al., in press). The top of the Mokami Formation is adjusted here to the top of the electric logs that indicate similar claystone and sandstone lithologies to 577.9 m (Fig. 6), rather than to the 472 m depth indicated by Moir (1989) from within the cased portion of the well; thus, the Mokami Formation extends from 1280.2–577.9 m (Table 6).

Lithostratigraphy

Based on the above discussion around lithostratigraphic refinements to the framework of Moir (1989) in Cartier D-70, the lithostratigraphic picks from the present study are summarized in Table 6, with modifications to reference sections are also noted.

Lithostratigraphic unit	Moir (1989)		The present study		Type or reference section
	Base (m)	Top (m)	Base (m)	Top (m)	
Saglek Fm	472	401	--	--	None
Mokami Fm	1275	472	1280.2	577.9	None
Kenamu Fm (Leif Mb)	1360	1280	1360.0	1280.2	None
Kenamu Fm	1713	1275	1713.0	1280.2	Reference section from 1713–1275 m of McWhae et al. (1980) is modified to 1713.0–1280.2 m
Gudrid Fm (upper)	1763	1713	1755.7	1713.0	Reference section from 1763–1713 m of McWhae et al. (1980) is modified to 1755.7–1713.0 m
Cartwright Fm	1795	1763	1795.8	1755.7	None
Gudrid Fm (lower)	1857	1795	1856.9	1795.8	Reference section from 1857–1795 m of McWhae et al. (1980) is modified to 1856.9–1795.8 m
Markland Fm	1910	1857	1909.9	1856.9	None
Unnamed Precambrian	1927	1910	1927.0	1909.9	None

Table 6: Lithostratigraphic assignment for Cartier D-70 from the present study and compared to that of Moir (1989). Fm=Formation; Mb=Member.

CORTE REAL P-85

Within the Hopedale Basin, Corte Real P-85 is located farther basinward on the shelf relative to nearby wells. The 1983 well history report for Corte Real P-85 (Steeves, 1983a) includes descriptions of rock cuttings from 3946–770 m. First drilled in 1981, the well was re-entered the following three years, with a further well history report produced in the final year (Steeves, 1984) that includes descriptions of rock cuttings from 4550–3946 m and from sidetrack #1 (4389–4040 m), as well as sidewall core descriptions from sidetrack #1 (at various depths between 4315 m and 3949 m). These descriptions, as well as the Petro-Canada Corte Real P-85 log (log EC-207) from Canadian Stratigraphic Service Ltd., which provides lithological, grain size, grain rounding, and sample descriptions, were used in developing the interval descriptions for this well. In the well plot for Corte Real P-85 shown in Figure 7, key well logs, lithology, grain size, rock colour, ages, and paleoenvironmental and lithostratigraphic information are depicted. The age assignments in the descriptions below are based on Williams (2017a). A summary of the paleoenvironments determined in the present study are provided in Table 7, and these settings are compared below with those of Miller and D'Eon (1987) and the palynological interpretations of Williams (2017a). The lithostratigraphy from Moir (1989) and the present study are shown in Figure 7 and documented in Table 8.

Base (m)	Top (m)	Paleoenvironment
4550	4042	OUTER SHELF
4042	3727	MIDDLE SHELF
3727	3518	INNER SHELF
3518	3233	OUTER SHELF
3233	2332	MIDDLE SHELF
2332	1798	INNER SHELF
1798	1453	MIDDLE SHELF
1453	1157	PRODELTA
1157	1092	DELTA FRONT
1092	1007	PRODELTA
1007	876	DELTA FRONT
876	849	PRODELTA
849	775	DELTA FRONT

Table 7: Paleoenvironmental determinations for Corte Real P-85 from the present study.

Outer shelf

At the base of Corte Real P-85, the interval from 4550 m to 4042 m comprises dark grey and brown shale with rare siltstone beds and limestone and marlstone near the top of the interval. The shale is mostly dark grey, silty, and micro-micaceous, with locally common fossil fragments (foraminifera and cephalopod, ostracod, echinoid and indeterminate shell material), carbonaceous flakes scattered throughout, rare limestone stringers, rare siderite, rare coal fragments, rare pyrite, and rare pyritized trace fossils. Siltstones are dark brown, argillaceous, slightly sandy, and contain trace carbonaceous flakes and rare coal fragments. Near the top of the interval, limestones and marlstones are brown, hard, silty, and argillaceous. Also reported in sidewall core are rounded, coarse shale and limestone clasts in a siltstone matrix (Steeves, 1984).

The silty nature of the shale indicates shelfal water depths and some distance from the shoreline, but normal marine conditions are indicated by the diversity of fossil material. Carbonaceous flakes suggest some terrigenous influx, but the overall lithology is consistent with outer shelf deposition. This type of setting is also typical for the onset of Kenamu Formation, which reflects a transgression onto the margin (Dickie et al., 2011; Dafoe, Dickie et al., in press). This outer shelf interpretation, however, contrasts with that of Miller and D'Eon (1987), which was reported as bathyal (with turbidites) or possibly abyssal. Williams (2017a), however, reported deeper-water, open ocean conditions that could be considered consistent with the outer shelf. Furthermore, the presence of shale and limestone clasts near the top of the interval could be explained by the deformation related to major fault structures (Balkwill and McMillan, 1990; Dickie et al., 2011; Dafoe, Dickie et al., in press). At the base of the well, this interval lies within the Kenamu Formation, with an age according to Williams (2017a) of Ypresian (Early Eocene) to earliest Lutetian (Middle Eocene), in good agreement with the age determination of Fenton and Pardon (2007).

Middle shelf

From 4042 m to 3727 m, the section is characterized by brown-grey shale or claystone with occasional sandstone, siltstone, and limestone beds. The shale is silty throughout, locally sandy (increasingly upwards), and micro-micaceous, and contains siltstone lenses, carbonaceous flakes throughout, scattered fossil fragments (foraminifera, ostracod, echinoid, and indeterminate shell material), rare sandstone lenses, rare coal stringers, rare pyritized trace fossils, rare glauconite, and rare pyrite. Rare sandstone beds are brown, very fine-grained, well sorted, argillaceous, slightly siliceous, and slightly calcareous, with subangular grains and chert. Brown, silty limestone and grey, sandy, argillaceous siltstones, with carbonaceous flakes are also locally present.

The overall increase in sand grains relative to the underlying interval, as well as increased carbonaceous flakes and the presence of rare coal fragments suggests increased proximity to the shoreline, reflecting shallowing to a middle shelf setting. The moderately diverse fossil assemblage further supports this interpretation. Again, there is reasonable correlation to Williams' (2017a) far offshore setting, but Miller and D'Eon (1987) place this section of the well in a bathyal setting in contrast to the evidence outlined above. Based on the lithostratigraphic picks of Moir (1989) and the present study, this interval falls within the Kenamu Formation, with an early Lutetian (Early Eocene) age (Williams, 2017a), similar to the findings of Fenton and Pardon (2007).

Inner shelf

The interval between 3727 m and 3518 m is composed of sandy claystone, with siltstone and sandstone beds. Brown, sandy, silty claystone includes localized carbonaceous flakes, localized fossil fragments (foraminifera, echinoid, and indeterminate shell material), sandstone stringers, siltstone stringers, and rare shale horizons. Light brown to white sandstone that is very fine-grained, calcareous, argillaceous, silty, and well sorted is also present and contains mica flakes and subangular grains. Siltstone beds are brown and sandy.

The increase in sand content and sandstone units compared to underlying strata suggests shallowing to an inner shelf paleoenvironment. A normal marine setting is supported by a moderately diverse fossil suite, and carbonaceous flakes indicate continued terrigenous influx and relative shoreline proximity. The settings interpreted by Williams (2017a) and Miller and D'Eon (1987) are deeper-water, open ocean or bathyal, respectively. These interpretations are not consistent with the findings from the present study, nor with the typical uppermost section of the Kenamu Formation that shows progradation, with local development of Leif Member shoreline sandstones (Balkwill and McMillan, 1990; Dafoe, Dickie et al., in press). This interval in the well belongs to the Kenamu Formation, and is Lutetian (Middle Eocene) in age as determined by Williams (2017a), with Fenton and Pardon reporting a similar Lutetian–Bartonian (Middle Eocene) age.

Middle shelf

Shale with siltstone, limestone, and rare sandstone beds is prevalent from 3518 m to 3379 m. The shale is brown, silty, locally sandy, and soft, with siltstone stringers, scattered carbonaceous flakes, scattered fossil fragments throughout (echinoderm, foraminifera, and indeterminate shell material), rare glauconite, and rare dark chert grains. Slightly sandy, grey, argillaceous, and micaceous siltstones are also present, as well as brown-grey, argillaceous, and silty sandstone. Rare brown, argillaceous, slightly silty limestone beds also occur.

The generally fine-grained nature of the rock, with some sand content, moderate fossil diversity, and scattered carbonaceous material is interpreted to reflect a return to middle shelf conditions. Conversely, both Williams (2017a) and Miller and D'Eon (1987) proposed deeper-marine settings: open ocean and bathyal, respectively that are inconsistent with the lithological evidence presented above. Encompassing the uppermost part of the Kenamu Formation, this interval is Lutetian (Middle Eocene) according to Williams (2017a), but the Lutetian–Bartonian (Middle Eocene) age proposed by Fenton and Pardon (2007) is more consistent with the presumed top of the Kenamu Formation based on regional studies (Dickie et al., 2011; Dafoe, Dickie et al., in press). Upturning and deformation of strata related to major fault structures in the region of Corte Real P-85 (Dickie et al., 2011) may have complicated biostratigraphic results for the Kenamu Formation. Regardless, the lithostratigraphic designation of Moir (1989) is retained in the present study (Table 8).

Outer shelf

Spanning the depths of 3379 m to 3272 m is a succession of shale with rare siltstone and limestone units. Dark grey shale is silty, with scattered fossil material (foraminifera and indeterminate shell debris), rare mica, rare carbonaceous flakes, and rare glauconite. Brown slightly sandy and argillaceous siltstones and rare argillaceous, silty limestones are also present.

The decrease in sand content and fossil abundance and diversity relative to the underlying interval suggests outer shelf conditions well beyond the shoreline, similar to the deeper-water, open ocean interpretation of Williams (2017a). Miller and D'Eon (1987), however, proposed a bathyal setting, suggesting even deeper marine conditions. Regardless of the precise depositional setting, marine flooding at the base of the Mokami Formation is consistent with established frameworks (Dickie et al., 2011; Dafoe, Dickie et al., in press). The age of this succession is Lutetian (Middle Eocene) according to Williams (2017a), but is most likely younger, ranging into the Bartonian (Middle Eocene), according to Fenton and Pardon (2007), an age that is in better agreement with the regional stratigraphic frameworks (Dickie et al., 2011; Dafoe, Dickie et al., in press).

Middle shelf

From 3272 m to 2332 m depth, shale transitions to claystone and contains abundant siltstone and lesser limestone and marlstone units. The shales are dark grey-brown, silty throughout, with siltstone beds scattered throughout, common carbonaceous flakes, fossil fragments scattered to common in places (echinoderm, arenaceous and agglutinated foraminifera, and indeterminate shell material), rare pyrite, rare very fine-grained sand grains, rare glauconite, rare siderite, rare dark chert at the top of the interval, and rare quartz pebbles or very coarse-grained sand grains. The dark brown, argillaceous, sandy siltstones include common carbonaceous flakes, micaceous flakes, and rare indeterminate fossil debris. Limestones and marlstones are brown and silty, with rare pyrite.

This interval becomes sandier upward, suggesting progressive shallowing. The fossil content and silty nature of the strata is interpreted to reflect a normal marine, middle shelf setting, which is further confirmed by the degree of terrigenous detritus indicating a reasonably proximity to the shoreline. This interpretation is comparable with the neritic setting of Williams (2017a), but not the bathyal and open ocean settings suggested by the same author and with the bathyal depths proposed by Miller and D'Eon (1987). The fossil content does not appear to be consistent with such deep-marine settings.

This thick interval comprises part of the Mokami Formation and is Lutetian–Bartonian (Middle Eocene) according to Williams (2017a). However, as with the underlying interval, these ages are inconsistent with the Mokami Formation as reported in regional studies (Dickie et al., 2011; Dafoe, Dickie et al., in press) in which it is considered to be late Bartonian (Middle Eocene) and younger. Whereas some authors give similar ages (e.g. Bujak Davies Group, 1987b), others provide younger Middle to Late Eocene to Early Oligocene ages for this same interval (LaBorde and Jenkins, 1983a, b; Fenton and Pardon, 2007), the latter of which is preferred in the present study. The Eocene section is exceptionally thick in this well, and major fault structures at the well location may have disrupted strata such that biostratigraphic assemblages are mixed or difficult to discern.

Inner shelf

Sandy claystone with sandstone, siltstone, and limestone beds dominates the well between 2332 m to 1798 m. Brown, silty, sandy claystone is further characterized by siltstone stringers, sandstone stringers, scattered carbonaceous flakes, scattered dark chert grains, rare fossil fragments (echinoderm, indeterminate shell material, and foraminifera), rare very coarse-grained sand grains, rare mica, rare pyritized trace fossils, and other rare ichnofossils. Sandstones are light brown, very fine-grained, well sorted, calcareous, argillaceous, and glauconitic, with common dark chert grains and subangular grains. The dark brown limestones are argillaceous and sandy, and contain rare glauconite. Notably, glauconite is present at the base and within the upper half of the interval.

The heterolithic character, sandstone content, and fossil assemblage are representative of an inner shelf paleoenvironment. Compared to the underlying interval, this interval reflects increased proximity to the shoreline. Williams (2017a) suggested a more generalized neritic setting that is reasonably compatible with the present study, but Miller and D'Eon (1987) found a possible bathyal setting with distal turbidite fan accumulations. The present study shows no evidence of turbidite accumulation or deep-water deposition, as sand content appears to be generally mixed into the claystone rather than defining fining-upward, discrete beds. This sandy claystone interval forms part of the Mokami Formation and is thought to be Bartonian to Priabonian (Middle–Late Eocene), and possibly earliest Rupelian (Early Oligocene; Williams, 2017a). These ages are consistent with Mokami Formation as described by Dafoe, Dickie et al. (in press); however, the interval could also be Oligocene to Early Miocene, as suggested by Fenton and Pardon (2007).

Middle shelf

Between the depths of 1798 m and 1453 m is an interval dominated by claystone, with rare sandstone, siltstone, and limestone beds. The brown claystones are, silty, partly sandy to sandy in the upper half of the interval, with scattered fossil fragments (arenaceous foraminifera, calcareous foraminifera, indeterminate shell material, echinoid), scattered carbonaceous flakes, mica flakes, rare pyrite, rare glauconite, rare siltstone and sandstone stringers, rare pyritized ichnofossils, and rare dark chert grains. Also present is brown, sandy, argillaceous siltstone and white or brown, very fine-grained, well sorted, silty sandstone that includes subangular grains and rare very coarse-grained sand grains. Sandy, silty, argillaceous brown limestone is further locally present.

Similar to some of the underlying intervals, the silt and sand content, fossil assemblage, and scattered carbonaceous material indicates a return to middle shelf deposition. This setting is comparable to Williams' (2017a) shallowing upwards neritic interpretation, but shallower than the outer shelf to bathyal settings proposed by Miller and D'Eon (1987). These latter authors further suggested a possible prodeltaic setting, which is, however, comparable with the present study. This claystone interval is Rupelian (Early Oligocene), (?)Burdigalian (Early Miocene) and Middle Miocene (Williams, 2017a) and forms part of the Mokami Formation. Missing section is implied by the above ages, but there is no lithological evidence for this, and Fenton and Pardon (2007) reported a Late Oligocene–Early Miocene age for part of the interval.

Prodelta

A brown-grey claystone with interbedded sandstone interval occurs between 1453 m and 1157 m. The brown-grey claystone is sandy and silty throughout, with sandstone stringers, mica, scattered chert grains, scattered quartz pebbles, scattered carbonaceous flakes, and rare fossil fragments (bivalve and foraminifera). In contrast, sandstones are white to light grey, argillaceous, fine- to coarse-grained, and moderately to well sorted. The sandstones also include chert grains, very coarse-grained sand grains, and clasts are subrounded to rounded.

The grain rounding suggests reworking of material and some degree of shoreline proximity. This, combined with the predominance of claystone, thinly bedded nature of the sandstones, and reduced diversity of fossils implies a brackish, prodeltaic paleoenvironment. This interpretation is similar to Williams' (2017a) shallowing-upward neritic setting and the inner to middle shelf setting of Miller and D'Eon (1987), which further included a suggestion of prodeltaic conditions. The age of this interval is Middle Miocene (Williams, 2017a), and it forms the uppermost part of the Mokami Formation preserved in the well. In the present study, the top of the Mokami Formation is defined at 1158 m, where the lithology changes from claystone- to sandstone-dominated. In contrast, Moir (1989) brought the base of the Saglek Formation down to 1355 m, within this claystone succession. Based on the present interpretation, the Mokami Formation extends from 3379–1157 m (Table 8).

Delta front

In the interval from 1157 m to 1092 m is a succession of heterolithic sandstone and lesser claystone. The sandstones are light grey to white, fine- to coarse-grained, argillaceous, and well to moderately sorted. They further contain scattered dark chert grains, very coarse-grained sand grains throughout, pebbles at top of the interval, light coloured chert, and subrounded to rounded clasts. Brown-grey, sandy, silty claystone contains rare fossil fragments (bivalve) and rare pyrite.

The sandstone-dominated, roughly cleaning- and coarsening-upward, but heterolithic nature of the strata is consistent with delta front deposition. The lack of abundance and diversity of fossil material further supports a brackish setting. However, in seismic data, Dickie et al. (2011) show these sandstones to form a channelized sequence at this well location. Perhaps reworking of pre-existing clinoforms, also shown by these authors, could explain the deltaic character interpreted in the present study. The present interpretation is slightly shallower than the neritic and inner to middle shelf settings interpreted by Miller and D'Eon (1987) and Williams (2017a), but deltaic conditions were also postulated by the former authors. Williams (2017a) found this section of the well to be Middle–Late Miocene in age. In the present study, this interval characterizes the base of the Saglek Formation and is consistent with the shoreline proximal facies seen in other wells of the Labrador Shelf (McWhae et al., 1980; Balkwill and McMillan, 1990).

Prodelta

The interval between 1092 m and 1007 m is predominantly claystone with lesser sandstone beds. The brown-grey claystone is sandy and silty, with coarse-grained sandstone stringers, mica flakes, locally common fossil fragments (bivalve), scattered very coarse-grained sand grains, scattered carbonaceous flakes, and scattered chert grains. Light grey, fine- to medium-grained, well to moderately sorted, argillaceous sandstone beds contain coarse mica flakes, chert grains, and subangular to subrounded grains.

The dominance of claystone, with low diversity of fossil fragments and coarse detritus suggests a return to prodeltaic deposition. Again, this setting is in agreement with the neritic and inner to middle shelf (deltaic) interpretations of Williams (2017a) and Miller and D'Eon (1987), respectively. Located near the base of the Saglek Formation, this interval is Pliocene in age (Williams, 2017a).

Delta front

From 1007 m to 876 m in Corte Real P-85 is an interval characterized by heterolithic sandstone and lesser claystone. The light grey sandstone is fine- to coarse-grained, argillaceous, silty, and well to moderately sorted. The sandstone beds also include very coarse-grained sand throughout, coarse mica flakes, scattered light and dark chert, subrounded to rounded grains, scattered white quartz pebbles (especially near the top of the interval), rare glauconite, rare fossil fragments (bivalve), and rare feldspar. Grey, sandy, silty claystone is also present and includes rare carbonaceous flakes and rare fossil fragments (bivalve). While there are no well logs for this part of the well, the grain size measurements indicate an overall coarsening-upward succession (Fig. 7).

The overall coarsening-upward nature of the strata, heterolithic character, and low fossil diversity suggests a return to a delta front paleoenvironment. This interpretation agrees well with that of Miller and D'Eon (1987), but is perhaps shallower than the generalized neritic setting identified by Williams (2017a). The age of this interval of the Saglek Formation is Pliocene according to Williams (2017a).

Prodelta

Another claystone-dominated interval with lesser sandstone beds is present between 876 m and 849 m. Claystones are grey, sandy, and silty, with coarse mica flakes, common fossil fragments (bivalve), scattered pebbles, and rare carbonaceous flakes. Fine- to medium-grained sandstones are light grey, argillaceous, and well to moderately sorted. The sandstones also contain chert grains and subangular to subrounded grains.

The claystone-dominated nature of the strata, combined with the abundance of bivalve fragments (a low diversity suite typical of brackish conditions) and coarse-grained detritus suggests prodeltaic deposition. The inner shelf (deltaic) interpretation of Miller and D'Eon (1987) is similar, as is the neritic, shallowing upward interpretation of Williams (2017a). This section is near the top of the Saglek Formation and is of Pliocene age according to Williams (2017a).

Delta front

The uppermost interval in Corte Real P-85, 849–775 m is characterized by sandstone with rare limestone and claystone. White to light grey, fine- to coarse-grained, moderately to well-sorted sandstone further includes subrounded to rounded grains, very coarse-grained sand throughout, scattered fossil fragments (bivalve), scattered mica, scattered pebbles, rare chert grains, rare feldspar, and rare glauconite. Light brown cryptocrystalline limestone is sandy and slightly dolomitic. The claystone beds are grey and sandy, with mica and rare fossil fragments (bivalve and foraminifera).

The coarse-grained nature of the clastic strata, combined with a heterolithic character with a low diversity fossil suite suggests delta front deposition. Again, the lack of fossil diversity is consistent with brackish deposition. As mentioned above, these deltaic interpretations may in fact reflect channelized successions and reworked clinoform deposits. In this well, Moir (1989) extended the Saglek Formation above the top of the lithological data. Here, the formation is restricted to below 774.8 m, which is the top of the cuttings descriptions and it thus ranges from 1157–774.8 m (Table 8). This uppermost interval is also Pliocene in age according to Williams (2017a).

Lithostratigraphy

Based on the above discussion around lithostratigraphic refinements to the framework of Moir (1989) in Corte Real P-85, the lithostratigraphic picks from the present study are summarized in Table 8. There are no type or reference sections documented from this well.

Lithostratigraphic unit	**Moir (1989)**		**The present study**		**Type or reference section**
	Base (m)	**Top (m)**	**Base (m)**	**Top (m)**	
Saglek Fm	1355	600	1157	774.8	None
Mokami Fm	3379	1355	3379	1157	None
Kenamu Fm	4551*	3379	4551	3379	None

Table 8: Lithostratigraphic assignment for Corte Real P-85 from the present study and compared to that of Moir (1989). *Moir (1989) did not report a base to the Kenamu Formation, but it is assumed here to be at the base of the well (4551 m). Fm=Formation.

FREYDIS B-87

The most southerly well in the Hopedale Basin is Freydis B-87 (Fig. 1). The Plé and Ferrero (1976) well history report for this well includes descriptions of rock cuttings and sidewall cores that were utilized in this study. The Canadian Stratigraphic Service Ltd. Eastcan et al Freydis B-87 log (log EC-109) further contains detailed lithological, grain size, grain rounding, and sample descriptions that were also used to compile the descriptions below. The Freydis B-87 well plot is shown in Figure 8, with key well logs, lithology, grain size, rock colour, ages, and paleoenvironmental and lithostratigraphic information depicted. Age assignments used below are mainly from Williams (1979c), but other biostratigraphic studies are also considered, especially for the upper portion of the well. A summary of the paleoenvironments described below is shown in Table 9, and comparisons are made with previous paleoenvironmental studies by LaBorde et al. (1975) based on micropaleontology and palynology and from Miller and D'Eon's (1987) lithologic results. Moir's (1989) lithostratigraphic assignments, as well as the modified picks from the present study are shown in Figure 8 and Table 10.

The unnamed Paleozoic basement interval at the base of Freydis B-87 remains unchanged from the assignment of Moir (1989; 2314–1905 m; Table 10).

Base (m)	Top (m)	Paleoenvironment
1905.0	1788.3	DELTAIC
1788.3	1731.3	SHOREFACE
1731.3	1691.7	MIDDLE SHELF
1691.7	1615.5	OUTER SHELF
1615.5	1493.5	SLOPE
1493.5	1469.2	SHOREFACE
1469.2	1421.9	INNER SHELF
1421.9	1387.8	SHOREFACE
1387.8	1188.7	UPPER SLOPE
1188.7	1063.8	OUTER SHELF
1063.8	944.9	MIDDLE SHELF
944.9	908.9	(?)INNER SHELF
908.9	731.5	MIDDLE SHELF
731.5	473.7	INNER SHELF
473.7	451.1	SHOREFACE

Table 9: Paleoenvironmental determinations for Freydis B-87 from the present study.

Deltaic

A heterolithic claystone, sandstone, lesser siltstone, and rare limestone unit extends from 1905.0 to 1788.3 m (6250–5867 ft.) in the well. The gamma-ray log shows some coarsening-upward units, but the log character is mostly ragged with an overall decrease in grain size upwards (Fig. 8). The claystone at the base of the interval is yellow-brown, silty, and partly sandy, with rare glauconite. Much of the interval is composed of silty, grey, partly sandy shale containing rare glauconite and rare coal stringers. The white to light brown sandstone is fine- to medium-grained, moderately to well sorted, silty, argillaceous, and glauconitic. The sandstone further contains subrounded grains, rare feldspar, rare pyrite, rare carbonaceous flakes, and rare quartz granules near the top of the interval. Siltstone beds are buff, sandy, argillaceous, and friable, and include rare glauconite. Less common limestone units are brown and sandy, with rare glauconite.

The overall lack of fossil content may be consistent with a brackish setting, although the presence of glauconite confirms marine conditions. This, combined with the coarsening-upward nature of units and ragged log character suggests deltaic deposition, possibly alternating between delta front and prodeltaic conditions, with an overall deepening upward trend. This section of the well lies above Paleozoic basement rock and is included in the Bjarni Formation, with much of the upper part of the interval forming the Snorri Member (a finer-grained unit) of that formation. Williams (1979c) found this part of the well to be late Albian to Cenomanian in age, but more recent work suggests that it is confined to the Albian (Fenton and Pardon, 2007; Ainsworth et al., 2016), which is consistent with the lithostratigraphic framework proposed by Dafoe, Dickie et al. (in press). The extents of the Bjarni Formation and Snorri Member, at 1905–1788 m and 1875–1788 m, respectively, are unchanged from the work of Moir (Table 10).

Shoreface

The interval from 1788.3 m to 1731.3 m (5867–5680 ft.) includes fine- to medium-grained, white sandstone, with moderate sorting, coarse-grained sand grains, quartz granules and pebbles, subrounded grains, glauconite throughout, feldspar throughout, rare limestone, and rare pyrite. Sidewall core results indicate a 'clean' sandstone lacking mud content. The gamma-ray log depicts a relatively blocky (homogeneous) sandstone succession (Fig. 8).

The blocky gamma-ray log signature, dominance of sandstone, and abundance of glauconite suggest a shoreface setting. A lack of fossil fragments could be explained by high-energy conditions and reworking in a proximal (?)upper shoreface setting that inhibited colonization by infaunal organisms. Similar settings were previously proposed, including inner sublittoral (LaBorde et al., 1975) and inner shelf tidal bars and channels (Miller and D'Eon, 1987). This part of the well is included in the Freydis Member of the Markland Formation, but the top is modified from Moir's (1989) original designation to 1731.3 m to better match the lithological and log breaks there (Fig. 8; Table 10). This refines the type section for the Freydis Member to 1788–1731.3 m, building on the original work of Moir (1989), McWhae et al. (1980), and Umpleby (1979). Williams (1979c) gave a Coniacian age for this part of the well, which was supported by Fenton and Pardon (2007), but Ainsworth et al. (2016) gave the age as Coniacian to early Santonian.

Middle shelf

Claystone with limestone interbeds occurs from 1731.3 m to 1691.7 m (5680–5550 ft.). The claystone is grey, silty, sandy, and calcareous, with glauconite throughout, limestone stringers, and rare pyrite. Dark brown limestone beds are argillaceous and sandy.

The overall sandy and calcareous nature of the claystone suggests a middle shelf setting. The lack of fossil material is atypical and could be explained by the transgressive nature of the claystone over the underlying proximal shoreline strata of the Freydis Member. The prevalence of glauconite attests to slow sedimentation rates typical of transgressive deposits (Amorosi, 2003). Previous authors also reported shelfal settings, including inner shelf (Miller and D'Eon, 1987) and inner to outer sublittoral (LaBorde et al., 1975); both are in reasonable agreement with the present study. This interval clearly marks a deepening and a transition from the shoreline facies below to deeper-water facies above. It is assigned to the Markland Formation and is of Santonian age according to Williams (1979c), but may range into the Campanian (Fenton and Pardon, 2007; Ainsworth et al., 2016).

Outer shelf

The interval from 1691.7–1615.5 m (5550–5300 ft.) is composed of grey, silty, rarely sandy shale that includes rare glauconite, rare pyrite, rare glauconitic sandstone stringers, and rare siderite nodules.

Lithologically, the strata are silty with glauconite and siderite formation suggesting periods of low sedimentation rates and reducing conditions (Amorosi, 2003; Scholle and Ulmer-Scholle, 2003). The lack of fossil material is unusual for such a setting, but otherwise the rocks are interpreted to represent distal outer shelf deposition. Perhaps some degree of dysoxia could account for the lack of fossil material. This interval in the well was interpreted to represent similar to slightly deeper settings by Miller and D'Eon (1987; outer shelf to bathyal) and LaBorde et al. (1975; deep outer sublittoral). Regardless, a progressive deepening is evident within the Markland Formation in all studies. This interval belongs to the Markland Formation and is of Campanian to earliest Maastrichtian in age according to Williams (1979c), an age generally corroborated by subsequent studies (Fenton and Pardon, 2007; Ainsworth et al., 2016).

Slope

Between the depths of 1615.5 m and 1493.5 m (5300–4900 ft.), the strata comprise grey, silty shales, with pyrite, rare sand grains, rare glauconite, and rare brown, fine-grained, glauconitic sandstone interbeds.

The characteristic homogeneity of the shale suggests a significant distance from the shoreline in a slope setting. This is supported by the abundance of pyrite, suggesting periods of reducing conditions (Wilkin, 2003), and lack of sand and fossil material. Thin, rare sand interbeds could represent turbidite fan accumulations since they are discrete entities within the section. Previous studies also indicated a distal marine setting of deep outer sublittoral (LaBorde et al., 1975) and outer shelf to bathyal (Miller and D'Eon, 1987) conditions. This part of the well makes up the uppermost part of the Markland Formation, with the upper boundary at 1493.5 m where it corresponds with the lithological, paleoenvironmental, and log changes at that depth. As a result, the reference section of Moir (1989) and McWhae et al. (1980) for the Markland Formation is modified to 1788–1493.5 m (Table 10). The age of this slope interval is Maastrichtian according to Williams (1979c) and Fenton and Pardon (2007), with Selandian (Middle Paleocene; but no Danian) strata further indicated by Ainsworth et al. (2016; Fig. 8).

Shoreface

The strata from 1493.5 m to 1469.2 m (4900–4820 ft.) consist of a thin claystone coarsening upward to a blocky sandstone, as also indicated by the gamma-ray logs (Fig. 8). The grey, silty, sandy claystone contains rare glauconite. The white sandstone is coarse-grained and includes very coarse-grained sand grains, pebbles, a clay matrix, quartz granules and pebbles, feldspar, subrounded to well rounded grains, moderate sorting, pyrite, and rare glauconite.

The blocky gamma-ray log signature and the predominance of coarse-grained sandstone suggests a shoreface paleoenvironment. This interpretation aligns well with that of LaBorde et al. (1975), whom interpreted a shallow inner sublittoral setting, but differs greatly from the outer shelf–(?)bathyal setting with turbidites proposed by Miller and D'Eon (1987). Dafoe and Williams (2020a) indicated that in the Snorri J-90 well the thin Gudrid Formation sandstone was likely overwhelmed by cavings from overlying deeper-water strata, resulting in a skewed paleoenvironmental interpretation there. A similar issue could account for the deep-marine interpretation from the cuttings samples in Freydis B-87.

This thin interval of the well is attributed to the lower Gudrid Formation as delineated in the present study. Moir (1989) picked the top of the formation at 1460 m, but the log character between 1469.2 m and 1460 m suggests a finer-grained, more claystone-dominated succession than is inconsistent with the Gudrid Formation (Fig. 8). The major log break in the gamma-ray, sonic, and resistivity logs at 1469.2 m is the best pick for the top of this part of Gudrid Formation, extending it from 1493.5–1469.2 m (Table 10). A Danian (Early Paleocene) age was assigned by both Williams (1979c) and

Fenton and Pardon (2007), but a Thanetian (Late Paleocene) age was given by Ainsworth et al. (2016), suggesting a variable Paleocene age for the interval.

Inner shelf

The interval from 1469.2 m to 1421.9 m (4820–4665 ft.) represents an interfingering of the Cartwright Formation within the Gudrid (*see* below), which consists of medium to dark grey claystone that is silty and micro-micaceous, with fine- to coarse-grained sand grains, rare limestone stringers, and rare argillaceous siltstone. Lesser sandstone beds occur and are fine- to coarse-grained and moderately sorted, but also include subrounded to well rounded grains, very coarse-grained sand grains, and clear to translucent quartz granules.

Sharp log breaks occur at the base and top of this unit, but the claystone unit is roughly coarsening-upward based on the gamma-ray log (Fig. 8). Despite the fine-grained nature of the rock, the incorporation of sand throughout suggests an inner shelf setting. However, a lack of fossil material implies brackish conditions, and a possible prodeltaic paleoenvironment, with a minor marine flooding surface characterizing the lower boundary. The sandstones below and above this interval, however, are rather blocky suggesting that a shoreface setting for the sandstones and corresponding inner shelf setting for this claystone unit are most likely interpretations. An inner shelf setting for this claystone is shallower than that proposed by others: LaBorde et al. (1975) indicated a deep outer sublittoral setting and Miller and D'Eon (1987) interpreted outer shelf to possible bathyal deposition. There is no evidence to suggest such deep-water settings, and more is now known about the shallow marine nature of the Gudrid Formation which brackets this interval (*see* Dickie et al., 2011; Dafoe, Dickie et al., in press).

This part of Freydis B-87 is correlated to the Cartwright Formation, a thin claystone-dominated succession lying between the lower and upper Gudrid Formation sandstones from 1469.2–1421.9 m (Table 10). The age of the interval is Late Paleocene (Thanetian) according to Williams (1979c) and Ainsworth et al. (2016), with possible early Ypresian (Early Eocene) strata also occurring at the very top of the interval based on the findings of Fenton and Pardon (2007).

Shoreface

The rocks found between 1421.9 m and 1387.8 m (4665–4553 ft.) include coarse-grained, moderately sorted sandstones that contains subrounded to well rounded grains, very coarse-grained sand grains, pebbles, glauconite throughout, clear to translucent quartz granules, limestone stringers, quartz pebbles, and a clay matrix. Similar to the underlying lower Gudrid Formation, the overall gamma-ray log character indicates a coarsening upward trend, but is also blocky.

A coarse-grained and glauconitic sandstone, with a blocky log character is consistent with shoreface deposition in a high-energy setting. The degree of wave action may explain the lack of fossil detritus, but certainly explains the grain rounding. The interpretation in the present study is much shallower than the outer shelf or outer sublittoral settings determined by previous authors (LaBorde et al., 1975; Miller and D'Eon, 1987). As with the lower Gudrid Formation interval, cavings from the overlying deep-water succession could have mislead interpretations of this interval. Forming the upper Gudrid Formation as defined in the present study, the base is modified from that indicated by Moir (1989) to 1421.9 m (Fig. 8; Table 10). This interval is Ypresian (Early Eocene) according to Williams (1979c) and Fenton and Pardon (2007), but could also range into the Thanetian (Late Paleocene) according to Ainsworth et al. (2016).

Upper slope

Claystone with occasional limestone interbeds occurs in the interval from 1387.8 m to 1188.7 m (4553–3900 ft.). The medium to dark brown claystone is slightly silty, with limestone stringers. Limestone interbeds are brown, argillaceous, and dense.

The overall calcareous nature of the claystone and lack of silt and sand suggests a paleoenvironment near the shelf edge, but more likely in an uppermost slope setting. A lack of fossil material is consistent with such a distal marine setting. The present interpretation is similar to the outer sublittoral setting proposed by LaBorde et al. (1975) and bathyal paleoenvironment of Miller and D'Eon (1987). This interval is in contrast to the underlying Gudrid Formation and represents the transgression associated with the base of the Kenamu Formation (Balkwill and McMillan, 1990; Dickie et al., 2011; Dafoe, Dickie et al., in press). The rocks are Early to Late Eocene according to Williams (1979c), but are most likely no younger than Middle Eocene (Fenton and Pardon, 2007; Ainsworth et al., 2016).

Outer shelf

In the interval spanning 1188.7 m to 1063.8 m (3900–3490 ft.), the strata are composed of claystone with limestone and siltstone interbeds. Claystones are medium to dark brown, silty, and locally sandy, and contain occasional fossil fragments (foraminifera and gastropod), occasional siltstone stringers, and rare limestone stringers. Dark brown limestones interbeds are argillaceous and silty.

The dominance of claystone and increase in silt and sand content upwards suggests some degree of shallowing over time. The lithology, combined with the fossil suite and presence of limestone stringers is consistent with an outer shelf setting. This is similar to the outer to inner sublittoral interpretation of LaBorde et al. (1975) and the outer shelf to bathyal setting proposed by Miller and D'Eon (1987).

This interval is part of the Kenamu Formation and is Late Eocene to Early Oligocene according to Williams (1979c). However, according to Ainsworth et al. (2016) it is Lutetian–Bartonian and similarly considered Middle Eocene by Fenton and Pardon (2007). Variation in age determinations at this level and above in the well (Fig. 8) may reflect factors such as reworking or caving. An Oligocene age is inconsistent with the proposed age of the Kenamu Formation (*see* Dafoe, Dickie et al., in press), and is discussed further below.

Middle shelf

Claystone with limestone, siltstone, and sandstone interbeds characterizes the interval from 1063.8 m to 944.9 m (3490–3100 ft.). Claystones are brown, silty, sandy, and partly calcareous, with locally common fossil fragments (foraminifera) and siltstone stringers. The sandstone units scattered throughout the claystone are brown, very fine- to fine-grained, calcareous, and well sorted, and further contain argillaceous and subrounded grains. Less common siltstones are brown, sandy, and argillaceous; and brown, sandy limestone beds are rare. The gamma-ray log shows decreasing values upward (Fig. 8), suggesting the presence of sandier strata; but this is not seen in the grain-size data, and the character of the log is overall ragged.

The increase in sand and silt content relative the underlying interval indicates upward shallowing. The prevalence of sandstone beds, in particular, seems to indicate a middle shelf paleoenvironment, but the limited fossil assemblage is atypical, possibly indicating storm-dominated conditions, which could explain the relatively ragged gamma-ray profile resulting from alternating fair-weather and storm beds. The present interpretation compares well with the inner sublittoral and inner shelf settings of previous authors (LaBorde et al., 1975; Miller and D'Eon, 1987).

This interval is near the top of the Kenamu Formation as defined herein, and is likely of Eocene age (Fenton and Pardon, 2007), but could be Early Oligocene (Rupelian; Ainsworth et al., 2016) or even younger (Williams, 1979c). The latter ages are inconsistent with the generally accepted age of the Kenamu Formation, which Dickie et al. (2011) and Dafoe, Dickie et al. (in press) suggested to be no younger than late Bartonian.

(?)Inner shelf

There was poor cuttings recovery in the interval from 944.9 m to 908.9 m (3100–2982 ft.), in which claystone with sandstone stringers dominate. However, the gamma-ray log indicates moderate API values and a relatively sandy succession relative to that shown on the Canstrat lithology log. Claystones recorded from this interval are medium to dark brown, silty, argillaceous, and sandy, with both limestone and sandstone stringers.

While the cuttings information for this interval are limited, the overall log character and evidence of a sandier succession suggest a plausible inner shelf succession, perhaps just seaward of a typical Leif Member sandstone. In comparison to other paleoenvironmental studies, the setting is in agreement with the inner sublittoral and inner shelf settings of LaBorde et al. (1975) and Miller and D'Eon (1987), respectively.

Based on the present study, this interval forms the top of the Kenamu Formation, but the sandstone-dominated Leif Member is not present (Table 10). The overlying interval appears to indicate a deepening event, which is typical for the transition between the Kenamu and Mokami formations (Dickie et al., 2011; Dafoe, Dickie et al., in press). The log signature further indicates a change from low to high gamma-ray, but the sonic and resistivity logs show increases rather than the decreases typically seen at this lithostratigraphic boundary (Fig. 8). Perhaps the extent of carbonates around this transition makes the log character atypical. As was the situation for some of the underlying intervals, there appears to be significant spread of ages that are generally younger than the Bartonian age for the top Kenamu Formation as indicated by Dickie et al. (2011) and Dafoe, Dickie et al. (in press): Gradstein, (1976) and Williams (1979c) determined an Early Miocene age and Fenton and Pardon (2007) and Ainsworth et al. (2016) gave a Middle Eocene to early Rupelian (Early Oligocene) age. However, the log character and nature of shallowing depositional environments is consistent with an interval in the Kenamu Formation. In contrast to Moir (1989), the top of the Kenamu Formation is here placed at 908.9 m rather than 860 m, as the former depth marks a deepening in the paleoenvironment consistent with the Mokami Formation transgression. Thus, the Kenamu Formation extends from 1387–908.9 m (Table 10).

Middle shelf

The interval from 908.9 m to 731.5 m (2982–2400 ft.) consists of claystone with limestone, siltstone, and sandstone interbeds. The claystones are brown, silty, sandy, and slightly micaceous, and contain common fossil fragments throughout (indeterminate shell material, bivalve, and foraminifera) and limestone stringers. Brown, sandy, argillaceous siltstones are less common, as is dark brown, argillaceous, silty, dense limestones. Rare sandstone beds are fine-grained, well sorted, silty, and loosely consolidated, with subangular grains

Based on the increase in the gamma-ray log signature relative to the underlying interval, the dominance of claystone, but the prevalence of silt and sand content, the setting is interpreted as middle shelf. The fossil suite and dominance of shell material is consistent with a middle shelf interpretation. This is, however, slightly deeper than the inner shelf (Miller and D'Eon, 1987) to inner or shallow inner sublittoral settings (LaBorde et al., 1975) previously proposed. The Canstrat log points to a definite decrease in sand content at the base of this interval, so it would appear that there is at least slight deepening.

In the present study, this interval lies at the base of the Mokami Formation and is likely Middle Eocene to Rupelian (Early Oligocene) as suggested by Fenton and Pardon (2007) and Ainsworth et al. (2016); the age framework of Williams (1979c) indicates a much younger age than seen in other Mokami Formation intervals in Labrador Shelf wells (*see* Dafoe, Dickie et al., in press).

Inner shelf

The strata between the depths of 731.5 m and 473.7 m (2400–1554 ft.) are composed of claystone with sandstone, siltstone, and limestone interbeds. The medium to dark brown, silty, very sandy, slightly calcareous, and slightly micaceous claystone contains abundant fossil fragments throughout (foraminifera, bivalve, gastropod, (?)*Orthoceras*, and indeterminate shell material), rare pyrite, and rare lignite. Sandstones are brown, argillaceous, silty, and fine- to medium-grained near the top of the interval, with subangular grains, moderate sorting, and bivalve shell fragments present. Siltstones are brown, sandy, and argillaceous, with dark brown, dense, argillaceous, and silty limestones containing rare sand grains.

The dominance of claystone with a high proportion of sand content and diverse fossil assemblage suggests a normal marine, inner shelf paleoenvironment. This interpretation agrees with that of Miller and D'Eon (1987), and the shallow inner sublittoral setting of LaBorde et al. (1975). The lithostratigraphic pick for the Mokami Formation is modified in the present study from that of Moir (1989) to span 908.9–473.7 m (Table 10). This inner shelf interval has been dated as Oligocene to Plio-Pleistocene (Gradstein, 1976a; Williams, 1979c; Fenton and Pardon, 2007; Ainsworth et al., 2016). However, based on the regional framework (Dafoe, Dickie et al., in press), a Plio-Pleistocene age is unlikely for this section in Freydis B-87; an Oligocene age would be more reasonable.

Shoreface

At the top of Freydis B-87, the interval spanning 473.7 m to 451.1 m (1554–480 ft.) consists of interbedded conglomerate and claystone. The conglomerate is characterized by white quartz pebbles, igneous pebbles, and a clay matrix, with subrounded grains, moderate sorting, bivalve shell fragments, and rare pyrite. The brown, silty, sandy, calcareous claystone beds contain bivalve and gastropod fragments, and brown siltstones and sandstones are rare.

The coarse-grained lithology is consistent with a high-energy setting, and the presence of a limited fossil assemblage is typical of a shoreline proximal setting where the energy and sedimentation rate deter extensive infaunal colonization. The presence of interbedded claystones is atypical and may indicate fluctuations in the depositional setting, but a shoreface paleoenvironment is envisioned here, perhaps ranging into the lower shoreface. The interpretation from the present study aligns well with the inner shelf to marginal marine (delta front, shoreface, upper offshore) interpretation of Miller and D'Eon (1987) and the shallow inner sublittoral setting of LaBorde et al. (1975). This short interval represents the Saglek Formation in the well, with the lithostratigraphic pick modified from that of Moir (1989) to include the extent of coarse-grained strata as indicated by the gamma-ray log signature up to 433.3 m (Figure 8; Table 10). The age is likely Chattian (Late Oligocene)–Burdigalian (Early Miocene; Ainsworth et al., 2016) based on the logic presented for underlying intervals.

Lithostratigraphy

Based on the above discussion around lithostratigraphic refinements to the framework of Moir (1989) in Freydis B-87, the lithostratigraphic picks from the present study are summarized in Table 10. Related modifications to reference and type sections are also indicated.

Lithostratigraphic unit	Moir (1989)		The present study		Type or reference section
	Base (m)	Top (m)	Base (m)	Top (m)	
Saglek Fm	489	230	473.7	433.3	None
Mokami Fm	860	489	908.9	473.7	None
Kenamu Fm (Leif Mb)	996	910	--	--	None
Kenamu Fm	1387	860	1387	908.9	None
Gudrid Fm (upper)	1420	1387	1421.9	1387	None
Cartwright Fm	1460	1420	1469.2	1421.9	None
Gudrid Fm (lower)	1492	1460	1493.5	1469.2	None
Markland Fm	1788	1492	1788	1493.5	Reference section from 1875–1492 m of McWhae et al. (1980) and 1788–1492 m of Moir (1989) is modified to 1788–1493.5 m
Markland Fm (Freydis Mb)	1788	1730	1788	1731.3	Type section from 1789–1734 m of Umpleby (1979), 1875–1731 m of McWhae et al. (1980), and 1788–1730 m of Moir (1989) is modified to 1788–1731.3 m
Bjarni Fm (Snorri Mb)	1875	1788	1875	1788	None
Bjarni Fm	1905	1788	1905	1788	None
Unnamed Paleozoic	2314	1905	2314	1905	None

Table 10: Lithostratigraphic assignment for Freydis B-87 from the present study and compared to that of Moir (1989). Fm=Formation; Mb=Member.

GILBERT F-53

For the Gilbert F-53 well, found in the southern portion of the Saglek Basin (Fig. 1), the well history report by Dungan (1980a) provides descriptions of conventional cores, cuttings, and sidewall cores. In addition, the Canadian Stratigraphic Service Ltd. Total Gilbert F-53 log (log EC-146) contains detailed lithological, grain size, grain rounding, and sample descriptions for the well. These data sources were used to compile the below descriptions for the well, in addition to conventional core descriptions from Dafoe and Williams (2020a) that provide key information on parts of the Freydis Member of the Markland Formation. Figure 9 shows data for Gilbert F-53, including key well logs, lithology, grain size, rock colour, ages, and paleoenvironmental and lithostratigraphic information. The ages determined by Nøhr-Hansen et al. (2016) are used in the present study. A summary of the paleoenvironments described below is shown in Table 11. In addition, the descriptions below make comparisons with previous depositional settings determined by Miller and D'Eon (1987) and Williams (2007f), the latter from palynological analyses. Minor revisions to the lithostratigraphic assignments of Moir (1989) are also presented below and shown in Figure 9 and Table 12.

The lowermost part of Gilbert F-53 from 3608–3550 m consists of an unnamed Precambrian basement rock (Table 12).

Base (m)	Top (m)	Paleoenvironment
3550	3498	DELTA FRONT
3498	3468	PRODELTA
3468	3399	DELTA FRONT TO DISTRIBUTARY CHANNEL
3399	3272	PRODELTA
3272	3195	DELTA FRONT TO DISTRIBUTARY CHANNEL
3195	3111	PRODELTA
3111	3040	MIDDLE TO OUTER SHELF
3040	2990	SLOPE
2990	2410	OUTER SHELF
2410	2301	PRODELTA
2301	1740	OUTER SHELF
1740	1527	MIDDLE SHELF
1527	1476	OUTER SHELF
1476	1314	PRODELTA
1314	1163	DELTA FRONT AND PRODELTA
1163	1052	DELTA FRONT
1052	873	PRODELTA
873	525	DELTA FRONT OR SHOREFACE

Table 11: Paleoenvironmental determinations for Gilbert F-53 from the present study.

Delta front

The interval lying above basement rock, between 3550 m to 3498 m, consists of interbedded sandstone and shale. The dark grey to black shale is sandy, with sandstone stringers and rare pyrite. The grey to white sandstone is very fine- to fine-grained, silty, well sorted, and calcareous, with subangular grains and muscovite. Brown-grey, sandy, argillaceous siltstone is found at the top of the interval.

Accordingly, the gamma-ray log shows a heterolithic, but overall coarsening-upward and cleaning-upward interval (Fig. 9).

The heterolithic nature of the succession, gamma-ray log character, and lack of macrofossil material typical of normal marine settings, suggest a delta front paleoenvironment. Miller and D'Eon (1987) proposed a possible nonmarine paleoenvironment, indicating a lacustrine delta front, and Williams (2007f) confirmed an inner neritic setting based on palynomorphs, in relative agreement with the present study. This interval forms the base of the Freydis Member of the Markland Formation and is early–late Campanian (Nøhr-Hansen et al., 2016).

Prodelta

Dark grey, silty shales with sandstone stringers and siltstone stringers are present in the interval from 3498 m to 3468 m.

The association of this shale with the under- and overlying sandstone intervals suggests a prodeltaic paleoenvironment. A lack of fossil content further conforms to brackish depositional conditions rather than normal marine salinity. This interpretation is somewhat in agreement with the inner neritic setting proposed by Williams (2007f) and the marginal marine setting of Miller and D'Eon (1987), but it is unclear why the latter authors indicated lacustrine deposition (Fig. 9).

This thin interval is part of the Freydis Member of the Markland Formation, but is an atypical lithology for the sandstone-dominated member. The cyclical nature of the Markland Formation in Gilbert F-53 (Fig. 9) does not permit clear distinctions between the shale-dominated Markland Formation and sandstone-dominated Freydis Member. The location of this well relative to a fluvial source likely accounts for some of the fluctuations noted in this interval and those above up to 3195 m depth. Accordingly, the present study agrees with Moir's (1989) interpretation that the entire succession from 3550–3195 m is part of the Freydis Member of the Markland Formation (Fig. 9; Table 12). The age of this prodeltaic interval is late Campanian (Nøhr-Hansen et al., 2016).

Delta front to distributary channel

From 3468 m to 3399 m is light grey to white sandstone, with shale and siltstone interbeds in an overall, coarsening- and cleaning-upward succession. The very fine- to fine-grained, silty, calcareous, moderately to well sorted, slightly siliceous, micaceous sandstone contains subangular grains, silty and shaly stringers, some kaolinite cement, chlorite, and rare pyrite. The shale is dark grey to black, silty, and micro-micaceous, and minor siltstone occurrences are brown-grey and argillaceous. The gamma-ray log confirms thickening- and coarsening-upward sandstones, but with an overall ragged or heterolithic character (Fig. 9).

This interval reflects a generally coarsening- and cleaning-upward unit as seen in the lithology and gamma-ray log. Combined with the heterolithic character and lack of fossil detritus, this suggests a return to delta front deposition. Conventional core 2 lies near the top of this interval at 3412–3403 m, and is late Campanian in age and representative of river-influenced, distributary channel and delta front strata (Dafoe and Williams, 2020a). Accordingly, the overall interval is interpreted to represent delta front to distributary channel deposits. Previous studies indicated inner neritic (Williams, 2007f) and inner shelf to marginal marine conditions (delta front and distributary bars; Miller and D'Eon, 1987); determinations that agree well with the present assessment. This interval is again part of the Freydis Member of the Markland Formation and is late Campanian in age according to Nøhr-Hansen et al. (2016).

Prodelta

The interval spanning 3399 m to 3272 m is shale-dominated with thin sandstone and siltstone interbeds. Black to grey shale is partly calcareous, silty, and micro-micaceous, with rare carbonaceous flakes and rare pyrite. Brown-grey siltstone beds are sandy and argillaceous, and thin limestone partings also occur. White to light grey sandstones are very fine- to fine-grained, moderately to well sorted, calcareous, argillaceous, silty, and micaceous, and contain subangular grains and chlorite.

Similar to the underlying shale-dominated interval, this heterolithic interval is associated with delta front sandstones; it lacks fossil material and contains carbonaceous detritus suggestive of nearby terrestrial influx, typical of prodeltaic settings. Dark shales attest to the organic nature of the mudstones. A slight deepening was also noted by Williams (2007f) to inner–outer neritic conditions, but Miller and D'Eon (1987) found the setting to be within the inner shelf to marginal marine realm. However, it is unclear how the latter authors derived a lacustrine depositional setting. This interval, dated as late Campanian (Nøhr-Hansen et al., 2016), is again finer-grained than typical for the Freydis Member of the Markland Formation.

Delta front to distributary channel

Sandstone with interbedded shale and siltstone characterize the interval between 3272 m and 3195 m. The sandstones are white to light grey, fine-grained, calcareous, siliceous, silty, and moderately to well sorted. Other observations include subangular grain surfaces, the presence of chlorite, rare mica, and rare glauconite near the top of the overall interval. Dark grey to black shale is silty, with rare pyrite. Rare brown, sandy limestone is also present, as is brown-grey, sandy, argillaceous siltstone. Interbedded coal occurs near the top of the interval and has a low resistivity. The overall gamma-ray log signature is ragged and subtly coarsening-upward (Fig. 9).

Within this interval, conventional core 1 (3258–3251 m) was interpreted as representing a late Campanian, river-influenced, distributary channel and delta front succession, with lesser lagoonal mudstones (Dafoe and Williams, 2020a). From the cuttings that make up the rest of the interval, the heterolithic lithology, presence of coal and lack of fossil material, in conjunction with the interpretation of conventional core 1, indicates a return to a delta front setting with distributary channels. However, it is unclear how much of the interval could reflect lagoonal deposition, since much of the interval is sandstone dominated. Williams (2007f) interpreted this interval as outer neritic, but Miller and D'Eon (1987) suggested an inner shelf to marginal marine and possible shelf setting. The core interpretation helps to confirm the shallow marine nature of this interval in Gilbert F-53, which forms the top of the Freydis Member of the Markland Formation. It is dated as late Campanian to Maastrichtian by Nøhr-Hansen et al. (2016). Accordingly, the extent of the Freydis Member in this well, 3550–3195 m is the same as originally reported by Moir (1989; Table 12).

Prodelta

In the interval from 3195 m to 3111 m, the succession subtly coarsens upward from shale to sandy siltstone. The shale is grey, silty, and locally sandy, with siltstone stringers, rare brown limestone, rare pyrite, and rare mica. Grey, argillaceous siltstone is interbedded within the shale and more prevalent near the top of the interval.

The overall weak coarsening-upward character suggests retrogradation of the shoreline relative to the underlying interval, but continued progradation within a prodeltaic setting. The heterolithic character, lack of fossil detritus, and sandy and silty nature further supports this paleoenvironmental interpretation. Miller and D'Eon (1987) and Williams (2007f) reported (?)outer shelf and outer neritic settings, respectively, deeper than proposed in the present study. These rocks form the base of the Markland Formation shales and were dated as Maastrichtian by Nøhr-Hansen et al. (2016).

Middle to outer shelf

Between the depths of 3111 m and 3040 m is an interval of brown-grey, argillaceous siltstone interbedded in a shale-dominated succession. The grey shale is silty, with thin limestone stringers and rare carbonaceous flakes and plant remains. Siltstone beds are brown-grey, calcareous, and very argillaceous.

The lack of sand grains suggests an increase in water depth relative to the underlying deltaic setting and consistent with a middle to outer shelf paleoenvironment. The influx of minor terrigenous detritus indicates a distal deltaic influence, an interpretation corroborated by the lack of fossil material that would be typical of strata deposited under normal marine salinity. Williams (2007f) also suggested an outer neritic setting, but Miller and D'Eon (1987) proposed a bathyal paleoenvironment. Within the Markland Formation, this interval was dated as latest Maastrichtian to early Danian (Early Paleocene) by Nøhr-Hansen et al. (2016).

Slope

Spanning the interval from 3040 m to 2990 m is a shale succession that differs from that of the underlying interval in its composition: a grey to dark grey, hard, platy, partly calcareous shale with rare silt content.

The overall lack of silt, sand, and fossil content indicates distal marine conditions, consistent with slope-equivalent water depths. The harder, platy nature may indicate a condensed section. This interpretation agrees well with that of Miller and D'Eon's (1987) postulated bathyal setting, and it is similar to the outer neritic conditions postulated by Williams (2007f). Located within the Markland Formation, this interval was dated as early Danian (Early Paleocene) by Nøhr-Hansen et al. (2016).

Outer shelf

A thick, relatively monotonous silty shale with less common siltstone beds and rare sandstone beds is present from 2990 m to 2410 m. The grey to dark grey shale is silty and locally calcareous, with carbonaceous flakes throughout (but more common near the base), limestone stringers, siltstone stringers, scattered fossil debris (bivalve fragments, foraminifera, and indeterminate shell material), and localized glauconite. The siltstones are grey, argillaceous, calcareous, and slightly sandy. Very rare, thin sandstone beds are grey, calcareous or dolomitic, silty, and glauconitic. Near the top of the interval, brown, silty, argillaceous, and glauconitic limestone is also present.

The overall diversity of fossil material, silt content, and rare plant remains suggest a distal setting consistent with the outer shelf. This agrees well with the outer neritic or shelf to bathyal or open ocean settings proposed by previous authors (Miller and D'Eon, 1987; Williams, 2007e). This extensive interval forms much of the Markland Formation and the lowermost Cartwright Formation. While Moir (1989) identified a lower Gudrid Formation that falls near the top of this interval (Table 12), the lithology and paleoenvironment are not consistent with this lithostratigraphic unit. Nøhr-Hansen et al. (2016) dated this outer shelf interval as early Danian (Early Paleocene) to Selandian (Middle Paleocene). Accordingly, the transition from the Markland to the Cartwright Formation occurs within the Selandian (Fig. 9). Williams (2007f) noted some missing Selandian section, but it is unclear how this ties to the lithostratigraphic boundary. A major log change also occurs at 2460 m at the Markland–Cartwright formation boundary, where it is marked by an increase in gamma-ray, sonic velocity, and resistivity log values. Based on the above, the Markland Formation extends from 3550–2460 m, as proposed by Moir (1989; Table 12).

Prodelta

Shale with limestone beds grades upward to sandy shale from 2410 m to 2301 m. Grey, silty, sandy shale contains localized fossil material (foraminifera and indeterminate shell fragments), localized limestone stringers, rare carbonaceous material, rare glauconite, and rare pyrite. Brown, sandy limestone and brown, sandy marlstone are also present. The interval is capped by a thin, light grey, very fine- to fine-grained, well sorted, calcareous, argillaceous, silty sandstone, with subangular grains.

The overall sandy nature of the shale and increase in sand grains upwards suggests distal progradation within a prodelta, a setting that would lie outboard of the shoreline and beyond deposition of the associated Gudrid Formation. This slight shallowing was not recognized by Williams (2007f), who interpreted the interval as outer neritic, although he indicated that the presence of *Areoligera gippingensis* could imply a shallower marine setting. Miller and D'Eon (1987) found the setting to be representative of bathyal water depths. Forming part of the lower Cartwright Formation, this interval was dated as Thanetian by Nøhr-Hansen et al. (2016). The top of the interval is characterized by abrupt log changes that tie with the presence of a thin sandstone there, but not to any lithostratigraphic boundaries (Fig. 9).

Outer shelf

Spanning the interval from 2301 m to 1740 m is a thick succession of silty claystone and shale with limestone interbeds. Claystones and shales are grey, silty, locally glauconitic (notably at the base of the interval), and dolomitized in places. These rocks further contain limestone stringers, common fossil fragments throughout (indeterminate shell material, foraminifera, and bivalve), rare pyrite, rare carbonaceous flakes, rare mica, and rare coarse-grained sand grains. Scattered limestone interbeds are brown, silty, and argillaceous.

The characteristic silty nature of the shale and claystone, the fossiliferous suite that suggests normal marine conditions, and the presence of limestone interbeds indicate an outer shelf paleoenvironment. This accords well with the outer neritic to open ocean setting interpreted by Williams (2007f), and Miller and D'Eon (1987) also indicated a similar, but slightly deeper, bathyal paleoenvironment. Including the upper part of the Cartwright Formation and lower half of the Kenamu Formation, this interval was dated as Thanetian (Late Paleocene) to Ypresian (Early Eocene) by Nøhr-Hansen et al. (2016). As the Gudrid Formation is not recognized in this well in the present study (in contrast to Moir, 1989), the Cartwright Formation is taken to extend from 2460 m to 2069 m (Table 12). The boundary with the overlying Kenamu Formation is marked by a change in character and overall decrease in the sonic velocity, as well as a subtle decrease in the resistivity (Fig. 9). There appears to be no major lithological break between the two formations.

Middle shelf

The interval from 1740 m to 1527 m consists of claystone and shale, with rare sandstone, siltstone, and limestone intervals. The claystone and shale are brown-grey, silty, and sandy, and include fossil fragments scattered throughout (bivalve, foraminifera, and indeterminate shell material). Very fine- to fine-grained sandstone is silty, argillaceous, calcareous, and well to moderately sorted, with clear quartz, very coarse-grained sand grains, and subangular to subrounded grains. Rare limestone units are dark brown, sandy, argillaceous, and silty.

The dominance of claystone, combined with the sandy and silty nature and relative abundance of fossil material suggest a middle shelf setting and slight shallowing relative to the underlying interval. This is somewhat shallower than the outer neritic or shelf to open ocean settings indicated by previous authors (Miller and D'Eon, 1987; Williams, 2007f). This interval represents the upper part of the Kenamu Formation, and is of latest Ypresian (Early Eocene) to Bartonian (Middle Eocene) age according to Nøhr-Hansen et al. (2016). The lithostratigraphic extent of the Kenamu Formation as a whole remains unchanged from that of Moir (1989; Table 12).

Outer shelf

A thin interval combining claystone, marlstone, and coal is found between 1527 m and 1476 m depth. The claystone is brown-grey, silty, with carbonaceous material, black coals, and common fossil material (foraminifera and indeterminate shell fragments). The dark-brown marlstone is calcareous, partly dolomitic, and partly silty, with rare pyrite.

The lithology is dominated by fine-grained sediment, but the juxtaposition of coal with foraminifera-bearing units is unusual and suggests that transgression may be responsible for reworking of more proximal, coal-bearing facies (perhaps from reworked Leif Member sandstones deposited in a more proximal setting relative to Gilbert F-53). The interpretation of a transgression is consistent with this unit being at the base of the Mokami Formation (Dickie et al., 2011; Dafoe, Dickie et al., in press), and the setting appears to be outer shelf. This assessment accords with the outer neritic to open ocean paleoenvironment proposed by Williams (2007f), but implies a deeper setting than the inner to middle shelf conditions proposed by Miller and D'Eon (1987). This interval marks the base of the Mokami Formation and was dated as late Bartonian (Middle Eocene) by Nøhr-Hansen et al. (2016).

Prodelta

The succession from 1476 m to 1314 m in Gilbert F-53 is dominated by shale, with scattered, thin, sandstone intervals. The grey shale units are sandy and silty, with scattered very coarse-grained sand grains, carbonaceous material, rare pyrite, rare limestone stringers, and rare bivalve and indeterminate shell fragments. Clear quartz to brown-grey sandstone is fine- to medium-grained, and partly silty, with subrounded grains, moderate sorting, siliceous pebbles, and chert grains.

The dominance of claystone and presence of sand with discrete sandstone beds indicates shallowing relative to the underlying interval. The lack of fossil diversity and influx of coarser (pebbly) detritus suggests strong terrigenous influx and is consistent with a prodelta setting. The interpretation in the present study aligns well with the inner neritic interpretation of Williams (2007f), as well as that of Miller and D'Eon (1987), whom proposed an inner to middle shelf setting with a regressive or possible prodeltaic character. This interval within the Mokami Formation was dated as latest Bartonian (Middle Eocene) to Rupelian (Early Oligocene) by Nøhr-Hansen et al. (2016).

Delta front and prodelta

The interval between 1314 m to 1163 m is claystone-dominated overall, but has thicker sandstone units than the underlying interval described above. Grey-brown, partly silty, sandy claystone contains locally abundant very coarse-grained sand grains, coal stringers, and rare bivalve fragments. Clear quartz to grey sandstone is fine- to coarse- grained, unconsolidated, and partly silty. The sandstone beds further include dark chert grains, light chert grains, siliceous pebbles throughout, subrounded grains, moderate sorting, and localized argillaceous components. The gamma-ray log shows blocky to coarsening-upward units, but a heterolithic character, alternating between sandstone and shale (Fig. 9).

The roughly coarsening-upward units combined with the coarse-grained nature of the sandstone, low fossil diversity and abundance, and presence of coaly material suggests prodeltaic deposition, with thin delta front sandstones developing. Williams (2007f) indicated a coastal-marginal marine to inner neritic setting, and Miller and D'Eon (1987) proposed marginal marine delta front and possible nonmarine (fluvial or lacustrine) deposition. There is no indication of nonmarine deposition, and the present study aligns well with the interpretation of Williams (2007f) from palynomorphs. This section in the well forms the upper part of the Mokami Formation, and is Rupelian (Early Oligocene) according to Nøhr-Hansen et al. (2016). The lithostratigraphic extents as defined by Moir (1989) for the Mokami Formation are retained in the present study (1527–1163 m; Table 12).

Delta front

Spanning the depths from 1163 m to 1052 m, is a succession of sandstone-dominated strata. Grey, fine- to medium-grained, argillaceous, moderately sorted, friable sandstone contains quartz grains, siliceous pebbles, shale stringers, subrounded grains, very coarse-grained sand grains throughout, scattered dark chert, rare feldspar, and rare limestone stringers. Rare claystone beds are brown-grey, sandy and silty, with rare bivalve fragments. The blocky to ragged gamma-ray log character exhibits a fining-upward character (Fig. 9).

In addition to the log character, the presence of coarse grains and pebbles and lack of fossil diversity are interpreted to represent delta front deposition. The fining-upward nature could indicate waning within distributary channels, delta-lobe switching, or a slight increase in relative sea level during deposition. This setting agrees well with those of previous authors, who indicated marginal marine to inner shelf and possible deltaic conditions (Miller and D'Eon, 1987; Williams, 2007f). This part of the well corresponds to the base of the Saglek Formation in Gilbert F-53 and was interpreted as Rupelian (Early Oligocene) by Nøhr-Hansen et al. (2016).

Prodelta

A heterolithic interval from 1052 m to 873 m is composed of claystone, sandstone, and siltstone. Claystone units are brown-grey, sandy, and silty, with fossil fragments throughout (indeterminate shell material and bivalve), mica, rare very coarse-grained sand grains, and pebbles within the claystone near the top of the interval. Brown-grey, argillaceous, and sandy siltstone is present, as well as white, fine- to medium-grained, silty, partly calcareous, clayey sandstone, with subrounded grains, moderate sorting, rare feldspar, and rare pebbles. Rare coal partings are also present, and a ragged gamma-ray log signature is observed, with some minor coarsening-upward trends (Fig. 9).

The heterolithic character, dominance of claystone, lack of fossil diversity, and influx of coaly detritus is suggestive of prodeltaic deposition and a minor increase in water depth relative to the underlying interval. The increase in fossil content, albeit of low diversity, could indicate wave or storm dominance of the delta and mitigation of the effects of riverine influx, resulting in the finely interbedded lithologies in this interval (Fig. 9). The setting aligns closely with the marginal marine to inner shelf interpretations of Miller and D'Eon (1987) and Williams (2007f). This interval is more fine-grained than is typical of the Saglek Formation, and it was found to be Rupelian (Early Oligocene) to earliest Chattian (Late Oligocene) by Nøhr-Hansen et al. (2016).

Delta front or shoreface

At the top of Gilbert F-53, between 873 m and 525 m, is a generally coarsening-upward sandstone package with rare shale partings and conglomeratic units. The sandstone coarsens from fine- to medium-grained to medium- grained, then coarse-grained. Clasts are subrounded and moderately to poorly sorted, and the sandstone is white, grey and light brown, as well as partly silty and rarely calcareous. In addition, these rocks contain chert grains, very coarse-grained quartz sand grains, a clay matrix, pebbles (siliceous, igneous, metamorphic, and siderite), mica, localized fossil material (indeterminate shell fragments), rare carbonaceous flakes, and rare siderite cement. Claystone units are grey, sandy, and silty. Conglomerates present in the upper half of the interval are white to light grey, with chert, igneous, limestone, and siliceous pebbles, as well as very coarse-grained sand grains, a clay matrix, and common to locally abundant bivalve shell fragments. While slightly ragged, the gamma-ray log signature also shows some blocky intervals and both coarsening- and fining-upward trends (Fig. 9).

The overall coarsening-upward nature and slightly heterolithic character suggests a delta front setting, but the abundance of shell fragments and subdued ragged gamma-ray profile could also indicate shoreface deposition. This interpretation agrees with the findings of Williams (2007f) as inner neritic to marginal marine, and also with the inner shelf, deltaic, and marginal marine interpretations of Miller and D'Eon (1987). This interval is at the top of the Saglek Formation, where the upper boundary is modified to 512 m and demarcated by the top of the gamma-ray log record, rather than the top at 303 m as proposed by Moir (1989; Table 12).

Lithostratigraphy

Based on the above discussion around lithostratigraphic refinements to the framework of Moir (1989) in Gilbert F-53, the lithostratigraphic picks from the present study are summarized in Table 12. There are no reference or type sections for this well.

Lithostratigraphic unit	Moir (1989)		The present study		Type or reference section
	Base (m)	Top (m)	Base (m)	Top (m)	
Saglek Fm	1163	303	1163	512	None
Mokami Fm	1527	1163	1527	1163	None
Kenamu Fm	2069	1527	2069	1527	None
Cartwright Fm	2453	2069	2460	2069	None
Gudrid Fm (lower)	2460	2453	--	--	None
Markland Fm	3550	2460	3550	2460	None
Markland Fm (Freydis Mb)	3550	3195	3550	3195	None
Unnamed Precambrian	3608	3550	3608	3550	None

Table 12: Lithostratigraphic assignment for Gilbert F-53 from the present study and compared to that of Moir (1989). Fm=Formation; Mb=Member.

GJOA G-37

Located in the northern part of the Saglek Basin and centrally within Davis Strait is the Gjoa G-37 well (Fig. 1). The well history report from Esso Resources Canada Ltd. (1979b) provides generalized geologic and conventional core descriptions, with the sidewall core and cutting descriptions in Esso Resources Canada Ltd. (1979a). Much of the data compiled for the interval descriptions below are also derived from the Canadian Stratigraphic Service Ltd. Esso Gjoa G-37 log (log EC-133), which contains detailed lithological, grain size, grain rounding, and sample descriptions for the well. Dafoe and Williams (2020a) included detailed core descriptions for core 1 within the Paleogene basalt interval also utilized in the present study. The Gjoa G-37 well plot is shown in Figure 10, with key well logs, lithology, grain size, rock colour, ages, and paleoenvironmental and lithostratigraphic information. The ages from Williams (2007d) are used in the present study based on the rationale presented in Dafoe, DesRoches et al. (in press). A summary of the paleoenvironments from the present study are shown in Table 13, and these are compared with the results of Miller and D'Eon (1987) and paleoenvironments based on palynomorphs from Williams (2007d) in the interval descriptions below. The revised lithostratigraphic picks of the present study are compared with those of Moir (1987b) and Dafoe, DesRoches et al. (in press) in Figure 10 and Table 14.

Base (m)	Top (m)	Paleoenvironment
3998	3794	SHALLOW MARINE TO NONMARINE
3794	2701	SHALLOW SHELF TO SUBAERIAL
2701	2529	(?)OUTER SHELF
2529	2337	MIDDLE SHELF
2337	2012	(?)LOWER SHOREFACE
2012	1727	PRODELTA
1727	1588	DELTA FRONT TO DELTA PLAIN
1588	1485	DISTAL DELTA FRONT
1485	1470	DELTA FRONT

Table 13: Paleoenvironmental determinations for Gjoa G-37 from the present study.

Shallow marine to nonmarine

At the base of Gjoa G-37, shale with thin siltstones and one thin basalt interval occurs between the depths of 3998 m and 3794 m. Grey to dark grey or brown-grey, slightly fissile, partly micro-micaceous, hard, silty shale dominates the interval. Siltstone units are brown, argillaceous, shaly, and partly sandy. A thin interval of volcanic rock is likely composed of yellow-brown basalt that is partly green, weathered, argillaceous, and hard, with rare amygdales. The gamma-ray log clearly shows an igneous unit in contrast to the relatively high API values of the shale-dominated succession (Fig. 10). Rare buff limestone was also reported, with possible skeletal grains and oolites.

The silty nature of the strata suggests a relatively nearby terrestrial source, but there is a complete lack of fossil material and other defining features. The volcanic rocks are described as weathered and were likely subaerially emplaced. The presence of limestones with skeletal grains and oolites suggests some shallow-water, high-energy conditions. Most likely, the setting is brackish, shallow marine, which would account for the general lack of fossil material in the shales and the presence of limestones. However, some subaerial exposure is indicated by the volcanic interval, implying fluctuating nonmarine and marginal marine conditions were likely. This interpretation fits within the range of previous studies that suggested nonmarine (Miller and D'Eon, 1987) and inner to outer neritic conditions (Williams, 2007d). This part of the well characterizes the Markland Formation of Danian (Early Paleocene) age according to Williams (2007d).

Shallow shelf to subaerial

The interval from 3794 m to 2701 m is characterized by alternating igneous rocks with shale or claystone, with localized interbedding of tuff and shale. Igneous rocks include basalt and tuff that are yellow-brown to green-brown, hard (basalt) to soft (tuff), slightly weathered, with white calcite and chert veins, rare mica, rare amygdales, and rare mottling. Shales are grey to dark grey, fissile, hard, slightly silty, rarely green and/or red in colour, with rare siltstone stringers and foraminifera were noted at 3275 m depth. Sidewall core intervals indicate altered basalt, aphanitic glassy amygdaloidal zeolites, calcareous white ash, calcareous siltstone, blocky hard shale, slightly sandy green siltstone, white-grey tuff, and rare grey-green mudstone. The gamma-ray log illustrates the interbedding of low API value igneous rocks with the high API shales, and some finely interbedded units (Fig. 10).

The development of tuff and indication of weathering indicates a subaerial or intermittently subaerial setting. This is consistent with the interpretation of core 1 from Dafoe and Williams (2020a; 2920.5–2912.0 m): basalt and amygdaloidal basalt representative of subaerial basalt flows at depth and capped by flow tops with evident weathering. Rare green and red shales may further indicate alternating reducing and oxidizing conditions typical of subaerial settings (Turner, 2003). However, the prevalence of thick grey shales could reflect some degree of subaqueous deposition, owing to the thickness of individual units and rare foraminifera, which support this interpretation. The lack of fossil material in marine shales is unusual and may indicate environmentally stressful conditions, possibly related to basalt emplacement and atypical water chemistry. The interbedding of basalt, tuff, and shale is interpreted to represent alternation between subaerial and shallow shelfal paleoenvironments. In some agreement with the present study, Williams (2007d) found the setting to be inner to outer neritic, but Miller and D'Eon (1987) reported middle shelf, outer shelf, and bathyal water depths (with turbidite fans). There is no evidence of such distal marine settings, and the interpretation of core 1 refutes consistent marine deposition.

This interval spans what Dafoe, DesRoches, et al. (in press) suggested was unnamed basalts interstratified with the Markland Formation, followed by a succession of unnamed basalts. The portion relating to the Markland Formation is Danian to Selandian (Early to Middle Paleocene) in age, and the upper basalt interval is Selandian (Middle Paleocene) according to Williams (2007d). Moir (1987b) did not recognize the interbedded shales as part of the Markland Formation. The assignment of these shales to the Markland Formation, with an uppermost age falling within the Selandian, conforms to the stratigraphic framework outlined in Dafoe, Dickie et al. (in press) for the Labrador margin. Accordingly, the findings of Dafoe, DesRoches et al. (in press) are retained in the present study (Table 14).

(?)Outer shelf

Spanning the depths from 2701 m to 2529 m is a silty claystone to shale interval. Brown-grey, silty claystone and shale includes siderite bands, rare very fine-grained sand grains, rare fossil fragments (2635–2630 m), and an increase in siltstone content upward.

The increase in silt content upward suggests some degree of shallowing over time, but the lack of fossil material is unusual for the marine shales typical of the Cartwright Formation (*see* Dafoe, Dickie et al., in press). Based on the lithology alone, the interval may reflect an outer shelf setting. This interpretation agrees with that of Williams (2007d), but is slightly shallower than the bathyal setting proposed by Miller and D'Eon (1987). Lying above the basalts, this interval forms the base of the Cartwright Formation, with a Selandian (Middle Paleocene) age assignment from Williams (2007d).

Middle shelf

Sandy and silty claystone persists in the well from 2529 m to 2337 m. The sandy, silty claystone is brown to grey-brown and locally shaly, with siderite bands, very fine-grained sand grains, sandstone stringers increasing in abundance upward, minor glauconite, and rare indeterminate shell fragments. Sidewall core indicate interbedded shale and sandstone with bird's-eye structures (features possibly indicative of sediment loading). The gamma-ray log further illustrates a coarsening-upward trend based on the decreasing log signature (Fig. 10).

The coarsening-upward nature, degree of sand and silt content, and presence of shell fragments is consistent with a middle shelf setting and overall progradation relative to the underlying outer shelf strata. Possible sediment loading (soft-sediment deformation) in sidewall core may suggest shoaling to inner shelf conditions near the top of the interval and associated elevated sedimentation rates. This setting is shallower than previously proposed: outer neritic and outer shelf to bathyal (Miller and D'Eon, 1987; Williams, 2007d). There is no evidence to suggest distal marine settings, nor turbidite fan accumulations. Forming part of the Cartwright Formation, Williams (2007d) dated this interval as Thanetian (Late Paleocene) to basal Ypresian (Early Eocene).

(?)Lower shoreface

In the interval spanning 2337 m to 2012 m is a succession of coarsening-upward sandy and silty claystone. The claystone is brown to grey-brown and partly shaly, with very fine-grained sand grains throughout, siderite, sandstone stringers increasing in abundance upward, rare fossil fragments (indeterminate shell material and gastropod), rare mica, rare pyrite, rare lithic fragments, rare medium-grained sand grains, rare glauconite, rare carbonaceous material, and rare plant fragments. Sidewall cores comprise: grey siltstone with fossil fragments; light green sandstone with rare volcanic grains; and interbedded shale, sandstone, and siltstone, with some indeterminate shell fragments. The interval is both coarsening- and cleaning-upward on the gamma-ray log, with a somewhat blocky character towards the top (Fig. 10).

The evident coarsening-upward trend, combined with indications of terrestrial influx (plant and carbonaceous detritus) and the fossil suite are interpreted to reflect a proximal shelf setting, possibly as shallow as the lower shoreface. This agrees well with the observations from sidewall cores within this interval. In contrast, outer neritic to open ocean and outer shelf to bathyal settings were proposed by Williams (2007d) and Miller and D'Eon (1987), respectively. The sand was explained by Miller and D'Eon (1987) to be related to turbidite fan accumulations, but both the coarsening-upward nature, terrestrial influx and fossil suite would indicate a much shallower setting. Williams (2007d) assigned a Ypresian (Early Eocene) age to this interval, which forms the upper part of the Cartwright Formation. The top of this lithostratigraphic interval is modified slightly based on the log, lithological, and corresponding paleoenvironmental interpretation from the present study to 2012 m, such that the formation extends from 2701–2012 m (Table 14).

Prodelta

Silty, sandy claystone dominates the section of the well from 2012 m to 1727 m. The claystone becomes increasingly sandy upward, with scattered very fine- to fine-grained sand grains, siderite, mica, locally abundant plant remains, scattered indeterminate shell fragments, locally fissile shale intervals, rare carbonaceous flakes, rare coal at the top of the interval, rare pyrite, rare glauconite, and rare pyritized plant remains. Within this interval, sidewall core are described as including: interbedded shale and siltstone; brown-grey sandstone; siltstone, with sandstone lenses, pyrite, clay interclasts, and possible bioturbation; and sandstone with carbonaceous material and mica. The gamma-ray log is relatively ragged (Fig. 10).

The interbedding noted in sidewall core may indicate a prodeltaic setting, which would be consistent with the sandy nature of the claystone, limited fossil preservation, and a ragged gamma-ray log indicating a heterolithic character. The commonality of plant remains further attests to a shoreline proximity. This setting is relatively shallow for the Kenamu Formation (*see* Dafoe, Dickie et al., in press), and differs from the outer neritic to open ocean paleoenvironments interpreted by Williams (2007d). However, Miller and D'Eon (1987) noted inner shelf, possible prodelta and delta front strata, which is relatively consistent with the present study. This claystone interval forms part of the Kenamu Formation, and is of Ypresian (Early Eocene) to Lutetian (Middle Eocene) in age according to Williams (2007d).

Delta front to delta plain

From 1727 m to 1588 m is a succession of very sandy, silty claystone. This sandy, silty claystone is brown, slightly sideritized, with very fine- to fine-grained sand grains, mica, scattered coal fragments, coal layers (black and impure), scattered glauconite, rare to locally abundant indeterminate shell fragments, and rare medium-grained sand grains. The sidewall core include light to medium brown sandstone, with very fine-grained carbonaceous material, a clay matrix, and a micaceous texture. The overall gamma-ray log shows a bell to fining-upward shape, but is slightly ragged in character (Fig. 10).

The fining-upward gamma-ray profile could indicate a fluvial setting, but the presence of locally abundant shell material and the palynological interpretations (Williams, 2007d) indicate a marine setting. However, the presence of coal suggests significant terrigenous influx consistent with delta front to delta plain accumulation. Miller and D'Eon (1987) interpreted a similar delta front and distributary bar to slightly deeper inner to middle shelf bar or storm sand paleoenvironment. Williams (2007d) suggested outer and inner neritic deposition, showing some correlation to the present study.

This part of the well is interpreted to represent the Leif Member of the Kenamu Formation, which is modified here to extend from 1728 m to 1588 m based on the log character, lithology, and ages as determined by Williams (2007d) and Nøhr-Hansen et al. (2016), which places the top of the formation in the Bartonian (Table 14; Fig. 10). This is in contrast to the interpretations of Moir (1987b) and Dafoe, DesRoches et al. (in press) where they placed the top of the member within the Lutetian, older than seen in key Labrador Shelf wells (*see* Dafoe, Dickie et al., in press). These previous interpretations also do not take into account the continuation of the sandstone lithology nor the gamma-ray and resistivity log increases at 1588 m that signify the start of the overlying Mokami Formation (Fig. 10).

Distal delta front

Between the depths of 1588 m and 1485 m in Gjoa G-37 is an interval of sandy, silty claystone. The claystone is brown and contains very fine- to fine-grained sand grains, mica, common coal fragments, scattered glauconite, rare medium-grained sand grains, rare indeterminate and gastropod shell fragments, and rare pyrite. Brown sandstone with carbonaceous material was reported from sidewall core, as well as sandy siltstone, with carbonaceous material and interbedded siltstone and sandstone.

The sandy claystone lithology, interbedding of lithologies, and presence of coal suggests a slight deepening to distal delta front conditions relative to the underlying strata. Sparse fossil occurrences further support deltaic, rather than normal marine conditions. This is similar to the inner neritic and marginal marine to inner shelf (delta front distributary bar) interpretations of previous authors (Miller and D'Eon, 1987; Williams, 2007d).

Lying above the Kenamu Formation, this interval is defined in the present study as comprising the entire Mokami Formation of Bartonian (Middle Eocene) to Rupelian (Early Oligocene) age according to Williams (2007d). A slight flooding at the top of the Kenamu Formation in the late Bartonian at the base of this interval is consistent with the framework established by Dickie et al. (2011) and Dafoe, Dickie et al. (in press). Both the base and top of the Mokami Formation are modified in the present study based on changes to the underlying Leif Member of the Kenamu Formation and the overlying Saglek Formation (see below). The Mokami Formation therefore extends from 1588–1485 m (Table 14).

Delta front

At the top of the well between 1485 m and 1470 m is a very sandy and silty claystone. These strata are brown with very fine- to fine-grained sand grains, common coal fragments, and rare medium-grained sand grains. Light grey, very fine- to fine-grained sandstone, with carbonaceous material and mica was found in sidewall core. The gamma-ray log illustrates coarsening-upward from the underlying interval and up to the cased portion of the well at 1402 m (Fig. 10).

Similar to the distal delta front interval below, the lithology and gamma-ray signature is consistent with a delta front setting. The paleoenvironment and implied increase in sand content upward to 1402 m (based on the gamma-ray log) are interpreted in the present study to signify the base of the Saglek Formation. Accordingly, the Saglek Formation ranges from 1485 m to 1402 m, with the top demarcated at the top of the electric logs (Fig. 10), a lithostratigraphic assignment that differs from that of Moir (1987b) and Dafoe, DesRoches et al. (in press; Table 14). This interval lies above the strata dated as Rupelian (Early Oligocene) by Williams (2007d), and below the Rupelian age denoted by Fenton and Pardon (2007).

Lithostratigraphy

Based on the discussion around lithostratigraphic refinements to the framework of Moir (1987b) and Dafoe, DesRoches et al. (in press) in Gjoa G-37, the lithostratigraphic picks from the present study are summarized in Table 14. There are no reference or type sections in this well.

Lithostratigraphic unit	Moir (1987b)		Dafoe, DesRoches et al. (in press)		The present study		Type or reference section
	Base (m)	Top (m)	Base (m)	Top (m)	Base (m)	Top (m)	
Saglek Fm	1455	1026	--	--	1485	1402	None
Mokami Fm	1646	1455	1646	1455	1588	1485	None
Kenamu Fm (Leif Mb)	1728	1650	1728	1646	1728	1588	None
Kenamu Fm	2013	1646	2013	1728	2012	1588	None
Cartwright Fm	2701	2013	2701	2013	2701	2012	None
Unnamed basalts	3794	2701	3145	2701	3145	2701	None
Unnamed basalts and interstratified Markland Fm	--	--	3794	3145	3794	3145	None
Markland Fm	3998	3794	3998	3794	3998	3794	None

Table 14: Lithostratigraphic assignment for Gjoa G-37 from the present study and compared to that of Moir (1987b) and Dafoe, DesRoches et al. (in press). Fm=Formation; Mb=Member.

GUDRID H-55

For the Gudrid H-55 well, found in the southern part of the Hopedale Basin (Fig. 1), the well history report by Corgnet and McWhae (1975) includes descriptions of both cuttings and sidewall cores utilized in the present study. Detailed lithological data also comes from the Canadian Stratigraphic Service Ltd. Eastcan et al Gudrid H-55 log (log EC-98), which contains lithological, grain size, grain rounding, and sample descriptions for the well. A plot of Gudrid H-55 is further shown in Figure 11, including key well logs, lithology, grain size, rock colour, ages, and paleoenvironmental and lithostratigraphic information. The biostratigraphically determined age assignments used in the present study are from Williams (pers. comm., 2016), a modified set of ages based on the initial palynomorph study by Williams (1979d). A summary of the paleoenvironments described below are shown in Table 15, and comparison with paleoenvironments from LaBorde et al. (1974; based on micropaleontology) and Miller and D'Eon (1987) are described below. The revised lithostratigraphic picks from the present study slightly modify those of Moir (1989; Table 16).

At the base of Gudrid H-55, unnamed Paleozoic basement from 2804–2663 m is early Ordovician (Fenton and Pardon, 2007) to possibly late Ordovician (Bingham-Koslowski et al., 2019) in age and sits atop an unnamed Precambrian basement interval spanning 2838–2804 m (Table 16).

Base (m)	Top (m)	Paleoenvironment
2662.8	2648.7	SHELFAL
2648.7	2636.6	OUTER SHELF TO SLOPE
2636.6	2391.2	SLOPE
2391.2	2179.3	SHOREFACE
2179.3	1959.3	SLOPE
1959.3	1679.5	MIDDLE SHELF SHALLOWING TO INNER SHELF
1679.5	1554.5	OUTER SHELF
1554.5	990.6	MIDDLE SHELF
990.6	724.8	MIDDLE TO INNER SHELF
724.8	506.0	SHOREFACE

Table 15: Paleoenvironmental determinations for Gudrid H-55 from the present study.

Shelfal

At the base of Gudrid H-55, spanning 2662.8 m to 2648.7 m (8736–8690 ft.), is a thin interval of shale. This green-grey shale is slightly silty and contains mica, abundant Upper Cretaceous foraminifera, 10–20% green nontronite fine-grained clasts (from the weathering of biotite and basalts), clasts of carbonates with Paleozoic foraminifera, rare sand, rare red shale, and rare granitic clasts.

The overall foraminiferal abundance indicates a marine setting, but reworking of the basement carbonate and granitic rocks and presumably nearby basalts of the Alexis Formation indicates that the basement was a subaerially exposed surface that was subsequently transgressed. The silt and sand content suggest a shelfal setting, but without further evidence it is difficult to assess shoreline proximity. Miller and D'Eon (1987) indicated a possible nonmarine setting for part of this interval overlain by a possible bathyal setting, but LaBorde et al. (1974), however, interpreted an outer sublittoral setting that is reasonably similar to the interpretation from the present study. Lying above the Paleozoic basement rock and forming the base of the Markland Formation, this interval was determined to be Maastrichtian by Williams (1979, pers. comm. 2016) and similarly late Maastrichtian by Fenton and Pardon (2007).

Outer shelf to slope

Another thin interval from 2648.7 m to 2636.6 m (8690–8650 ft.) includes medium to dark grey shale that is silty, with mica, dark green to black clasts that decrease in abundance up section, rare sand, rare green shale fragments, and rare rounded quartz grains.

Compared to the underlying interval, the reduction in sand content and decreased incorporation of basement clasts, as well as lack of fossil material are interpreted to represent increasing water depth to an outer shelf or slope paleoenvironment. LaBorde et al. (1974) documented an outer sublittoral setting, and Miller and D'Eon (1987) reported possible bathyal deposition, both in relative agreement with the present study. Within the Markland Formation, this thin interval is Maastrichtian according to Williams (1979, pers. comm. 2016), but could be restricted to the late Maastrichtian (Fenton and Pardon, 2007).

Slope

A thick interval of medium to dark grey shale is present from 2636.6 m to 2391.2 m (8650–7845 ft.). The shale is silty, micro-micaceous, slightly calcareous, rarely fissile, and soft, and contains rare dark brown limestone, rare siderite, rare marlstone, and rare pyrite.

The overall fine-grained lithology, lack of sand content, and lack of fossil material is indicative of a slope-equivalent paleoenvironment. This interpretation aligns well with the bathyal (Miller and D'Eon, 1987) and outer sublittoral to deep outer sublittoral (LaBorde et al., 1974) settings proposed by previous authors. This shale succession forms the bulk of the Markland Formation in Gudrid H-55 and is Maastrichtian to Early Paleocene in age according to Williams (1979, pers. comm. 2016), and likely Danian (Early Paleocene) as indicated by Fenton and Pardon (2007). The top of the Markland Formation is modified slightly in the present study to better align with the log break and paleoenvironmental change at 2391.2 m, modifying the lithostratigraphic assignment of Moir (1989) and reference section of McWhae et al. (1980) to 2663–2391.2 m (Fig. 11; Table 16).

Shoreface

In striking contrast to the underlying interval, two coarsening-upward sandstone units occur between 2391.2 m to 2179.3 m (7845–7150 ft.) depth (Fig. 11). The sandstone successions are fine- to medium-grained and medium- to coarse-grained, white to cream or brown, loosely consolidated, friable, glauconitic, and dolomitic at the base. The sandstones are also moderately sorted and contain subangular to rounded grains (mostly subrounded), kaolinite cement at the very base and top of the interval, very coarse-grained sand grains increasing in abundance upwards, quartz pebbles especially in the middle of the interval, a siltier disposition in upper half of interval, rare feldspar throughout, rare pyrite, and rare lignite. The gamma-ray log exhibits a coarsening-upward to somewhat blocky appearance, with a higher API noted in the middle of the interval and associated with a shaly sandstone there (Fig. 11).

The generally coarsening-upward nature of the sandstone, combined with the presence of pebbles, lignite, and glauconite suggest a shallow marine setting. The dolomitic character at the base of the interval would appear to reflect erosion of nearby exposed Paleozoic basement rocks during regression. Accordingly, a shoreface setting in which erosion at the base of the lower shoreface took place best defines this interval. The interpretation from the present study aligns well with the supralitoral to inner sublittoral settings of LaBorde et al. (1974), but the bathyal (turbidite) to outer shelf setting suggested by Miller and D'Eon (1987) are inconsistent with the above observations. These stark paleoenvironmental discrepancies are discussed further in Dafoe, Dickie et al. (in press) where they reasoned that the Gudrid Formation was, in fact, shallow marine in origin.

This sandstone interval forms the Gudrid Formation in the well, which is Late Paleocene (possibly Thanetian) to Ypresian (Early Eocene) based on results from Williams (1979d, pers. comm.

2016) and Fenton and Pardon (2007). Moir (1989) identified this interval as part of the upper Gudrid Formation. However, the shaly sandstone from about 2280 m to 2270 m is interpreted in the present study to indicate a break in the Gudrid Formation and stacking of the lower and upper members. The lithostratigraphic assignment and type section as originally defined by Umpleby (1979) and McWhae et al. (1980) are modified slightly to better align with the log changes at the top and base of the interval, and related changes in paleoenvironments as indicated in the present study (Fig. 11). The Gudrid Formation and revised type section thus extends from 2391.2–2179.3 m (Table 16).

Slope

Capping the underlying sandstone is a claystone interval spanning 2179.3 m to 1959.3 m (7150–6428 ft.). This medium to dark brown claystone is slightly silty and micaceous, with interbeds of dark brown marlstone and limestone, rare foraminifera, rare pyrite, and rare bivalve fragments.

The dominance of clay, paucity of silt and sand, presence of limestone interbeds, and very rare fossil material suggests a setting beyond the shelf and consistent with slope-equivalent water depths. This interpretation agrees with the bathyal and outer sublittoral settings indicated by previous studies (LaBorde et al., 1974; Miller and D'Eon, 1987). Forming the base of the Kenamu Formation, this claystone interval is Ypresian (Early Eocene) to Middle Eocene in age according to Williams (pers. comm. 2016).

Middle shelf shallowing to inner shelf

There is an abrupt lithological change from the underlying interval to a claystone with siltstone, lesser sandstone, and rare limestone beds from 1959.3 m to 1679.5 m (6428–5510 ft.). Claystones are medium to dark brown, very silty and sandy (very fine-grained), micaceous, and slightly calcareous, with rare limestone nodules and rare foraminifera. Brown, very fine-grained sandy, argillaceous, and slightly calcareous siltstone is common. Sandstone beds are dark brown, very fine-grained, argillaceous, silty, and calcareous, and limestones are dark brown and sandy.

The increase in both silt and sand content suggests abrupt shallowing to middle shelf conditions from the underlying slope-equivalent water depths. The uppermost part of the interval is sandier and likely reflects continued shallowing to an inner shelf setting (Fig. 11). The heterolithic lithology is consistent with these interpretations, but there is an unusual lack of fossil abundance and diversity, possibly indicative of distal riverine influence and associated reduced marine salinity. Previous studies, however, have indicated outer sublittoral to bathyal water depths (LaBorde et al., 1974; Miller and D'Eon, 1987). The consistent presence of silt and sand intermixed within the claystone is not compatible with these interpretations.

This interval forms the upper part of the Kenamu Formation defined here, a unit which is known to shallow upwards (Balkwill and McMillan, 1990; Dafoe, Dickie et al., in press). Moir (1989) interpreted a thin interval of Leif Member sandstones, but there is insufficient rationale to assign the Leif Member since a more distal paleoenvironment is observed than is typical for these shoreline sandstones (Umpleby, 1979; McWhae et al., 1980; Dafoe, Dickie et al., in press). With the base of the Kenamu Formation modified as discussed above, the Kenamu Formation in Gudrid H-55 ranges from 2179.3–1679 m (Table 16). Williams (pers. comm. 2016) gave a Middle Eocene (including Bartonian) age for this middle to inner shelf section of the well.

Outer shelf

Spanning the depths of 1679.5 m to 1554.5 m (5510–5100 ft.), dark brown, silty claystone is present. This claystone is also slightly calcareous and slightly micaceous, with rare sand, rare siltstone and marlstone, and rare foraminifera.

The overall grain size, consistent silty nature of the claystone and fossil content is suggestive of outer shelf deposition. This interpretation agrees well with the outer shelf and outer sublittoral to bathyal settings of Miller and D'Eon (1987) and LaBorde et al. (1974). Located at the base of the Mokami Formation in Gudrid H-55, this interval is latest Bartonian (Middle Eocene) to Priabonian (Late Eocene) according to Williams (pers. comm. 2016).

Middle shelf

A thick interval of sandy, silty claystone containing scattered sandstone, siltstone, and limestone beds persists from 1554.5 m to 990.6 m (5100–3250 ft.). This medium to dark brown claystone is silty, sandy (very fine-grained), micaceous, and slightly calcareous, and also includes rare medium- to coarse-grained sand and rare bivalve fragments that increase in abundance up section. Dark brown limestone beds are silty and sandy, and sandstones are correspondingly dark brown and limy. Siltstone beds are brown, sandy, argillaceous, and calcareous.

The sandy and silty nature of the claystone is consistent with a middle shelf setting. The fossil suite is very limited in diversity, possibly indicating some degree of environmental stress. LaBorde et al. (1974) interpreted similar outer sublittoral to shallow inner sublittoral settings for this interval, but Miller and D'Eon (1987) reported outer shelf to bathyal conditions, the latter including turbidites to explain the presence of sand within the claystone. The consistent incorporation of sand within the claystone is, however, not compatible with the development of turbidite fan deposits that are typified by discrete sandstone units. This interval forms part of the Mokami Formation, and Williams (pers. comm. 2016) gave it a latest Priabonian (Late Eocene) to Rupelian (Early Oligocene) age.

Middle to inner shelf

The interval between 990.6 m and 724.8 m (3250–2378 ft.) is characterized by silty, sandy claystone, with the top of the interval being more calcareous. The brown, silty, very fine-grained sandy, slightly micaceous claystone contains scattered bivalve fragments, very coarse-grained sand grains, brown siltstone stringers, coarse-grained sand and pebbles (possibly caved from the overlying interval), rare lignite, rare pyrite, rare carbonaceous plant remains, and rare gastropod fossil fragments.

These strata resemble those of the underlying interval, but enhanced fossil diversity and abundance in the uppermost part of the interval and influx of coarser grains suggests shallowing from the middle to inner shelf. This agrees well with the shallow inner sublittoral interpretation of LaBorde et al. (1974) and with the inner shelf succession described by Miller and D'Eon (1987); however, the latter authors also indicated outer shelf to bathyal water depths for part of this interval.

Characterizing the top of the Mokami Formation, Williams (pers. comm. 2016) assigned this section of the well to the Rupelian (Early Oligocene) and Early to Middle Miocene. No Chattian (Late Oligocene) section was identified, but there is no evidence to indicate an unconformity within this interval (Fig. 11). Cavings may have complicated biostratigraphic study of the upper part of the well, with Chattian strata possibly removed during emplacement of the overlying Saglek Formation. The upper boundary of the Mokami Formation is modified here to better match the log and lithological breaks, and corresponding paleoenvironmental change at 724.8 m; thus the formation spans 1679–724.8 m in Gudrid H-55 (Table 16).

Shoreface

Lying at the top of Gudrid H-55 from 724.8 m to 506.0 m (2378–1660 ft.) is a coarse-grained interval of sandstone and lesser conglomerate, with rare siltstone and claystone beds. Sandstone and conglomerate units are white to light brown or grey and loosely consolidated. These rocks include very coarse-grained sand grains throughout, a clay matrix, subrounded grains, moderate sorting, quartz and dark chert pebbles, rare bivalve fragments throughout, rare pyrite throughout, rare lignite, rare ostracod fragments, and rare glauconite. Claystones are grey, sandy, silty, and calcareous. The gamma-ray log character is generally coarsening upward and blocky to slightly ragged (Fig. 11).

The coarse-grained nature of this interval, log character, limited fossil occurrences, rounding of grains, and presence of glauconite is consistent with a shoreface setting. This interpretation is in good agreement with the shoreface, lower shoreface, and delta front interpretations of Miller and D'Eon (1987), as well as the shallow inner sublittoral setting proposed by LaBorde et al. (1974). This sandstone and conglomeratic interval comprises the Saglek Formation. Moir (1989) extended the top of the formation to 402 m, but it is restricted here to the top of the electric logs at 467 m, where coarse-grained clastic sedimentation is confirmed by log character. Accordingly, the Saglek Formation spans 724.8 m to 467 m (Table 16), and Williams (pers. comm. 2016) assigned an Early–Middle Miocene age for the base of the interval.

Lithostratigraphy

Based on the discussion around lithostratigraphic refinements to the framework of Moir (1989) in Gudrid H-55, the lithostratigraphic picks from the present study are summarized in Table 16. Modifications to type and reference sections are also noted.

Lithostratigraphic unit	**Moir (1989)**		**The present study**		**Type or reference section**
	Base (m)	**Top (m)**	**Base (m)**	**Top (m)**	
Saglek Fm	722	402	724.8	467	None
Mokami Fm	1679	722	1679	724.8	None
Kenamu Fm (Leif Mb)	1711	1679	--	--	None
Kenamu Fm	2180	1679	2179.3	1679	None
Gudrid Fm	2393	2180	2391.2	2179.3	Type section from 2393–2179 m of Umpleby (1979) and McWhae et al. (1980) is modified to 2391.2–2179.3 m
Markland Fm	2663	2393	2663	2391.2	Reference section from 2663–2393 m of McWhae et al. (1980) is modified to 2663–2391.2 m
Unnamed Paleozoic	2804	2663	2804	2663	None
Unnamed Precambrian	2838	2804	2838	2804	None

Table 16: Lithostratigraphic assignment for Gudrid H-55 from the present study and compared to that of Moir (1989). Fm=Formation; Mb=Member.

HEKJA O-71

In the northern part of the Saglek Basin, Hekja O-71 penetrated an important gas discovery offshore of Baffin Island (Fig. 1). The Aquitaine Company of Canada Ltd (1980b) well history report includes core descriptions and cuttings descriptions for the well from 4566–740 m. The re-entry into the well has a separate well history report with only general descriptions of the lower part of the well from 4566–3270 m (Aquitaine Company of Canada Ltd, 1980a). The most significant set of observations comes from Canadian Stratigraphic Service Ltd. Aquitaine Hekja O-71 log (log EC-150), which contains detailed lithological, grain size, grain rounding, and sample descriptions for the well. Dafoe and Williams (2020a) described and interpreted core 1 from the Gudrid Formation and cores 2 and 3 from the unnamed Paleogene basalts further down section. A plot of the Hekja O-71 well is shown in Figure 12, with key well logs, lithology, grain size, rock colour, ages, and paleoenvironmental and lithostratigraphic information shown. The ages from Williams (2007a) are used in the present study, based on discussion in Dafoe, DesRoches et al. (in press). A summary of the paleoenvironments described below are shown in Table 17, and these are further compared with previous studies of Miller and D'Eon (1987) and Williams (2007a), the latter based on palynomorphs, in the text below. The lithostratigraphic picks from Moir (1987a) and Dafoe, DesRoches et al. (in press) are compared with those of the present study in Figure 12 and Table 18.

Base (m)	Top (m)	Paleoenvironment
4566	3568	SHALLOW MARINE TO SUBAERIAL VOLCANIC ROCKS
3568	3545	SUBAERIAL VOLCANIC ROCKS
3545	3343	LAGOONAL
3343	3333	BARRIER BEACH
3333	3287	LAGOONAL
3287	3200	TIDAL CHANNEL AND MARSH
3200	3100	SHELFAL
3100	2975	LAGOONAL OR RESTRICTED MARINE EMBAYMENT
2975	2950	BARRIER BEACH
2950	2859	LAGOONAL TO MARSH
2859	2291	ESTUARINE
2291	2006	ESTUARINE TO BAYHEAD DELTA
2006	1976	SHELFAL
1976	1575	PRODELTA
1575	1504	DISTAL DELTA FRONT
1504	1415	DELTA FRONT
1415	1329	DISTAL DELTA FRONT
1329	1066	SHOREFACE
1066	1017	LOWER SHOREFACE
1017	963	SHOREFACE
963	952	LOWER SHOREFACE
952	795	SHOREFACE

Table 17: Paleoenvironmental determinations for Hekja O-71 from the present study.

Shallow marine to subaerial volcanic rocks

Between the depths of 4566 m and 3568 m is a thick interval comprising mostly igneous basalt, with tuffaceous units that are tens of meters thick. The basalt is brown to green and lesser purple to red, slightly mottled and weathered, calcareous, locally weathered, and locally argillaceous, with chert veins, numerous amygdales (calcite filled), rare zeolites, rare red staining along fractures, and rare serpentine. The volcanic tuff units are brown to green, slightly soft, mottled, ashy, partly phenocrystic, locally welded, locally brecciated, and contain calcite veins and rare amygdales. Very rare green shale also occurs near base of the interval, which is fissile and slightly calcareous. Forams, seeds, and spores were noted from 4005–3950 m, as well as rare indeterminate shell fragments. The gamma-ray log shows low API values, with corresponding high sonic velocity (Fig. 12).

The description of core 3 (4355.31–4351.6 m) and interpretation as a subaqueous hyaloclastic lava delta by Dafoe and Williams (2020a) is consistent with parts of the general description for this interval, primarily where basalt units are brecciated. Tuffaceous material can collect in a subaqueous or subaerial setting, but weathering suggests some subaerial conditions. Accordingly, the paleoenvironment is considered shallow marine to subaerial. The inclusion of forams and shell fragments further attests to some degree of marine accumulation, but green shales could have formed in subaerial settings under reducing conditions (Turner, 2003). The interpretation here is in accord with the inner shelf and inner neritic to marginal marine (mixed subaerial and subaqueous) settings of Miller and D'Eon (1987) and Williams (2007a). This thick interval forms the majority of a succession of unnamed basalts in the well. Despite the igneous lithology, Williams (2007a) assigned a Selandian to Thanetian (Middle to Late Paleocene) age, similar to the findings of Fenton and Pardon (2007) and Nøhr-Hansen et al. (2016).

Subaerial volcanic rocks

A thin interval at the top of the basalts from 3568 m to 3545 m shows a slight variation in log character, with higher API values and reduced sonic velocity and resistivity. The rock is green to red-brown and weathered. The description of core 2, which is found in this interval, includes a succession of volcaniclastic rocks with varicoloured clasts that were soft to indurated and showed signs of significant weathering (Dafoe and Williams, 2020a).

This interval appears to reflect a subaerially exposed, weathered basalt surface resulting in volcaniclastic accumulation and alteration. Accordingly, a subaerial or nonmarine setting is interpreted. Lying at the top of the unnamed basalt unit, this interval is Thanetian (Late Paleocene) according to Williams (2007a), as well Fenton and Pardon (2007) and Nøhr-Hansen et al. (2016).

Lagoonal

The interval spanning 3545 m to 3343 m is composed of silty shale with siderite. The grey silty shale locally grades to claystone and is slightly dolomitic, with siderite, minor mica, rare siltstone stringers, rare pyrite, and rare very fine-grained sand grains.

The lack of macrofossil content makes a paleoenvironmental assessment difficult. The silty shales are typical of middle shelf deposition, but the lack of fossil detritus is unusual. Conversely, the coarsening-upward nature of this interval and transition into the overlying thin sandstone as indicated by the gamma-ray log (Fig. 12), could suggest a lagoonal setting with restricted marine conditions that hampered faunal colonization. This paleoenvironmental interpretation is shallower than the inner to middle shelf or neritic conditions postulated by Miller and D'Eon (1987) and by Williams (2007a), but within reasonable range of these previous interpretations.

This interval defines the Cartwright Formation in the well, which is extended here to 3343 m above the top picked by Dafoe, DesRoches et al. (in press) at 3364 m, but below Moir's (1987a) top given at 3104 m (Table 18). This revision is made in order to better align with the lithological change to siltier and sandier strata at 3343 m, which is consistent with the overlying Gudrid Formation (*see* below). The Cartwright Formation thus spans 3545–3343 m in Hekja O-71 (Table 18), and Williams (2007a) gave a Thanetian (Late Paleocene) age for the succession, consistent with the findings of Fenton and Pardon (2007) and Nøhr-Hansen et al. (2016).

Barrier beach

The interval from 3343 m to 3333 m is composed of a coarsening-upward siltstone to sandstone unit with shale interbeds. Brown, sandy, dolomitic siltstone grades upward to brown, fine-grained, well sorted, dolomitic, silty, and argillaceous sandstone containing subangular grains and possible glauconite. Grey, dolomitic shale is less common in this interval. The gamma-ray log shows a clear coarsening-upward trend (Fig. 12).

The well sorted sandstone with possible glauconite is interpreted to be a barrier beach succession lying above the underlying lagoonal strata. A paucity of fossil material would be consistent with such a proximal setting and progradation is evident from the log character. Williams (2007a) interpreted inner neritic conditions above and below this interval, but Miller and D'Eon (1987) found a marginal marine beach setting, consistent with the present study. The base of the Gudrid Formation as defined in the present study is represented by this interval (Table 18), and is Thanetian (Late Paleocene) in age based on the findings of Fenton and Pardon (2007) and Nøhr-Hansen et al. (2016).

Lagoonal

There is a return to a shale-dominated succession between 3333 m and 3287 m. This silty, grey, dolomitic shale includes siltstone stringers, rare sand grains, and rare carbonaceous detritus. Notably, there is a sharp transition to the overlying interval (*see* below; Fig. 12).

A lack of macrofossil material within the shale makes a paleoenvironmental assessment difficult. The lithology is consistent with a middle or outer shelf setting, but the lack of fossil detritus is atypical. Based on the interpretations of the underlying and overlying shallow marine intervals (*see* below), the lack of fossil detritus may suggest restricted marine deposition. Accordingly, a lagoonal setting in which sedimentation by suspension dominated, but brackish conditions hampered marine fauna, is the most likely scenario. Miller and D'Eon (1987) also found this interval to be representative of a lagoonal paleoenvironment, and the inner shelf setting of Williams (2007a) is within range of the present interpretation.

This interval is included within the Gudrid Formation, but reflects an atypical lithology. Rather than separating the shalier intervals from the sandstone-dominated intervals, this thin succession is retained within the Gudrid Formation, consistent with the work of Moir (1987a) and Dafoe, DesRoches et al. (in press; Table 18). Williams (2007a) assigned a basal Ypresian (Early Eocene) age, but the Thanetian age indicated by Fenton and Pardon (2007) and Nøhr-Hansen et al. (2016) is more likely based on results from core 1 in the overlying interval (*see* below).

Tidal channel and marsh

The interval between 3287 m and 3200 m is missing significant cuttings information for much of the lower half of interval, otherwise the interval is dominated by sandstone with shale, coal, and siltstone (Fig. 12). Light brown, fine-grained sandstone is argillaceous and slightly calcareous, with siderite present. Siltstone units are brown and argillaceous, with siderite present. Grey shales contain coal stringers, and there are also black coal units. In regards to the overall interval, the gamma-ray log shows a sharp base to the sandstone and blocky to fining-upward units (Fig. 12).

Core 1 of the well samples this interval (3257.1–3250.1 m) and was interpreted as a tidal channel succession with significant terrestrial influx (Dafoe and Williams, 2020a). Channelized deposits are confirmed by the fining-upward log character also interpreted here to be tidal in origin, with a marsh setting accounting for the shalier units and abundance of coal. Miller and D'Eon (1987) determined a similar marginal marine setting, but they suggested fluvial channels, meandering estuarine settings, and marsh deposits. Williams (2007a) indicated continued inner neritic deposition, in reasonable agreement with the present study.

This part of the well is attributed to the Gudrid Formation. Moir (1987a) defined the Gudrid Formation to include the shaly lagoonal succession from 3333 m to 3287 m, with the base of the formation extending deeper in the well and apparently based on a change in log character and the paleoenvironmental interpretations of Miller and D'Eon (1987). In the present study, the top of the Gudrid Formation is brought higher in the well to 3200 m to the top of coal beds and a break in lithology and log character with the overlying shelfal strata (*see* below). At this depth, there is a sharp increase in the gamma-ray log and sonic velocity, with a decrease in resistivity (Fig. 12). Above his Gudrid Formation, Moir (1987a) placed a second interval of Cartwright Formation, but Dafoe, DesRoches et al. (in press) designated this shale to the base of the Kenamu Formation (Fig. 12). In the present study, we agree with the findings of Dafoe, DesRoches et al. (in press), but extend the Gudrid Formation to 3200 m (Table 18). While the Gudrid Formation is generally not considered to include shale and coal intervals (Dafoe, Dickie et al., in press), shallow marine paleoenvironments in the northern part of the Saglek Basin dominate the succession (Dafoe, DesRoches et al., in press). In terms of the age, core 1 provides evidence for a latest Thanetian (Late Paleocene) age based on the findings of Dafoe and Williams (2020a), but the cuttings were found to be basal Ypresian (Early Eocene; Williams, 2007a) or Thanetian (Late Paleocene; Fenton and Pardon, 2007; Nøhr-Hansen et al., 2016) in age. Accordingly, a Thanetian–basal Ypresian age is likely for the entire interval.

Shelfal

Grey to brown shale and/or claystone characterizes the interval from 3200 m to 3100 m. These fine-grained strata are partly silty and contain siderite, rare limestone stringers, rare carbonaceous flakes, rare coal fragments, rare sand grains, rare foraminifera ((?)Rotaliida), and glauconite at the base of the interval. The overall gamma-ray signature shows a generally fining-upward succession (Fig. 12).

The presence of foraminifera to the exclusion of other fossils suggests at least shelfal conditions. In addition, the glauconite at the base of the unit implies a period of initially low sedimentation rates consistent with transgression at the base of the Kenamu Formation (Balkwill and McMillan, 1990; Dickie et al., 2011; Dafoe, Dickie et al., in press) and with the fining-upward log character. The presence of carbonaceous and coal material reflects some terrestrial influx, but could also reflect reworking. It is difficult to narrow down a setting other than to indicate shelfal conditions. Inner to middle shelf settings were reported by others (Miller and D'Eon, 1987; Williams, 2007a), relatively consistent with the present study. Forming the base of the Kenamu Formation as defined in the present study, this shale and claystone interval is basal Ypresian (Early Eocene) according to Williams (2007a).

Lagoonal or restricted marine embayment

Claystone dominates the interval from 3100 m to 2975 m in Hekja O-71. The claystone is brown, with increasing silt content up section, siderite bands, rare mica, and rare coal fragments.

The fine-grained nature of the strata and lack of fossils suggests possible restricted marine deposition. The coarsening-upward nature into the overlying beach interval above (*see* below) is suggestive that the setting could be lagoonal or a restricted marine embayment. Similar shallow marine settings (inner shelf) to nonmarine were interpreted previously (Miller and D'Eon, 1987; Williams, 2007a). This interval forms part of the Kenamu Formation, and Williams (2007a) determined an age of Ypresian (Early Eocene) for this part of the well, in good agreement with other studies (Fenton and Pardon, 2007; Nøhr-Hansen et al., 2016).

Barrier beach

From 2975 m to 2950 m, is a thin, coarsening-upward claystone to sandstone interval. The lithology does not imply a dominance of sandstone up section, but the decrease in gamma-ray values is consistent with sandstone accumulation. From the lithological information, the claystone is brown and silty, and includes increasing sand content upward (very fine- to fine-grained), sandstone stringers, common siderite, and rare mica.

The cuttings history appears to be somewhat misleading and the logs suggest a much sandier succession with a clear coarsening-upward profile. The presumed sandy nature, thin, coarsening-upward profile of this interval and lack of fossils is interpreted to indicate barrier beach progradation. Miller and D'Eon (1987) also suggested a beach paleoenvironment and the inner neritic to nonmarine interpretation of Williams (2007a) is also within range of the present study's interpretation. This interval was assigned a Ypresian (Early Eocene) age by Williams (2007a), in good agreement with Fenton and Pardon (2007) and Nøhr-Hansen et al. (2016), and forms part of the Kenamu Formation.

Lagoonal to marsh

In the interval from 2950 m to 2859 m, claystone dominates the succession, with coaly horizons and rare thin sandstones and limestones. Brown, slightly sandy, silty claystone is siderite-bearing and locally grades to shale. Coal stringers and partings are more common at top of interval. Brown to white, medium- to coarse-grained sandstone is further characterized by very coarse-grained sand grains, subangular grains, moderate to poor sorting, and very rare indeterminate shell fragments. Less common limestone units are white, sandy, and slightly silty. The gamma-ray log character varies from fining-upward to more ragged.

Increasing coal content up section in the interval and the fine-grained nature of the strata and limited fossil detritus suggests lagoonal to marsh deposition. The thin sandstones may represent wash-over deposits, channels, or barrier beaches. Marginal marine to nonmarine deposition was proposed by Miller and D'Eon (1987) including estuarine and lagoonal setting, and Williams (2007a) also found nonmarine to inner shelf conditions for this part of the well, both in agreement with the present study. This interval is also found within the Kenamu Formation, and Williams (2007a) gave this part of the well a Ypresian (Early Eocene) age, which agrees with the findings of Fenton and Pardon (2007) and Nøhr-Hansen et al. (2016).

Estuarine

Silty and sandy claystone characterize the succession from 2859 m to 2291 m. The gamma-ray values are lower than expected for claystone, possibly due to the generally sandy nature of the interval (Fig. 12). The claystone is grey-brown, partly sandy to very sandy, siderite bearing, and silty. Siderite stringers, fine- to medium-grained sand grains, rare mica, rare sandstone stringers, rare glauconite, rare carbonaceous flakes, rare shaly horizons, rare indeterminate shell fragments, rare interbedded limestone, and rare coal fragments are also present. Very rare sandstone units are medium-grained, light brown, subangular, and moderately sorted. The overall log character shows a ragged profile consistent with lithological heterogeneity, but also show an increase in API values suggestive of an overall fining-upward character.

The sandy nature of the claystone, combined with a lack of fossil material indicates shoreline proximity, but restricted marine conditions. The fining-upward trend can be interpreted to reflect relative sea level rise within an estuarine setting, possibly within a central estuarine setting where sandy claystones could reflect a mix of the central basin mudstones with wash-over and bayhead delta deposits (Dalrymple et al., 1992). Similar settings were proposed by Miller and D'Eon (1987), including lagoonal, brackish, and interdeltaic, but they also suggested nonmarine and possible lacustrine settings. Williams (2007a) interpreted nonmarine, marginal marine, and inner neritic settings, in relative agreement with the present study. This thick interval comprises a significant portion of the Kenamu Formation, and based on the age assignments of Williams (2007a) it is Ypresian (Early Eocene) to Lutetian (Middle Eocene), an age determination supported by the findings of Nøhr-Hansen et al. (2016). Moir (1987a) suggested that the upper part of this interval equated to the Leif Member of the Kenamu Formation (Fig. 12; Table 18), but this was rejected by Dafoe, DesRoches et al. (in press) and in the present study, as the lithology is atypical for that sandstone-dominated member.

Estuarine to bayhead delta

Sandy and silty claystone with sandstone, rare siltstone, rare limestone, and rare dolostone units is present between the depths of 2291 m to 2006 m. Brown, silty, sandy to very sandy claystone comprises most of the interval, with sandstone units also common. The sandstone units are light brown to white, very argillaceous, slightly calcareous, fine- to coarse-grained, and moderately to poorly sorted. They further contain very coarse-grained sand grains, subangular grains, scattered light and dark chert fragments, and rare quartz pebbles. Limestones are white, weathered, and silty, with coal fragments, rare very coarse-grained sand grains, and rare carbonaceous flakes. Black coal partings are locally seen, as well as brown, silty, argillaceous dolostone. Siltstone units are grey-brown and argillaceous. The ragged gamma-ray profile shows both coarsening- and fining-upward trends, with an overall coarsening-upward nature within the sandstone units (Fig. 12).

The gamma-ray profile, lack of fossil material, and mixed lithology suggests bayhead delta influence within an estuarine setting. Nonmarine deltaic, fluvial, and lacustrine settings were proposed by Miller and D'Eon (1987), but the lithology and presence of limestones suggests a shallow marine nature. Williams (2007a) found a nonmarine to marginal marine signature, similar to the present study. This interval lies within the Kenamu Formation as described by Dafoe, DesRoches et al. (in press) and in accord with the present study (Fig. 12; Table 18). According to Williams (2007a), this interval is Lutetian (Middle Eocene) in age, which agrees well with the findings of both Fenton and Pardon (2007) and Nøhr-Hansen et al. (2016).

Shelf

A thin, silty claystone interval between the depths of 2006 m and 1976 m shows a significant change in the paleoenvironment relative to the underlying interval. The claystone is silty and calcareous, with indeterminate shell fragments, rare limestone, and rare coal. Notably, the gamma-ray log values are high and there is a striking lack of sand in this interval (Fig. 12).

This interval resembles the under and overlying units, except for the presence of fossil material and evident break in the overall sandy claystone succession. The presence of fossil fragments suggests more marine conditions and transgressive flooding indicative of shelfal deposition; however, a precise setting cannot be determined. A more distal marine setting was not noted by previous authors, where they interpreted nonmarine to marginal marine conditions (Miller and D'Eon, 1987; Williams, 2007a). This discrepancy could be explained by the thin nature of the interval and averaging of cuttings samples, or by cavings affecting palynomorph assemblages. Residing within the thick Kenamu Formation defined previously (Dafoe, DesRoches et al., in press) and also for the present study, this interval was assigned a Lutetian (Middle Eocene) age by Williams (2007a), an age assignment that agrees well with the findings of Fenton and Pardon (2007) and Nøhr-Hansen et al. (2016).

Prodelta

The interval from 1976 m to 1575 m is composed of sandy, silty claystone with sandstone beds and rare limestone, siltstone, and conglomerate beds. Claystones are brown, silty, sandy (very fine-grained), and partly calcareous, and include thin sandstone stringers, limestone stringers, rare carbonaceous flakes, rare very coarse-grained sand grains, and rare indeterminate shell fragments.

Brown to white sandstone is medium- to coarse-grained, partly calcareous, and argillaceous, with limestone stringers, very coarse-grained sand grains common throughout, scattered dark and light chert, subrounded clasts, and rare quartz pebbles. Brown, sandy, argillaceous siltstone is also present, as well as cream, argillaceous, slightly sandy limestone, with indeterminate fossil fragments. Thin, varicoloured conglomerate units include quartz and chert pebbles, pyrite, and interbedded claystone. Gamma-ray log signatures for this interval exhibit a ragged, heterolithic character, but with increasing sand and lower API values up section (Fig. 12).

The heterolithic nature of the strata and sandy character of the claystone suggests relative proximity to the shoreline. Furthermore, the lack of fossil material implies a restricted marine, or brackish setting. The increase in sandstone up section and thickening of sandstone beds upward implies a prodeltaic setting. This interpretation agrees well with the coastal-marginal marine to inner neritic interpretation of Williams (2007a), but Miller and D'Eon (1987) suggested a nonmarine lacustrine delta front setting or alluvial fan delta. This interval is found near the top of the Kenamu Formation defined by Dafoe, DesRoches et al. (in press) and the present study. According to Williams (2007a) and Nøhr-Hansen et al. (2016) this sandy claystone is latest Lutetian to Bartonian (Middle Eocene) in age.

Distal delta front

An overall coarsening- and cleaning-upward interval with thicker sandstone beds up section occurs between the depths of 1575 m and 1504 m. Sandstones are white to brown, medium- to coarse-grained, poorly sorted, and argillaceous, and contain quartz pebbles, very coarse-grained sand grains, subrounded clasts, and dark and light chert. Grey, silty, partly to very sandy claystone also contains limestone stringers, sandstone stringers, and rare chert grains. The gamma-ray profile shows several, coarsening-upward units (Fig. 12).

The overall rounding of sand grains, as well as the coarse-grained nature of the sandstone, suggests more prevalent reworking in a relatively high-energy setting. The coarsening- and cleaning-upward of the interval are interpreted to indicate progradation, and the interbedded lithology is consistent with distal delta front deposition. This setting is similar to the marginal marine to inner neritic settings proposed by Williams (2007a), but Miller and D'Eon (1987) determined nonmarine lacustrine delta front to fluvial or alluvial fan accumulation. This sandstone-dominated section of the well forms part of the Leif Member of the Kenamu Formation as designated by Dafoe, DesRoches et al. (in press) and followed in the present study, which differs greatly from the lithostratigraphic assignment of Moir (1987a; Fig. 12; Table 18). Williams (2007a) determined a Bartonian age for this part of Hekja O-71, in agreement with the age assignment of Nøhr-Hansen et al. (2016).

Delta front

The interval spanning 1504 m to 1415 m is composed of thin claystones that are interbedded between thicker sandstone units. Sandstones are brown to white and fine- to coarse-grained (mostly coarse-grained), with pyrite, siderite, very coarse-grained sand grains, subangular to subrounded grains, moderate to poor sorting, scattered chert, scattered quartz pebbles, and minor glauconite near the top of the interval (also noted in sidewall core). Thin claystone units are grey and sandy, and include rare siderite. The sandstones are somewhat blocky to ragged in the gamma-ray log (Fig. 12).

The overall thickness of the sandstone units, with some claystone interbedding is consistent with a delta front setting. The ragged gamma-ray log character and lack of fossils further support a deltaic and brackish setting, respectively. This agrees well with the coastal-marginal marine to inner neritic settings interpreted by Williams (2007a), but the nonmarine settings reported by Miller and D'Eon (1987) are not supported by the above evidence, as glauconite is a marine indicator. This interval caps the top of the Kenamu Formation, as well as the Leif Member. Dafoe, DesRoches et al. (in press) assigned the Leif Member to 1575–1415 m based on both the sandstone-dominated lithology and top

Bartonian age, consistent with the lithostratigraphic framework described by Dafoe, Dickie et al. (in press; Table 18). Accordingly, the lithostratigraphic assignment for the Kenamu Formation is 3200–1415 m according to the present study (Table 18). This sandstone unit is Bartonian (Middle Eocene) in age based on findings of both Williams (2007a) and Nøhr-Hansen et al. (2016).

Distal delta front

A thicker claystone is present at the base of the interval from 1415 m to 1329 m and is followed by thick sandstone beds, with thinner claystone units. The sandstones are white to grey, medium- to coarse-grained, clayey, argillaceous, locally silty, and slightly calcareous, with quartz pebbles, very coarse-grained sand grains, and scattered chert. The claystone units are grey, very sandy, and silty. In the gamma-ray log, coarsening-upward units are evident (Fig. 12).

The clear interbedding of claystone with coarse-grained sandstone is consistent with a high-energy distal delta front setting during progradation. This interpretation is similar to the marginal marine to inner neritic and inner shelf settings proposed by previous authors (Miller and D'Eon, 1987; Williams, 2007a). The claystone at the base of the interval was proposed to be nonmarine by Miller and D'Eon (1987), however, this is unlikely given the nature of the under- and overlying strata.

This interval forms the base of the Saglek Formation, with the thin shale break corresponding to a log break between the formations. The overall interval is latest Bartonian to Priabonian (Middle to Late Eocene) according to Williams (2007a), but this age in older than is generally seen for the Saglek Formation along the Labrador margin (Dafoe, Dickie et al., in press). However, as described by Balkwill and McMillan (1990) and Dafoe, DesRoches et al. (in press), strata in the northern part of the Saglek Basin are generally representative of more proximal paleoenvironments compared to strata encountered farther south, resulting in older ages for the Saglek Formation. Accordingly, Dafoe, DesRoches et al. (in press) did not recognize a Mokami Formation in Hekja O-71, which is in accord with the present study (Fig. 12; Table 18).

Shoreface

A thick sandstone succession is present between 1329 m and 1066 m and is dominated by medium- to coarse-grained (mostly coarse-grained) sandstone that is white to grey, only locally silty, and slightly calcareous. The sandstones further contain pyrite, abundant light and dark chert and quartz pebbles, very coarse-grained sand grains throughout, thin conglomerate beds, subrounded grains, moderate to poor sorting, and rare indeterminate shell fragments in the upper half of the interval. The gamma-ray log character is somewhat ragged to partly blocky (Fig. 12).

The grain size, relatively blocky gamma-ray log character, lack of claystone interbeds, and influx of some fossil material is suggestive of shoreface deposition. Williams (2007a) also found a marine signature based on dinocysts, and his nonmarine to marginal marine to inner neritic settings are relatively consistent with the present interpretation. Miller and D'Eon (1987) also found similar marginal marine to inner shelf (delta front) settings. This sandstone forms part of the Saglek Formation and is Priabonian (Late Eocene) to Rupelian (Early Oligocene) in age based on the findings of Williams (2007a) and Nøhr-Hansen et al. (2016).

Lower shoreface

Compared to the underlying interval, there is a lithological change at 1066 m to 1017 m to a finer-grained sandstone with limestone and claystone interbeds. Sandstone units are more thinly bedded and are light grey, fine- to coarse-grained (mostly fine-grained), calcareous, glauconitic, and argillaceous. These rocks further include very coarse-grained sand grains throughout, subangular grains, moderate sorting, common bivalve fragments, scattered pebbles, and scattered light and dark chert. Cream limestones contain abundant bivalve fragments, and grey claystones are sandy and silty.

The decrease in grain size compared to the underlying sandstone succession, presence of enhanced fossil content and limestone beds, with more common glauconite suggests a slight increase in water depth relative to the underlying shoreface interval and consistent with a lower shoreface paleoenvironment. This interpretation is in reasonable agreement with the marginal marine to inner shelf settings suggested by previous authors (Miller and D'Eon, 1987; Williams, 2007a), but the slight increase in water depth proposed in the present study was not recorded in their findings. This sandstone is attributed to the Saglek Formation, and was assigned to the Rupelian (Early Oligocene) by Williams (2007a) and Nøhr-Hansen et al. (2016).

Shoreface

Thickly bedded sandstones characterize the succession from 1017 m to 963 m. The sandstone is white to varicoloured, coarse-grained, and poorly sorted, and also contains very coarse-grained sand grains throughout, common bivalve and indeterminate shell fragments at the base of the interval, subrounded grains, scattered light and dark chert, and scattered quartz pebbles. The gamma-ray log profile indicates a relatively blocky succession (Fig. 12).

The thickly bedded sandstones, blocky gamma-ray log character, fossil lag at the base of the interval, and grain rounding suggest shoreface deposition. This setting is in agreement with the inner shelf (delta front) setting proposed by Miller and D'Eon (1987), and the nonmarine to marginal marine interpretation of Williams (2007a). This part of the Saglek Formation was given a Rupelian age by Williams (2007a) and Nøhr-Hansen et al. (2016).

Lower shoreface

The interval spanning 963 m to 952 m includes thinly bedded sandstones and claystones. At the base of the interval, brown, sandy, silty claystone contains scattered indeterminate shell fragments and possible bivalve fragments. Light grey, fine- to coarse-grained, calcareous sandstone also includes indeterminate shell fragments, interbedded grey shale, quartz pebbles, conglomeratic beds, very coarse-grained sand grains, subangular to subrounded grains, moderate to poor sorting, scattered chert grains, and rare pyrite. The gamma-ray log is overall coarsening-upward (Fig. 12).

The finer-grained, more thinly bedded, and calcareous nature of the sandstone, with the inclusion of claystone suggests a slight increase in water depth to a lower shoreface setting. The coarsening-upward nature indicates a subsequent return to shoreface progradation. Williams (2007a) documented marginal marine to nonmarine conditions and Miller and D'Eon (1987) reported an inner shelf ((?)deltaic) setting, both in range of the present study's interpretation. This part of the Saglek Formation was considered to be Rupelian by Williams (2007a) and Nøhr-Hansen et al. (2016).

Shoreface

The uppermost part of Hekja O-71 between 952 m and 795 m shows a return to thickly bedded, coarse-grained sandstone. The coarse-grained sandstone contains subrounded grains, is moderately to poorly sorted, white to brown-yellow, and locally calcareous, with pebbles throughout, very coarse-grained sand grains throughout, scattered light chert, and minor feldspar. The gamma-ray log character is generally blocky and consistent with coarse-grained sandstone accumulation (Fig. 12).

The log profile, coarse-grained nature, and grain rounding suggest a shoreface paleoenvironment. This agrees with Williams' (2007a) inner neritic to nonmarine to marginal marine interpretations, but Miller and D'Eon (1987) suggested a nonmarine deltaic braid plain setting, that does not conform well with the blocky log signature. This interval comprises the upper part of the Saglek Formation, which Dafoe, DesRoches et al. (in press) continued to 417 m at the top of the electric logs (Fig. 12; Table 18). The age of this interval is latest Rupelian, Chattian, and Miocene as indicated by

Williams (2007a) and similar to the interpretation of Nøhr-Hansen et al. (2016). Accordingly, the Saglek Formation extends from 1415 m to 417 m (Table 18).

Lithostratigraphy

Based on the discussion around lithostratigraphic refinements to the framework of Dafoe, DesRoches et al. (in press) and Moir (1987a) in Hekja O-71, the lithostratigraphic picks from the present study are summarized in Table 18. There are no type or reference sections in Hekja O-71.

Lithostratigraphic unit	**Moir (1987a)**		**Dafoe, DesRoches et al. (in press)**		**The present study**		**Type or reference section**
	Base (m)	**Top (m)**	**Base (m)**	**Top (m)**	**Base (m)**	**Top (m)**	
Saglek Fm	1730	363	1415	417	1415	417	None
Mokami Fm	2175	1730	--	--	--	--	None
Kenamu Fm (Leif Mb)	2428	2175	1575	1415	1575	1415	None
Kenamu Fm	3104	2175	3212	1575	3200	1415	None
Gudrid Fm	3364	3212	3364	3212	3343	3200	None
Cartwright Fm	3545	3104	3545	3364	3545	3343	None
Unnamed basalts	4566	3545	4566	3545	4566	3545	None

Table 18: Lithostratigraphic assignment for Hekja O-71 from the present study and compared to that of Moir (1987a) and Dafoe, DesRoches et al. (in press). Fm=Formation; Mb=Member.

HERJOLF M-92

Near the Bjarni wells in the Hopedale Basin is the Herjolf M-92 well (Fig. 1). The well history report for this well (Ferrero and Plé, 1977a) contains descriptions for both cuttings and sidewall cores that were used in the present study. The Canadian Stratigraphic Service Ltd. Eastcan et al Herjolf M-92 log (log EC-120) includes the most comprehensive information for the well, with detailed lithological, grain size, grain rounding, and sample descriptions for the well. Four conventional core intervals from Herjolf M-92 were assessed by Dafoe and Williams (2020a) including two from the Bjarni Formation, one from the Alexis Formation (4048–3751 m), and one from the unnamed Precambrian basement rock at the base of the well (4086–4048 m). In Figure 13, a plot of Herjolf M-92 is shown, with key well logs, lithology, grain size, rock colour, and ages, as well as paleoenvironmental and lithostratigraphic information. The ages from Williams (1979) and Ainsworth et al. (2014) are used in the present study, with consideration of the work by Fenton and Pardon (2007). A summary of the paleoenvironments described below are listed in Table 19. Gradstein (1977a) determined paleoenvironments based on micropaleontology and Miller and D'Eon (1987) also provide results for Herjolf M-92, both of which are compared with those derived from the present study in the descriptions below. The lithostratigraphic picks from Moir (1989) are modified in the present study as shown in Figure 13 and in Table 20.

At the base of the well, the unnamed Precambrian basement rock and the Alexis Formation basalts are well defined by their log and lithological characteristics as shown in Figure 13. The reference section from 4048–3751 m of McWhae et al. (1980) is retained (Table 20).

Base (m)	Top (m)	Paleoenvironment
3750.9	3696.0	NONMARINE FLUVIAL
3696.0	3541.8	DELTAIC AND RESTRICTED MARINE EMBAYMENT
3541.8	2804.2	NONMARINE ALLUVIAL FAN DELTA AND LACUSTRINE
2804.2	2614.6	DELTA FRONT AND INTERMITTENT NONMARINE CONDITIONS
2614.6	2438.4	OUTER SHELF
2438.4	2286.0	SLOPE
2286.0	2126.0	OUTER SHELF
2126.0	2042.2	SHELF EDGE
2042.2	1859.3	OUTER SHELF
1859.3	1688.6	MIDDLE SHELF
1688.6	1566.7	OUTER SHELF
1566.7	1402.0	MIDDLE SHELF
1402.0	1356.3	OUTER SHELF
1356.3	944.9	MIDDLE SHELF
944.9	773.6	INNER SHELF
773.6	454.2	SHOREFACE

Table 19: Paleoenvironmental determinations for Herjolf M-92 from the present study.

Nonmarine fluvial

The base of the sedimentary succession includes an interval of brown-grey shales and light brown-grey to green sandstones from 3750.9 m to 3696 m (12306–12126 ft.). Coal is commonly interbedded in the shales at the base of the overall interval. The shales are dark brown-grey, platy, and silty, with siderite nodules, sandstone stringers, plant remains, and coal fragments. Sandstone units increase in thickness and abundance up section and are fine- to coarse-grained, moderately sorted, and silty. The sandstones notably contain common feldspar and common kaolinite (altered feldspar), as well as plant remains, angular grains, siliceous and calcareous cements, shale stringers, coal fragments, localized mottled white and green units, scattered coal stringers, and rare chlorite.

The interbedding of sandstone and shale indicates varying energy regimes during deposition. This, combined with the abundance of coal and plant detritus suggests a fluvial setting. The lack of fossil material, greenish colouration of the sandstones, and mottling further suggest a nonmarine setting, with possible accumulation under reducing conditions (Myrow, 2003) and incipient soil formation. The sandstones do not appear to show channel-like successions, and this may be related to the fluvial style, as ephemeral or sheet-like channels can occupy an early rift setting (e.g., Castro et al., 2019). This shalier expression of the Bjarni Formation is consistent with the Snorri Member and is Barremian–Aptian in age according to both Williams (1979e) and Ainsworth et al. (2014), but Fenton and Pardon (2007) indicated Aptian–Albian was also possible.

Deltaic and restricted marine embayment

The interval from 3696 m to 3541.8 m (12126–11620 ft.) is characterized by a mix of shales and sandstones, with only rare coal. The shales are dark brown-grey, silty, and platy, and include sandstones stringers, common plant detritus near the top of the interval, pyrite, and rare coal fragments. Sandstones are light cream to light grey, fine- to medium-grained, very calcareous, moderately sorted, argillaceous, and silty, with common feldspar and kaolinite (weathered feldspar) and subangular grains. Some roughly coarsening-upward units are seen in the gamma-ray log (Fig. 13).

There is a subtle lithological difference between this interval and the underlying interval: a lack of coal, lack of green colouration, no mottled horizons, and an increase in the calcareous nature of the sandstones. In addition to this, core 2 falls within this interval of the well (3564.07–3561.02 m) and was interpreted as a highly brackish, restricted marine bay deposit (Dafoe and Williams, 2020a). Accordingly, a lack of nonmarine indicators, a lack of fossil detritus, the heterolithic lithology, and the nature of core 2 suggest a deltaic and restricted marine embayment setting for the entire interval. Contrary to this, Miller and D'Eon (1987) proposed a nonmarine fluvial (braided, meandering, lacustrine, and delta front) setting, which does not appear to be consistent with the evidence described above.

This succession forms the upper part of the Snorri Member of the Bjarni Formation as designated in the present study. Moir (1989) took the top of the member to 3550 m, but it is extended in the present study to the top of this interval at 3541.8 m where there is a significant lithological change (Fig. 13; Table 20). The age of this interval is Barremian–Aptian or Aptian–Albian based on previous studies (Williams, 1979e; Fenton and Pardon, 2007; Ainsworth et al., 2014), with a Barremian–Aptian age confirmed by core 2 (Dafoe and Williams, 2020a).

Nonmarine alluvial fan delta and lacustrine

A thick interval of blocky sandstones and thin shales persists from 3541.8 m to 2804.2 m (11620–9200 ft.). The sandstones are often mottled orange or pink to white, or grey, brown or light cream, with a grain size that increases slightly up section from dominantly medium-grained to more coarse-grained at the top of the overall interval. The sandstones are silty, highly feldspathic, locally argillaceous, and locally siliceous, with common kaolinite and the inclusion of very coarse-grained sand grains and pebbles (feldspar) increasing upward. Grains are mostly subangular to lesser subrounded and poorly sorted. The sandstones are further locally calcareous, with rare coal, rare chert, rare chlorite, rare wood, rare mica, and rare bioturbation is noted at several depths. Brown-grey shale is dark grey, platy, silty, and micaceous, and also contains coal and one instance of fish remains (3242.9 m, 10640 ft.). The API values are somewhat high for sandstones, but this is related to the feldspathic composition (Umpleby, 1979), and sandstones show a variety of gamma-ray log shapes, but are generally blocky (Fig. 13).

The varicoloured and mottled nature of the sandstone is suggestive of oxidizing conditions likely related to subaerial exposure (Turner, 2003). Localized evidence of mottling and bioturbation in the sandstones may be suggestive of pedogenic-like conditions. However, fish remains in the shale may indicate periodic subaqueous conditions, with the presence of wood and coal attesting to measurable terrestrial influx. Overall the setting appears to be nonmarine with alluvial fan delta accumulations accounting for the poorly sorted, coarse-grained, and subaerial nature of the sandstone accumulations, while the shales may indicate some shallow aquatic conditions, possibly lacustrine. Miller and D'Eon (1987) also suggested a nonmarine setting, but they interpreted fluvial (braided) and alluvial fan or fan-delta accumulations. This thick interval forms a significant portion of the Bjarni Formation, and was assigned a Barremian–Aptian age by Williams (1979e), although a younger early Aptian–middle Albian age may also be possible (Ainsworth et al., 2014).

Delta front and intermittent nonmarine conditions

While the lithology resembles that of the underlying interval, there are subtle differences in the interval spanning 2804.2 m to 2614.6 m (9200–8578 ft.). This interval is characterized by white to light grey or cream, blocky to thin sandstones with lesser grey shales. The sandstones are coarse- to very coarse-grained, argillaceous, micaceous, poorly to moderately sorted, rarely mottled or pink to orange in colour, with subangular to subrounded grains (subrounded, especially at the top of the interval), abundant feldspar, common kaolinite, feldspar and granitic pebbles, rare glauconite throughout, scattered pyrite, common chert fragments at the top of the interval, and rare coal and siderite nodules. Shale units are thin, glauconitic, and locally sandy, with siderite nodules, pyrite, and rare coal stringers. The gamma-ray log is characteristically ragged, but with blockier sandstones occurring in the upper part of the interval (Fig. 13).

The presence of glauconite and lack of mottled and oxidized sandstones suggests shallow marine conditions. In addition, increased sorting and grain rounding are consistent with enhanced reworking and increased maturity of the sediment, typical of shallow marine settings under intense wave activity. The presence of a few mottled horizons, however, indicates some remaining periods of nonmarine deposition. Furthermore, core 1 (2639.9–2632.28 m) was interpreted as a river-influenced delta front and distributary channel succession (Dafoe and Williams, 2020a). This interpretation agrees with the ragged gamma-ray log signature and indicates that much of the interval likely reflects delta front deposition, with an increasing marine signature up section and some interfingering of nonmarine deposits near the base of the interval. This interpretation is similar to that of Miller and D'Eon (1987) as they proposed nonmarine deposition shifting to marginal marine to inner shelf, delta front conditions up section.

Forming the top of the Bjarni Formation, this interval was assigned an Albian to Albian–Cenomanian age by Williams (1979e), late Albian by Ainsworth et al. (2014), and late Albian to possibly Coniacian age by Fenton and Pardon (2007). However, near the top of this interval, Dafoe and Williams (2020a) found the coarse-grained sandstones and thin shales of core 1 to be Albian in age, implying that neither Cenomanian nor Coniacian section is likely present as suggested by the results derived from cuttings. In the present study, the top of the Bjarni Formation is also modified slightly to 2614.6 m, which modifies the type section of Umpleby (1979) and McWhae et al. (1980) to 3751–2614.6 m (Table 20).

Outer shelf

Lying above the sandstones of the Bjarni Formation is a succession of silty shale from 2614.6 m to 2438.4 m (8578–8000 ft.). The silty grey-brown, micro-micaceous shales have common siderite nodules and glauconite throughout, with scattered pyrite and rare calcareous intervals. Generally fragmented fossil material includes rare foraminifera, crinoids, bivalves, Inoceramus, and tubular structures.

The presence of glauconite throughout the interval is consistent with the onset of marine transgression (Amorosi, 2003) that characterizes the Markland Formation (*see* Dickie et al., 2011; Dafoe, Dickie et al., in press). The diversity of fossil material indicates a normal marine setting, and the silty nature of the shale indicates significant distance from the shoreline that is consistent with an outer shelf paleoenvironment. It is unclear why Miller and D'Eon (1987) interpreted nonmarine (delta plain) to inner shelf conditions for this shale interval, but their bathyal setting, and the deep neritic to bathyal interpretation of Gradstein (1977a), are in range of the outer shelf setting proposed here.

This shale interval contrasts with the underlying Bjarni Formation sandstones and forms the base of the Markland Formation. Williams (1979e) interpreted an Albian–Cenomanian and Santonian to Maastrichtian age; however, as discussed below, the Cenomanian age is suspect and there is no evidence of missing section between the Cenomanian and Santonian–Campanian units defined by Williams (1979e). Ainsworth et al. (2014) suggested a Santonian age and an unconformity with missing Campanian section, with the Maastrichtian at the top of the interval. Again, there is no evidence of missing or condensed section in this shale interval. Fenton and Pardon (2007) further assigned Coniacian to late Maastrichtian ages, similar to that of Williams (1979e). Based on these results, an Upper Cretaceous age is certain, and the likely age of this interval is Santonian to Maastrichtian. The base of the Markland is modified slightly to 2614.6 m in the present study as described above (Table 20).

Slope

The interval from 2438.4 m to 2286.0 m (8000–7500 ft.) is composed of a succession of intermittently silty shale. This grey to brown shale is locally silty, platy, and fossil barren, and contains common pyrite, rare siderite nodules, and rare limestone stringers.

The overall lack of fossil material and platy shales with pyrite present suggests reducing conditions (Wilkin, 2003) and is interpreted to represent a distal marine setting consistent with slope-equivalent water depths. This is similar to the deep neritic to bathyal and bathyal settings of Gradstein (1977a) and Miller and D'Eon (1987), respectively. This interval forms part of the Markland Formation, and is Maastrichtian to Early Paleocene according to Williams (1979e), likely Danian (Early Paleocene) based on the findings of Fenton and Pardon (2007). Ainsworth et al. (2014) proposed an unconformity between the Maastrichtian and Selandian (Middle Paleocene), which could reflect a condensed interval. However, Dafoe, Dickie et al. (in press) found Danian section to be present in several Labrador Shelf wells, whereas Ainsworth et al. (2014, 2016) suggested that Danian strata were absent along the margin.

Outer shelf

From 2286.0 m to 2126.0 m (7500–6975 ft.) is an interval of grey-brown shale with limestone beds. The shale is silty, platy, partly calcareous, and glauconitic in the upper half of the interval, and is further characterized by siderite nodules throughout, limestone stringers, fossil fragments (gastropod and foraminifera), and rare pyrite. Dark brown, silty, argillaceous limestone contains glauconite and siderite nodules.

In relation to the underlying interval, there is an increase in silt content and the presence of some fossil material indicating a shallowing to outer shelf conditions. Increased limestone is consistent with this interpretation, but the presence of glauconite indicates low sedimentation rates. Relative to the under- and overlying intervals, this slight shallowing was not noted by previous authors (Gradstein, 1977; Miller and D'Eon, 1987), but is within range of their deep neritic to bathyal interpretations.

This interval spans the uppermost Markland Formation and the entire Cartwright Formation as they are defined in the present study (Fig. 13; Table 20). Williams (1979e) assigned this section of the well to the Early Paleocene to Early Eocene, with Fenton and Pardon (2007) and Ainsworth et al. (2014)

interpreting similar ages, but with Danian (Early Paleocene) section omitted by the latter authors. The unconformities within the interval that were noted by Fenton and Pardon (2007) cannot be resolved in the lithological information; however, Selandian-aged (Middle Paleocene) Markland Formation fits within the overall lithostratigraphic framework discussed by Dafoe, Dickie et al. (in press). In regard to the Markland to Cartwright formation boundary, the gamma-ray, sonic, and resistivity logs all increase at 2211 m to define the boundary. Accordingly, the reference section of McWhae et al. (1980) is modified slightly in the present study to 2614.6–2211 m (Table 20). The top of the Cartwright Formation is also modified in the present study to 2126 m at another shift in the well logs, which is best indicated by the decrease in resistivity and overall change in sonic velocity log character (Fig. 13). McWhae et al.'s (1980) original reference section for this formation is thus modified to 2211–2126 m (Table 20).

Shelf edge

The nature of the shale succession changes between 2126.0 m to 2042.2 m (6975–6700 ft.) to an intermittently silty shale. The brown-grey, silty, slightly calcareous shale includes pyrite throughout and rare limestone stringers.

The slightly silty shale with a paucity of fossil material suggests a return to more distal marine deposition. Some calcareous component to the lithology indicates deposition likely near the shelf edge. This interpretation agrees well with the deep-neritic to bathyal settings of Gradstein (1977a) and Miller and D'Eon (1987). This interval lies at the base of the Kenamu Formation, and was assigned to the Early Eocene by Williams (1979e), which is in good agreement with the Ypresian (Early Eocene) findings of Fenton and Pardon (2007) and Ainsworth et al. (2014).

Outer shelf

The interval from 2042.2 m to 1859.3 m (6700–6100 ft.) shows a return to silty, calcareous shale. The brown-grey shale is partly calcareous, with limestone stringers throughout, as well as rare pyrite, rare lignite wood fragments, rare white (?)specks, and rare fossil fragments (scaphopod and foraminifera).

The silty nature of the shale, calcareous content, fossil suite, and rare wood fragments imply some degree of shallowing to outer shelf conditions relative to the underlying strata. This shallowing was not documented by Gradstein (1977a) and Miller and D'Eon (1987), as they suggested continued bathyal deposition. As part of the Kenamu Formation, this section of the well is Ypresian (Early Eocene) in age according to Williams (1979e), Fenton and Pardon (2007), and Ainsworth et al. (2014).

Middle shelf

Between the depths of 1859.3 m to 1688.6 m (6100–5540 ft.) is a silty brown shale and claystone succession. This silty, fine-grained rock is calcareous and micro-micaceous, with localized carbonaceous plant remains, localized coal fragments or lignite wood fragments, fossil fragments (foraminifera, scaphopod, bivalve, and indeterminate shell material), rare limestone stringers, rare pyrite, and rare sand grains.

The silty nature of the shale, diverse fossil suite, and influx of terrestrial material (wood, plant, and coal) is interpreted to reflect a middle shelf paleoenvironment. This shallow shelf setting has not been documented previously, as bathyal conditions were proposed for this part of the well (Gradstein, 1977a; Miller and D'Eon, 1987). However, the above lithological and sedimentological evidence does not support a deep-water interpretation. In Herjolf M-92, this interval falls within the Kenamu Formation and is Early Eocene to Late Eocene in age according to Williams (1979e), but Ainsworth et al. (2014) found the age to extend into the Lutetian–Bartonian (Middle Eocene), and Fenton and Pardon (2007) similarly gave a Middle Eocene age as the youngest. Accordingly, the age of this interval is most likely restricted to the Early–Middle Eocene.

Outer shelf

The next interval in Herjolf M-92 spans the depths from 1688.6 m to 1566.7 m (5540–5140 ft.) and is composed of silty claystone to shale. This brown, silty claystone to shale interval is slightly calcareous, with rare fossil fragments (foraminifera, scaphopod, and indeterminate shell material), rare limestone stringers, and rare pyrite.

Although similar to the underlying interval, the decrease in terrestrial influx and fossil material indicates a return to an outer shelf paleoenvironment. Both Gradstein (1977a) and Miller and D'Eon (1987) found bathyal water depths, which are in range of the present study's interpretation. The Middle–Late Eocene ages of Fenton and Pardon (2007) and Ainsworth et al. (2014) align well with the lithostratigraphic framework of Dickie et al. (2011) and Dafoe, Dickie et al. (in press) whereby deposition of the Kenamu Formation ended in the late Bartonian (late Middle Eocene).

Middle shelf

The interval in the well from 1566.7 m to 1402.0 m (5140–4600 ft.) is characterized by silty and slightly sandy claystone, with rare limestone interbeds. The brown, silty, micro-micaceous, calcareous claystone is locally sandy, with limestone stringers, scattered fossil fragments (foraminifera, indeterminate shell material, and gastropod), rare coal and lignite wood fragments, rare plant remains, rare pyrite, and rare medium- to coarse-grained sand grains. Dark brown-grey limestone is silty and argillaceous.

The silt nature of the claystone, incorporation of sand grains, and relative abundance and diversity of fossils is suggestive of a middle shelf paleoenvironment. This shallow shelf setting was not recognized previously, and Miller and D'Eon (1987) explained the presence of sand in this interval as distal turbidite fan deposits that accumulated in bathyal water depths. However, the fossil content and dispersion of sand and silt is inconsistent with accumulation via discrete turbidity flows.

These strata lie at the top of the Kenamu Formation and are most likely Middle–Late Eocene in age (Williams, 1979e; Fenton and Pardon, 2007; Ainsworth et al., 2014). Despite the lack of Leif Member sandstone development in this well, there is a log break that clearly defines the top of the Kenamu Formation and corresponds to the top of this interval (1402.0 m; Fig. 13). Here, there is an increase in gamma-ray values and decrease in sonic velocity and resistivity values. This lithostratigraphic boundary varies slightly from that of Moir (1989) to better match the log and paleoenvironmental change (Table 20; also note that there is a casing point at about 1390 m that further affects the logs).

Outer shelf

The section of the well from 1402.0 m to 1356.3 m (4600–4450 ft.) is dominated by claystone. This claystone contains only rare silt and sand and is calcareous, with limestone stringers, scattered pyrite throughout, rare fossil fragments (foraminifera and bivalve), and very rare plant remains.

The lack of significant silt or sand in this thin claystone interval and a reduction in both the degree of limestone and fossil fragments is indicative of an increase in water depth to outer shelf conditions. This setting agrees well with that of previous authors whom interpreted outer shelf and deep neritic settings (Gradstein, 1977a; Miller and D'Eon, 1987). This interval lies at the base of the Mokami Formation as defined in the present study (Table 20). The age of this claystone is Rupelian (Early Oligocene) according to Ainsworth et al. (2014), which is preferred over the Oligocene to Early Miocene age assignments of Williams (1979e) that are younger ages than typical for this part of the Mokami Formation on the Labrador Shelf (*see* Dafoe, Dickie et al., in press). The age designation of Ainsworth et al. (2014) is also similar to that of Fenton and Pardon (2007).

Middle shelf

Silty and slightly sandy claystone, with rare limestone interbeds is present between 1356.3 m to 944.9 m (4450–3100 ft.). The brown-grey, silty claystone is locally sandy, with fossil fragments throughout (foraminifera, bivalve, and mollusc), locally common limestone stringers, locally common plant remains, scattered pyrite throughout, rare coal and lignite wood fragments, and rare medium- to coarse-grained sand grains. Dark brown-grey limestone is silty and argillaceous.

As with some of the underlying intervals, the silty and sandy nature of the claystone, combined with the relative fossil diversity, are interpreted to indicate a return to a middle shelf paleoenvironment. Gradstein (1977a) also noted a shallowing to shallow neritic and even marginal marine conditions, but Miller and D'Eon (1987) interpreted the persistence of outer shelf (possibly even bathyal) conditions. Results from the present study thus fall within range of these previous studies. This interval forms a significant portion of the Mokami Formation, and this section of the well is Rupelian (Early Oligocene) according to Ainsworth et al. (2014).

Inner shelf

In the interval from 944.9 m to 773.6 m (3100–2538 ft.), the claystone is sandy throughout. Grey-brown, silty and sandy throughout, locally calcareous claystone contains limestone stringers, rare plant remains, rare coarse-grained sand grains, and rare pyrite. Towards the top of the interval, some brown sandstone units are present and are argillaceous and calcareous, with pyrite, chert grains (fine- to medium-grained), feldspar, and rare fish fossils.

The sandy nature of the claystone and presence of some coarse-grained sand implies increasingly shallower marine conditions compared to the underlying strata, likely inner shelf. The lack of significant fossils is unusual and could indicate some brackish or deltaic influence. This part of the well caps the top of the Mokami Formation, defined here from 1402–773.6 m (Table 20), and the age is Chattian (Late Oligocene) according to Ainsworth et al. (2014).

Shoreface

At the very top of Herjolf M-92 is a thick sandstone succession from 773.6 m to 454.2 m (2538–1490 ft.). The yellow-brown, red-brown, and white sandstone is medium- to coarse-grained (mostly coarse-grained), argillaceous, unconsolidated, quartz-rich, and locally calcareous. Grains are subrounded and moderately sorted, but pebbles and very coarse-grained sand grains are found throughout and increase in abundance upward in the interval and include igneous clasts, chert, and granite. The strata also include scattered plant fragments, scattered wood fragments, coal fragments at the top of the interval, and mineral grains (feldspar, agate, chert, and rare tourmaline). Rare pyrite, rare shale, rare siltstone, and a shark tooth were also noted. The gamma-ray log signature shows a slightly coarsening-upward, but blocky log character (Fig. 13).

The consistent coarse-grained nature of the sandstone, blocky log signature, relative rounding of clasts, presence of rare marine fossils and wood and plant fragments is consistent with a shoreface paleoenvironment. This interpretation agrees well with previous studies where Miller and D'Eon (1987) proposed inner shelf to marginal marine conditions including delta front, beach, shoreface and distributary bar settings. Gradstein (1977a) also indicated shallow to marginal marine conditions. This part of the well encompasses the Saglek Formation, which is extended here to 435 m at the top of the electric logs (Table 20). Both Williams (1979e) and Ainsworth et al. (2014) gave a Pliocene–Pleistocene age for this part of the well, but other nearby wells, such as Bjarni O-82 have older ages for correlative strata (Williams, 2007e; Nøhr-Hansen et al., 2016).

Lithostratigraphy

Based on the discussion around lithostratigraphic refinements to the framework of and Moir (1989) in Herjolf M-92, the lithostratigraphic picks from the present study are summarized in Table 20. Type and reference sections are also noted below, with most modified from the original designations.

Lithostratigraphic unit	Moir (1989)		The present study		Type or reference section
	Base (m)	Top (m)	Base (m)	Top (m)	
Saglek Fm	773	239	773.6	435	None
Mokami Fm	1398	773	1402	773.6	None
Kenamu Fm	1963	1398	2126	1402	None
Cartwright Fm	2211	1963	2211	2126	Reference section from 2211–1963 m of McWhae et al. (1980) is modified to 2211–2126 m
Markland Fm	2614	2211	2614.6	2211	Reference section from 2614–2211 m of McWhae et al. (1980) is modified to 2614.6–2211 m
Bjarni Fm	3751	2614	3751	2614.6	Type section from 3767–2614 m of Umpleby (1979) and from 3751–2614 m of McWhae et al. (1980) is modified to 3751–2614.6 m
Bjarni Fm (Snorri Mb)	3751	3550	3751	3541.8	None
Alexis Fm	4048	3751	4048	3751	Reference section from 4048–3751 m of McWhae et al. (1980) is retained
Unnamed Precambrian	4086	4048	4086	4048	None

Table 20: Lithostratigraphic assignment for Herjolf M-92 from the present study and compared to that of Moir (1989). Fm=Formation; Mb=Member.

HOPEDALE E-33

Situated in a proximal setting, the Hopedale E-33 well is found in the central part of the Hopedale Basin (Fig. 1). The well history report for Hopedale E-33 (Pandachuck and Lewis, 1978) includes cuttings descriptions, a conventional core description, and sidewall core descriptions, all of which were used in the present study to compile the interval descriptions. In addition to this, the Canadian Stratigraphic Service Ltd. Chevron Hopedale E-33 log (log EC-126) includes the most comprehensive details for the well including: lithology, grain size, grain rounding, and sample descriptions. One conventional core from the Bjarni Formation was described in terms of its age and paleoenvironment in Dafoe and Williams (2020a). Figure 14 shows a plot of Hopedale E-33, including key well logs, lithology, grain size, rock colour, ages, and paleoenvironmental and lithostratigraphic information. The age assignments from Williams (1981) are used in the present study, except for the upper portion of the well, where those of Bujak Davies Group (1987d) fit better with the lithostratigraphic framework presented by Dafoe, Dickie et al. (in press). A summary of the paleoenvironments described below are shown in Table 21. These settings are further compared in the descriptions below with those of Miller and D'Eon (1987) and those of Bujak Davies Group (1989d), the latter based on both micropaleontology and palynology. Lithostratigraphic assignments from Moir (1989) are modified in the present study and summarized in Table 22.

The sedimentary section sits above unnamed Precambrian and unnamed Paleozoic basement rocks. While the log breaks are not fully definitive, the Precambrian basement appears to extend from 2070–2000 m, an interpretation that brings the top higher in the well than interpreted by Moir (1989; Fig. 14; Table 22). Above this, Paleozoic strata are then defined from 2000 m to 1976 m based on the carbonate lithology and log break in the gamma-ray, sonic, and resistivity logs that define the upper boundary (Fig. 14; Table 22).

Base (m)	Top (m)	Paleoenvironment
1976	1947	BAYHEAD DELTA AND RESTRICTED EMBAYMENT
1947	1901	SHOREFACE
1901	1894	OUTER SHELF
1894	1850	SLOPE
1850	1698	(?)OUTER SHELF
1698	1650	MIDDLE SHELF
1650	1350	OUTER SHELF
1350	900	INNER SHELF

Table 21: Paleoenvironmental determinations for Hopedale E-33 from the present study.

Bayhead delta and restricted embayment

At the base of the Mesozoic–Cenozoic sedimentary section in Hopedale E-33 is the interval from 1976 m to 1947 m, which is composed of heterolithic sandstone, shale, and lesser siltstone. Fine- to coarse-grained, light grey sandstone is characterized by subangular to angular grains and is poorly sorted, with feldspar, igneous, and quartz pebbles, very coarse-grained sand grains, and localized glauconite. Grey shale units are silty with coal stringers. The gamma-ray log is rather ragged (Fig. 14), with the sandstones possessing a high API value due to the feldspar content, a log character previously noted for the Bjarni Formation (Umpleby, 1979).

Core 1 sampled this interval and was analyzed by Dafoe and Williams (2020a) where they indicated that the dark grey shales accumulated in a highly brackish, restricted marine bay, with progradation of bayhead delta sandstones. The heterolithic character of the sandstone and shale units, coarse-grained nature, and presence of coal and glauconite indicates a shallow marine setting with terrestrial influx, consistent with a bayhead delta feeding into a restricted marine embayment. The lower bathyal setting proposed by Bujak Davies Group (1989d) could be explained by cavings of overlying, deep-water cuttings of the Markland Formation, as this setting is inconsistent with the sedimentological evidence noted above. Miller and D'Eon (1987) also suggested deltaic conditions, but in a nonmarine, possibly lacustrine setting. The presence of glauconite and evidence from Dafoe and Williams (2020a) confirms the brackish nature of the strata.

As a result of the refinement to the top of the unnamed Paleozoic section, the base of the Bjarni Formation sits at 1976 m at the base of this interval (Table 22). The top is further constrained to the top of this interval at 1947 m where there is a distinct log change to lower API sandstones and reduced resistivity (Fig. 14). The sandstone-dominated nature of this interval implies a Bjarni Formation designation, but not Snorri Member. Accordingly, the Bjarni Formation designation is similar to that of Moir (1989), but the present study assigns no Snorri Member interval (Table 22). In addition, there is a major unconformity at about 1947 m in the well as noted by Williams (1981). Sample spacing of the cuttings analyzed in that study extend from 1925–1935 m and 1940–1950 m, with the latter interval spanning the log break at 1947 m and explaining the Campanian ages at that depth. Accordingly, the Bjarni Formation in Hopedale E-33 is Barremian–Aptian, and possibly as old as middle Barremian (Williams, 1981). However, analysis of core 1, which lies in the middle of the interval, revealed an early Aptian to early Albian or older age (Dafoe and Williams, 2020a), so a Barremian age is possible, but not likely.

Shoreface

Spanning 1947 m to 1901 m, is a coarsening-upward sandstone that is fine- to coarse-grained. This light brown to light grey and white sandstone succession is composed of subangular to angular clasts and is poorly to well sorted (mostly poorly sorted). The strata further contain pyrite throughout, common feldspar, rare kaolinite, rare glauconite, and very coarse-grained sand grains and pebbles increase in abundance towards the top of the interval (quartz and feldspar). The gamma-ray log further depicts the clearly coarsening-upward nature of the interval (Fig. 14).

The gamma-ray profile and coarse clastic lithology is consistent with a shoreface paleoenvironment. A lack of significant terrestrial influx and fossil material could indicate an upper shoreface setting and persistent high-energy conditions and reworking. The relative angularity of the clasts is unusual and may be a function of rapid sedimentation rates, sediment sourced from the underlying immature Bjarni Formation, and/or degradation of feldspar grains during burial and diagenesis. The lower bathyal paleoenvironmental interpretation of Bujak Davies Group (1989d) can only be explained by cavings from the overlying Markland Formation shales as it is not consistent with the evidence presented above, but Miller and D'Eon (1987) suggested marginal marine (lagoonal and embayment) to nonmarine settings, in reasonable agreement with the present study.

Constituting the base of the Markland Formation in Hopedale E-33, this sandstone interval forms the Freydis Member as defined in the present study, but was previously recognized as both Bjarni Formation (Snorri Member) and Markland Formation strata by Moir (1989; Fig. 14). The top of the interval at 1901 m marks an increase in gamma-ray, density, and resistivity logs marking the boundary between the Freydis Member sandstone and Markland Formation shales above (Fig. 14; Table 22). The age of the Freydis Member is Campanian to middle Maastrichtian according to Williams (1981). The Albian assignment of Bujak Davies Group (1989d) is possibly related to reworking of Bjarni Formation sediments at the base of the Freydis Member shoreface succession.

Outer shelf

A thin grey, platy shale from 1901 m to 1894 m contains rare sandstone. A thin brown, very fine- to fine-grained, well sorted sandstone is composed of subangular grains, calcareous cement, rare kaolinite, and rare glauconite.

There is little information in this shale interval to construct a paleoenvironmental interpretation, but an outer shelf setting is likely based on the interpretation of the overlying interval. Glauconite in the sandstone could indicate slow sedimentation rates typical of transgressive units (Amorosi, 2003). The sandstone within the shale was likely incorporated during transgression and sourced from the underlying Freydis Member. An outer shelf setting was not recognized by previous authors, but certainly falls between the lower bathyal (Bujak Davies Group, 1989d) and marginal marine (Miller and D'Eon, 1987) settings previously reported. This interval forms part of the Markland Formation and is middle Maastrichtian in age according to Williams (1981).

Slope

Between the depths of 1894 m and 1850 m is a shale succession. This grey, platy shale contains rare carbonaceous flakes, rare pyrite nodules, rare siderite nodules, and one instance of a sandstone stringer.

The lack of silt and sand and fossil detritus suggests a distal marine setting consistent with slope-equivalent water depths. In general, the bathyal settings interpreted by previous authors (Miller and D'Eon, 1987; Bujak Davies Group, 1989d) are in good agreement with the present study. Forming part of the Markland Formation, these strata are middle Maastrichtian based the findings of Williams (1981).

(?)Outer shelf

Spanning the interval from 1850 m to 1698 m is a succession of shale with interspersed sandstone units that are generally thin, with one thicker sandstone present. Shale is grey-brown, massive, and sandy with sandstone stringers, pyrite, siderite nodules, rare fossil fragments (including foraminifera), and rare carbonaceous flakes. The green-brown to brown-grey, silty sandstone is very fine- to medium-grained, very glauconitic, slightly argillaceous, and well to moderately sorted, with subrounded to subangular grains, calcareous cement, and rare kaolinite.

The interpretation for this interval is a little uncertain due to the general lack of fossils, but sandy shale and thin sandstones could suggest a prodeltaic setting. However, the strata may also reflect ongoing transgression and deeper-water conditions based on the underlying interval of the Markland Formation (*see* above). In this regard, the sandstones are likely tempestites deposited in an outer shelf (or possibly shallower) setting. The glauconitic nature of the sandstones is suggestive of low sedimentation rates consistent with distal marine, sediment starved conditions. Miller and D'Eon (1987) also suggested a similar turbiditic interpretation, but in slightly deeper water, and Bujak Davies Group (1989d) also documented bathyal water depths.

This interval caps the top of the Markland Formation, which is slightly revised in the present study, with the top placed at 1698 m to match the log breaks (increase in gamma-ray and resistivity logs) at this depth and the paleoenvironmental changes described in the present study (Fig. 14). Accordingly, the Markland Formation extends from 1947–1698 m (Table 22). Williams (1981) gave an age of middle to late Maastrichtian; although, Danian (Early Paleocene) strata could also be present based on the findings of van Helden (1978) and Bujak Davies Group (1989d).

Middle shelf

A thin interval of sandy claystone characterizes the well from 1698 m to 1650 m. Grey-brown claystone is silty, sandy, and partly calcareous, with decreasing sand content upward. Scattered fossil fragments are present (foraminifera and mollusc), as well as limestone beds and stringers. Argillaceous, dark grey limestone beds are marly and found at the base of the interval.

The sandy, calcareous nature of the claystone, with the fossil suite suggests a shallowing to middle shelf conditions relative to the underlying strata. This shallowing was not observed by either Miller and D'Eon (1987) nor Bujak Davies Group (1989d), as they both reported bathyal deposition. However, these distal marine settings do not appear to correlate with the observations described above. This interval characterizes the base of the Cartwright Formation as defined in the present study (Table 22). Williams (1981) gave a Middle Paleocene age assignment, but it is unclear if Danian (Early Paleocene) section is missing as Bujak Davies Group (1989d) reported an Early Paleocene age for this interval).

Outer shelf

From 1650 m to 1350 m is a relatively thick succession of silty claystone with rare limestone units. The grey-brown claystone, is silty throughout, micaceous, and calcareous, with dark grey limestone stringers, scattered fossil fragments throughout (foraminifera, indeterminate mollusc material, and bivalve), rare glauconite, rare white calcareous (?)specks, rare pyrite, rare carbonaceous plant remains, and rare coarse-grained sand grains.

The overall silty nature of the claystone, with incorporation of rare terrigenous plant material and relatively common fossil fragments is consistent with an outer shelf paleoenvironment and slight deepening relative to the underlying strata. This interval was previously found to be bathyal for the most part (Miller and D'Eon, 1987; Bujak Davies Group, 1989d); however, these previous studies also indicated shallowing to outer shelf or outer neritic deposition as well. Williams (1981) gave the age of this interval as Late Paleocene to Early Eocene. This claystone includes the upper part of the Cartwright Formation, as indicated in the present study from 1698–1593 m (Table 22), and base of the overlying Kenamu Formation. The log break at the lithostratigraphic boundary is best noted as a decrease in the resistivity logs and a subtle increase in the density log (Fig. 14).

Inner shelf

The uppermost interval in Hopedale E-33 includes a relatively monotonous succession of silty and sandy claystone between 1350 m and 900 m. Dark brown claystone is sandy and silty throughout, with dark grey limestone stringers, mica flakes, scattered very coarse-grained sand grains, white calcareous (?)specks, scattered fossil fragments (foraminifera, bivalve, indeterminate mollusc material, and gastropod), scattered chert pebbles near the top of the interval, rare pyrite, and rare carbonaceous plant remains. A single sandstone bed at about 1090 m is dark brown, dolomitic, argillaceous, and silty, and further contains feldspar, chert, mica flakes, glauconite, kaolinite, and indeterminate fossil fragments.

The diverse and abundant fossil content and sandy and silty nature of the claystone, with coarse-grained detritus is suggestive of inner shelf conditions. The sandstone unit could reflect a thick storm deposit, but its interpretation is unclear. Similar inner, middle, and outer shelf or neritic settings were proposed by previous authors (Miller and D'Eon, 1987; Bujak Davies Group, 1989d).

This thick interval includes the top of the Kenamu Formation as defined by Moir (1989) and is unchanged in the present study (1593–982 m; Table 22). However, the Leif Member is not included in the present study as the nature of the thin sandstone unit is unclear and does not warrant designation to the member. The boundary between the Kenamu and Mokami formations is based on an increase in the gamma-ray log, and the top of the Mokami Formation is defined in the present study by the top of the electric logs. The gamma-ray log shows a decrease in API values at the very top of the well that could indicate that sandstones are present (i.e. the Saglek Formation), but this is not clear from the given data (Fig. 14). Accordingly, the Mokami Formation is designated in the present study from 982–855 m and there is no Saglek Formation as was suggested by Moir (1989; Table 22). This inner shelf interval appears to be late Early Eocene to Early Miocene, with missing Oligocene section according to Williams (1981). The Lutetian to Rupelian age of Ainsworth et al. (2016) at the top of the interval could accommodate a Bartonian top for the Kenamu Formation as was determined in the regional studies by Dickie et al. (2011) and Dafoe, Dickie et al. (in press). As there is no lithological evidence to confirm missing Oligocene section, the ages of Ainsworth et al. (2016) are preferred.

Lithostratigraphy

Based on the discussion around lithostratigraphic refinements to the framework of Moir (1989) in Hopedale E-33, the lithostratigraphic picks from the present study are summarized in Table 22. There are no type or reference sections in this well.

Lithostratigraphic unit	Moir (1989)		The present study		Type or reference section
	Base (m)	Top (m)	Base (m)	Top (m)	
Saglek Fm	840	613	--	--	None
Mokami Fm	982	840	982	855	None
Kenamu Fm	1593	982	1593	982	None
Kenamu Fm (Leif Mb)	1093	1071	--	--	None
Cartwright Fm	1696	1593	1698	1593	None
Markland Fm	1920	1696	1947	1698	None
Markland Fm (Freydis Mb)	--	--	1947	1901	None
Bjarni Fm	1980	1920	1976	1947	None
Bjarni Fm (Snorri Mb)	1948	1920	--	--	None
Unnamed Paleozoic	2009	1980	2000	1976	None
Unnamed Precambrian	2070	2009	2070	2000	None

Table 22: Lithostratigraphic assignment for Hopedale E-33 from the present study and compared to that of Moir (1989). Fm=Formation; Mb=Member.

INDIAN HARBOUR M-52

In the southern reaches of Hopedale Basin and located farther outboard on the Labrador Shelf than most wells, is Indian Harbour M-52 (Fig. 1). Two well history reports were used to compile the descriptions below, with the report from BP Exploration Canada Ltd. (1975) including cuttings descriptions from 2362.2 m to 304.8 m (7750–1000 ft.). The second report from BP Exploration Canada Ltd. (1976) outlines cuttings descriptions from 3952.0 m to 2377.4 m (12966–7800 ft.) and sidewall core descriptions from select depths between 3907.2 m and 1572.8 m (12819–5160 ft.). The most complete set of information for the well comes from the Canadian Stratigraphic Service Ltd. BP Columbia Indian Harbour M-52 logs (logs EC-111 and EC-111a), which include detailed lithological, grain size, grain rounding, and sample descriptions. The well plot in Figure 15 shows key well logs, lithology, grain size, rock colour, ages, and paleoenvironmental and lithostratigraphic information. The ages preferred in the present study are from Williams (pers. comm., 2016), which are based on a reassessment of the species listings originally identified by Williams (1979f). A summary of the paleoenvironments described below are listed in Table 23. Gradstein (1977b) used micropaleontology to derive his paleoenvironmental interpretations, in addition to those of Miller and D'Eon (1987), both of which are compared with the present study's results. Modified lithostratigraphic assignments from the present study are compiled in Table 24 and compared against those of Moir (1989).

The Mesozoic–Cenozoic section sits above a siliceous and/or cherty interval containing common indeterminate and pelecypod fossil fragments that is interpreted here to reflect an altered interval of Paleozoic section affected by contact metamorphism due to emplacement of the overlying Alexis Formation basalts, as well as a possible sill at about 3500 m (11490 ft.). This siliceous interval extends down to 3536.9 m at a clear resistivity log break and lithological change to the underlying carbonate rocks (Fig. 15; Table 24). The underlying unnamed Paleozoic carbonate rocks are early Ordovician (Fenton and Pardon, 2007) or Late Ordovician (Sandbian; Bingham-Koslowski et al., 2019) in age.

Base (m)	Top (m)	Paleoenvironment
3483.9	3249.2	SUBAERIAL VOLCANIC ROCKS
3249.2	3200.4	OUTER SHELF TO UPPER SLOPE
3200.4	3145.6	SLOPE
3145.6	2362.2	OUTER SHELF TO UPPER SLOPE
2362.2	2286.0	OUTER SHELF
2286.0	2002.6	MIDDLE SHELF
2002.6	1865.4	OUTER SHELF
1865.4	1318.3	MIDDLE TO INNER SHELF
1318.3	1201.5	INNER SHELF OR PRODELTA (STORM DOMINATED)
1201.5	859.5	MIDDLE SHELF
859.5	492.6	INNER SHELF OR PRODELTA (STORM DOMINATED)
492.6	385.0	SHOREFACE
385.0	304.8	INNER SHELF OR PRODELTA (STORM DOMINATED)

Table 23: Paleoenvironmental determinations for Indian Harbour M-52 from the present study.

Subaerial volcanic rocks

Lying above the basement rock is an igneous succession from 3483.9 m to 3249.2 m (11430–10660 ft.). This part of the well is characterized by basalt and tuff. Basalts are brown-grey to green-grey, locally red, with localized amygdaloidal character, calcareous and zeolites minerals, and rare brecciated intervals, as well as weathered intervals, glass shards, rare olivine, rare biotite, apparent phenocrysts, and possible chlorite. Tuffaceous units are light grey-green, partly red, with rock fragments, a frothy appearance, lapilli, and vesicles. The tuff are also weathered, calcareous, and sandy. Rare green-grey and red shale is platy and calcareous.

The alternation between basalts and tuff, with evident weathering suggests an accumulation of subaerial volcanic rocks alternating between flows and ash and rockfall accumulations. Miller and D'Eon (1987) proposed possible subaqueous accumulations below 3340 m, but generally suggested nonmarine to marginal marine conditions.

This interval comprises the Alexis Formation, which has been dated by Krueger Enterprises Ltd in BP Exploration Canada Ltd. (1976) at 90.1 +/- 3.8 Ma (approximately Turonian on the time scale of Gradstein et al. (2012)), but it is not clear how accurate this age is (*see* Dafoe, Dickie et al., in press). Fenton and Pardon (2007) suggested a Barremian–Aptian age, but it is unclear how this age was derived from the igneous lithologies. The Campanian and early Maastrichtian section of Williams (pers. comm., 2016) are likely the result of cavings, especially considering the lithology. The Alexis Formation top is modified only marginally from that of Moir (1989) to better fit the log breaks and thus ranges from 3484–3249.2 m (Table 24).

Outer shelf to upper slope

Above the Alexis Formation is a thin interval of shale spanning 3249.2 m to 3200.4 m (10660–10500 ft.). The green-grey shale is platy, mottled (possible bioturbated), with common fossil fragments (a variety of foraminifera including *Bathysiphon* and ostracods), interbedded brown limestone, locally slightly calcareous units, finely disseminated pyrite, possible rare bentonite (but not reported in sidewall cores), and rare silt.

Overall, the interval is comprised of a fine-grained lithology, and the abundance of foraminifera with ostracods and possible bioturbation suggests an outer shelf to upper slope setting where sediment reworking is prevalent due to low sedimentation rates. This setting is comparable to that of Gradstein (1977b) and Miller and D'Eon (1987), as they reported bathyal water depths. Forming the base of the Markland Formation, this interval is early Maastrichtian to Danian (Early Paleocene) according to Williams (pers. comm., 2016), but could be restricted to the Maastrichtian based on the finding of Fenton and Pardon (2007), as there is no evidence of missing late Maastrichtian section.

Slope

The interval from 3200.4 m to 3145.6 m (10500–10320 ft.) encompasses a succession of relatively monotonous shale. This green-grey shale is platy and contains possible ichnofossils, a possible bentonitic character throughout, scattered pyrite throughout, rare crinoid fragments, and very rare plant remains.

These strata are unique in their general lack of fossils and green colouration, which suggests a distal marine paleoenvironment under reducing conditions (Myrow, 2003), consistent with continued transgression and a slope-equivalent setting, typical for the Markland Formation. Previous studies documented similar neritic to bathyal paleoenvironments (Gradstein, 1977b; Miller and D'Eon, 1987).

Comprising the upper part of the Markland Formation in this well, this slope-equivalent interval is Danian (Early Paleocene) to Thanetian (Late Paleocene) according to Williams (pers. comm., 2016). However, the Thanetian age is younger than expected for the Markland Formation according to Dafoe, Dickie et al. (in press), but the log change (increased gamma-ray, sonic and resistivity logs) and colouration change at the top of the formation provides a good indication for the lithostratigraphic break. The generally Danian interpretation of Fenton and Pardon (2007) forms a more reasonable age assignment for the uppermost Markland Formation. Accordingly, the Markland Formation is modified to extend from 3249.2–3145.6 m, with boundaries varying slightly from those of Moir (1989; Table 24).

Outer shelf to upper slope

A significant change in colouration marks the transition to the next interval from 3145.6 m to 2362.2 m (10320–7750 ft.). This thick interval is characterized by a relatively consistent brown-grey, platy shale that includes common pyrite throughout, localized calcareous units, locally common glauconitic intervals, rare fossil fragments (foraminifera and ostracod), rare brown dolostone stringers, rare siderite nodules, rare worm tubes, and rare pyritized wood fragments. Scattered limestone is brown, silty, argillaceous, and slightly glauconitic, with rare bivalve fossil fragments.

The shale lithology, silt content, and fossil suite suggests an outer shelf to upper slope setting. The abundance of glauconite is consistent with slow sedimentation rates in a distal marine setting (Amorosi, 2003). Gradstein (1977b) and Miller and D'Eon (1987) found similar depositional settings, but favoured slightly deeper, bathyal water depths. This thick shale interval spans the Cartwright Formation and lower half of the Kenamu Formation. In the present study, the top of the Cartwright Formation is refined based on the decrease in resistivity seen at 3031.8 m, typical for the uppermost boundary of the formation. This limits the extent of the Cartwright Formation as compared to Moir's (1989) lithostratigraphic picks (Table 24). Williams (pers. comm., 2016) interpreted an age of Thanetian (Late Paleocene) through Lutetian (Middle Eocene) for the shale interval, with the Cartwright Formation ending within the early Ypresian (Early Eocene), in good agreement with the framework presented by Dafoe, Dickie et al. (in press).

Outer shelf

Very silty and slightly sandy shale to claystone characterizes the interval from 2362.2 m to 2286.0 m (7750–7500 ft.). This medium to dark grey shale is partly sandy, very silty, micro-micaceous and contains brown limestone stringers and common fossil fragments (foraminifera). A light grey-brown, silty, argillaceous, very fine-grained sandstone interval contains rare glauconite.

The overall abundance of fossils, but dominance of foraminifera, combined with the silt content suggests outer shelf deposition. The sandstone unit could reflect storm or turbidity current deposits, but is glauconitic, suggesting low sedimentation rates (Amorosi, 2003) that likely followed emplacement. This interval was interpreted to reflect bathyal water depths by previous authors (Gradstein, 1977b; Miller and D'Eon, 1987), in range of the present study's interpretation. This interval forms part of the Kenamu Formation, and Williams (pers. comm., 2016) gave a Lutetian (Middle Eocene) age that is consistent with the findings of others (e.g. Fenton and Pardon, 2007).

Middle shelf

Between the depths of 2286.0 m to 2002.6 m (7500–6570 ft.) is a shale interval with common siltstone and sandstone interbeds, and lesser limestone interbeds. The brown-grey shale to claystone is silty and commonly sandy, with common to abundant fossil fragments (foraminifera and bivalve), localized sandstone stringers, and rare glauconite. White to light grey sandstone is silty, siliceous, argillaceous, very fine-grained, and well sorted, and also contains subangular grains and rare glauconite. Siltstones are brown-grey, very argillaceous, sandy and friable. Brown, argillaceous, silty limestone is rarely chalky and locally dolomitic with glauconite.

The overall sandy and silty nature of the shale and claystone and mix of foraminifera and bivalve fossil material suggests a middle shelf setting. This shallowing was not documented in previous studies, as bathyal settings were reported (Gradstein, 1977b; Miller and D'Eon, 1987). The evidence presented above does not agree well with these interpretations, and the top of the Kenamu Formation is generally thought to reflect shallowing (Balkwill and McMillan, 1990; Dafoe, Dickie et al., in press). This middle shelf interval forms the upper part of the Kenamu Formation, which is demarcated in Indian Harbour M-52 by significant log changes: a decrease in gamma ray, decrease in sonic velocity and decrease in resistivity at 2002.6 m. Accordingly, the formation extends from 3031.8–2002.6 m as defined in the present study (Table 24). Williams (pers. comm. 2016) determined a Lutetian (Middle Eocene) through Priabonian (Late Eocene) age for this interval, with an attenuated Bartonian section, and Fenton and Pardon (2007) reported a similar Middle–Late Eocene age.

Outer shelf

Spanning the interval from 2002.6 m to 1865.4 m (6570–6120 ft.) is shale and claystone. This brown-grey shale to claystone is micro-micaceous, locally silty, and locally carbonaceous, with siltstone stringers and common fossil fragments throughout (foraminifera). Rare brown-grey limestones are silty and argillaceous.

The foraminifera-dominated nature of the shale and lack of sand and silt suggests a return to an outer shelf paleoenvironment. Other studies report continuing bathyal water depths through this interval (Gradstein, 1977b; Miller and D'Eon, 1987), which are only marginally deeper than the paleoenvironment proposed in the present study. This interval characterizes the base of the Mokami Formation, and was found to be Priabonian (Late Eocene) by Williams (pers. comm., 2016). The increase in water depth compared to the top of the Kenamu Formation is typical for the transgression associated with the base of the Mokami Formation (Dickie et al., 2011; Dafoe, Dickie et al., in press).

Middle to inner shelf

The interval from 1865.4 m to 1318.3 m (6120–4325 ft.) is characterized by silty and sandy claystone, with sandstone and siltstone interbeds. Overall the shale to claystone unit is sandier upward, with some coarse-grained sandstone beds and rare limestone and siltstone units. Brown-grey shale to claystone is silty, commonly locally sandy, and micro-micaceous, and contains fossil fragments throughout (foraminifera, indeterminate shell material, and bivalve), limestone and marlstone stringers, rare pyrite, rare carbonaceous remains, and rare glauconite. White, clayey, silty, medium- to coarse-grained sandstone is moderately sorted and includes subrounded grains, granules, and rare glauconite. Dark brown, argillaceous, sandy limestone units possess fossil fragments (foraminifera) and rare lignite.

The increase in sand grains upward suggests progradation, and the fossil content indicates shallowing from a middle to inner shelf setting. The sandy nature of this strata was interpreted by Miller and D'Eon (1987) to reflect turbidites in a bathyal setting, but the generally sandy character of the claystone (as opposed to discrete sandstone beds) and fossil content is inconsistent with this type of setting. Gradstein (1977b) also proposed a bathyal setting for much of this interval. This thick interval comprises part of the Mokami Formation. Williams (pers. comm., 2016) indicated a Priabonian (Late Eocene) to Rupelian (Early Oligocene) age for this part of the well.

Inner shelf or prodelta (storm-dominated)

The interval from 1318.3 m to 1201.5 m (4325–3942 ft.) is characterized by an interbedded succession of claystone and sandstone. Sandstone units are white to light brown, medium- to coarse-grained, silty, clayey, unconsolidated, and moderately sorted, with quartz granules, subrounded grains, occasional quartz pebbles, and rare glauconite. Claystone interbeds are brown, silty, sandy, and soft, and further contain rare glauconite, rare bivalve shell fragments, and rare pyrobitumen. Rare brown, silty, sandy limestone is also present. Despite the alternating sandstone and claystone lithology, the gamma-ray log displays little variation (Fig. 15), but this may be a function of the overall log scale that accommodates the low API basement rocks and high API basalts at the base of the well.

The sandy and heterolithic character of the strata are suggestive of an inner shelf setting dominated by storms, where fair-weather muds alternate with storm sands. However, the lack of fossils suggests that prodeltaic deposition and brackish conditions could also be possible. Previous studies found the same interval of Indian Harbour M-52 to have been deposited in bathyal to outer shelf or deep neritic settings, with turbidites explaining the presence of sandstone beds (Gradstein, 1977b;

Miller and D'Eon, 1987). In contrast to these findings, the presence of bivalve shell fragments is suggestive of inner shelf sedimentation, as well as the coarse-grained lithology. This interval forms part of the Mokami Formation, and the strata are Rupelian (Early Oligocene) based on the findings of Williams (pers. comm., 2016).

Middle shelf

The interval between the depths of 1201.5 m and 859.5 m (3942–2820 ft.) is dominated by silty and lesser sandy claystone with some sandstone, siltstone, and limestone beds. Claystone units are brown, silty, sandy, micro-micaceous, and soft, with fossil fragments common at base of unit (indeterminate shell material, foraminifera, and gastropod), rare limestone stringers, rare pyrite, and rare coarse-grained sand grains. Siltstone interbeds are brown, argillaceous, sandy, limy, and friable. White, unconsolidated, medium- to coarse-grained, moderately to poorly sorted sandstone includes subrounded grains, quartz granules, clay matrix, rare glauconite, rare fossil fragments (gastropod and foraminifera), and possible limestone pebbles. Limestone interbeds are dark brown, sandy, and argillaceous.

The sandy character of the claystone and relative abundance and diversity of fossil material is consistent with middle shelf deposition. Similar settings were proposed by previous authors, ranging from deep neritic or outer shelf to shallow neritic (Gradstein, 1977b; Miller and D'Eon, 1987). This interval is found within the Mokami Formation, and is Rupelian (Early Oligocene) to Chattian (Late Oligocene) based on the palynological assessment by Williams (pers. comm., 2016).

Inner shelf or prodelta (storm-dominated)

An overall sandier upwards, heterolithic sandstone, siltstone, and claystone succession characterizes the succession between 859.5 m and 492.6 m (2820–1616 ft.). Sandstones are white, very fine- to medium-grained, argillaceous, silty, unconsolidated, glauconitic throughout (locally abundant), well to moderately sorted, and overall coarsening upward. Furthermore, grains are subrounded and the rocks contain dark chert grains, locally common fossil fragments (foraminifera and indeterminate shell material), rare pyrite, and rare lignite near the top of the overall interval. Siltstones are light brown, sandy, glauconitic, and argillaceous, with very fine- to coarse-grained sand grains and rare foraminifera. Claystones are light brown and silty, and contain fine- to coarse-grained sand grains, glauconitic limestone stringers, and rare foraminifera. In the gamma-ray log, a slightly ragged, but overall coarsening upward nature is observed (Fig. 15).

This heterolithic interval coarsens and cleans upward and is consistent with a storm-dominated inner shelf succession where fair-weather mudstones alternated with storm sandstones. A prodeltaic setting is also possible based on the lack of fossil diversity. Miller and D'Eon (1987) interpreted a comparable inner shelf setting and also suggested storm-generated turbidites as a means of explaining the sandstone beds. Gradstein (1977b) interpreted a general neritic setting, but related part of the interval to preglacial conditions, possibly due to the inclusion of coarse grains. This interval forms the uppermost part of the Mokami Formation; thus, the lithostratigraphic assignment of the overall formation is modified slightly to 2002.6–492.6 m (Table 24). Williams (pers. comm., 2016) reported the age of this interval to be Chattian (Late Oligocene) to Middle Miocene.

Shoreface

A thin succession of sandstone occurs between the depths of 492.6 m and 385.0 m (1616–1263 ft.). The sandstone possesses a consistent medium- to coarse-grained nature and is moderately (rarely poorly) sorted, with subrounded grains. The sandstone is also yellow to white and unconsolidated, with a clay matrix, glauconite throughout, dark chert grains throughout, possible hematite stain, rare quartz granules, rare pyrite, rare indeterminate shell fragments, and rare igneous grains. Notably, there is a blocky gamma-ray log signature (Fig. 15).

The overall grain size, log character, grain rounding, and presence of only shell material suggests a shoreface setting. Miller and D'Eon (1987) also proposed an inner shelf to marginal marine setting, but suggested barrier or tidal bars, but Gradstein (1977b) interpreted non-shallow marine conditions and glacial influence – an interpretation not supported by the evidence above. This interval forms the base of the Saglek Formation, and was assessed as Middle Miocene to likely Miocene in age by Williams (pers. comm., 2016).

Inner shelf or prodelta (storm-dominated)

The final interval in Indian Harbour M-52 is a heterolithic sandstone and claystone from 385.0 m to 304.8 m (1263–1000 ft.). Sandstones are white, unconsolidated, fine- to coarse-grained, moderately sorted, and contain a clay matrix, igneous pebbles, quartz granules, subrounded to rounded grains, dark chert grains throughout, rare feldspar, rare glauconite, rare igneous grains, and rare indeterminate shell fragments. Grey, sandy, silty, soft claystone is slightly less common, and gives the interval a ragged gamma-ray log character (Fig. 15).

The gamma ray profile, heterolithic nature, and presence of shell material is consistent with a storm-dominated inner shelf or prodeltaic setting, similar to underlying units (*see* above). Miller and D'Eon (1987) also interpreted shallow marine conditions, but suggested a lagoonal setting, and Gradstein (1977) interpreted non-shallow marine conditions related to glaciation. Again, there does not appear to be evidence of this latter setting. This interval caps the Saglek Formation in Indian Harbour M-52 and is likely Miocene according to Williams (pers. comm., 2016). The Saglek Formation thus ranges from 492.6–298 m at the top of the electric logs, an interpretation that varies from Moir (1989; Table 24).

Lithostratigraphy

Based on the discussion around lithostratigraphic refinements to the framework of and Moir (1989) in Indian Harbour M-52, the lithostratigraphic picks from the present study are summarized in Table 24. There are no type or reference sections in this well.

Lithostratigraphic unit	Moir (1989)		The present study		Type or reference section
	Base (m)	Top (m)	Base (m)	Top (m)	
Saglek Fm	494	234	492.6	298	None
Mokami Fm	2002	494	2002.6	492.6	None
Kenamu Fm	2913	2002	3031.8	2002.6	None
Cartwright Fm	3143	2913	3145.6	3031.8	None
Markland Fm	3250	3143	3249.2	3145.6	None
Alexis Fm	3484	3250	3484	3249.2	None
Unnamed	3528	3484	--	--	None
Unnamed Paleozoic (altered)	--	--	3536.9	3484	None
Unnamed Paleozoic	3959	3528	3959	3536.9	None

Table 24: Lithostratigraphic assignment for Indian Harbour M-52 from the present study and compared to that of Moir (1989). Fm=Formation; Mb=Member.

KARLSEFNI A-13

The Karlsefni A-13 well is located in the southern part of the Saglek Basin (Fig. 1), and several sources of information were used to compile the descriptions below. The well history report by Ferrero et al. (1975) includes sidewall core descriptions for select depths between 3279.6 m and 1488.6 m (10760–4884 ft.) and cuttings descriptions between 3282.7 m and 534.0 m (10770–1752 ft.). The second well history report by Ferrero and Plé (1977b) further includes sidewall core descriptions for select intervals between the depths of 4128.2 m and 3312.6 m (13544–10868 ft.), core descriptions, and cuttings descriptions for 4145.3 m to 3282.7 m (13600–10770 ft.). Umpleby (1975b) also described the sidewall cores for the well. Detailed lithological, grain size, grain rounding, and sample descriptions from the Canadian Stratigraphic Service Ltd. Eastcan et al Karlsefni H-13 log (log EC-107a) and Eastcan Karlsefni H-13 log (log EC-107; note that there was a correction in the well name following drilling to A-13 instead of H-13) were also used. The well is shown in a plot in Figure 16, with key well logs, lithology, grain size, rock colour, ages, and paleoenvironmental and lithostratigraphic information. Paleoenvironmental determinations from the present study are summarized in Table 25, and the ages used herein are from Nøhr-Hansen et al. (2016). Comparisons are made in the descriptions below between the depositional settings of the present study and those of Gradstein (1978; from micropaleontology) and Miller and D'Eon (1987). Revised lithostratigraphic assignments from the present study are shown on Figure 16 and included in Table 26.

Below the sedimentary section, the underlying Precambrian basement rock, which is encountered from 4149.0 m to 4134.6 m (13612–13565 ft.), represents a modified interval from that proposed by Moir (1989). The revised interval is based on the lithology information from Canadian Stratigraphic Service Ltd., as the well logs do not extend to this depth in the well (Fig. 16; Table 26).

Base (m)	Top (m)	Paleoenvironment
4134.6	3566.2	OUTER SHELF
3566.2	3355.9	MIDDLE SHELF OR PRODELTA
3355.9	3038.9	PRODELTA
3038.9	2575.6	OUTER SHELF
2575.6	2476.8	MIDDLE TO INNER SHELF
2476.8	2463.4	LOWER SHOREFACE
2463.4	2392.7	INNER SHELF OR PRODELTA
2392.7	2268.7	DISTAL DELTA FRONT
2268.7	2241.8	INNER SHELF OR PRODELTA
2241.8	2190.9	LOWER SHOREFACE
2190.9	2151.9	OUTER SHELF TO UPPER SLOPE
2151.9	2042.2	MIDDLE SHELF
2042.2	1511.8	INNER SHELF TO PRODELTA
1511.8	805.6	ESTUARINE OR LAGOONAL
805.6	734.6	(?)LAGOONAL
734.6	597.4	SHOREFACE
597.4	533.4	SHOREFACE

Table 25: Paleoenvironmental determinations for Karlsefni A-13 from the present study.

Outer shelf

Sitting atop the unconformity with basement rock is an interval that extends from 4134.6 m to 3566.2 m (13565–11700 ft.) that is composed of silty and calcareous shale. The shale is dark brown-grey, with pyrite throughout, limestone stringers scattered throughout, rare glauconite scattered throughout, rare fossil fragments (bivalve and (?)belemnite), rare plant remains, rare siltstone stringers near the top of the interval, and rare lignite also near the top of the interval. Rare dark grey-brown marlstone and rare brown, silty, argillaceous limestone are also present.

The consistently fine-grained nature of the strata with rare fossil material, but silt content throughout suggests outer shelf deposition. The predominance of pyrite may indicate some reducing conditions during deposition (Wilkin, 2003). Previous authors interpreted paleoenvironments that are either deeper (bathyal; Miller and D'Eon, 1987) or shallower (shallow neritic; Gradstein, 1978); accordingly, the present study appears to be within range of these paleoenvironments.

This shale interval spans the entire Markland Formation, as well as part of the Cartwright Formation. The top of the Markland Formation is modified from that of Moir (1989) to reflect the major log change showing an increase in the sonic velocity and resistivity logs, with corresponding decrease in the gamma-ray log at 3770.4 m. The age of the interval is Danian to Thanetian (Early to Late Paleocene) according to Nøhr-Hansen et al. (2016), with the top of the Markland Formation within the earliest Thanetian according to several biostratigraphic studies. This is younger than predicted by the lithostratigraphic framework of Dafoe, Dickie et al. (in press), but the log change is typical of the boundary. Furthermore, the Selandian section is rather condensed, with a thick overlying Thanetian section according to Nøhr-Hansen et al. (2106), perhaps cavings of Thanetian strata could account for the discrepancy between the reported age and well-defined log break.

Middle shelf or prodelta

A shale interval spans the depths between 3566.2 m and 3355.9 m (11700–11010 ft.). This shale includes increasing siltstone upward towards the top of the succession. The dark brown-grey shale is silty and partly calcareous, and includes scattered pyrite, rare glauconite, rare plant remains, and rare lignite stringers. Siltstones are brown, dolomitic, calcareous, and argillaceous. Sandy siltstone at the top of the interval is argillaceous and micaceous, with rare glauconite and rare pyrite. Rare very fine-grained, brown sandstone also is found at the top of the interval.

Compared to the underlying interval, the increase in terrestrial detritus (although rare), as well as silt and sand content suggests shallowing to a middle shelf setting. The lack of fossil material, however, may indicate reduced oxygenation or brackish conditions, possibly reflecting a distal prodeltaic setting. Miller and D'Eon (1987) interpreted a much deeper, bathyal setting, but Gradstein (1978) alternatively proposed a shallow neritic setting, within range of the present study's interpretation. This interval comprises part of the Cartwright Formation, and Nøhr-Hansen et al. (2106) assigned a Thanetian (Late Paleocene) age.

Prodelta

Between 3355.9 m and 3038.9 m (11010–9970 ft.) is a very silty shale with rare siltstone and limestone interbeds. The brown-grey, very silty, platy, micaceous, locally calcareous shale further includes common siltstone stringers, limestone stringers, fossil fragments scattered throughout (foraminifera, arenaceous foraminifera, and bivalve), rare glauconite at the base of the interval, rare sand, rare plant remains, rare lignite stringers, and rare wood fragments. Brown siltstone interbeds are sandy and argillaceous, with trace glauconite. Dark grey-brown, silty, argillaceous, glauconitic limestone includes fossil fragments.

The terrestrial influx recorded by the presence of wood, lignite, and plant fragments, but fine-grained nature of the strata suggests the presence of a nearby delta and resultant prodeltaic conditions.

Dafoe and Williams (2020a) analyzed core 1 (3333.94–3325.1 m) and indicated a wave-influenced prodeltaic setting, further confirming the present interpretation. The inclusion of fossil fragments further indicates a limited brackish influence, which agrees well with the wave-influenced interpretation of core 1, whereby wave activity mitigates the environmental stresses related to fluvial discharge. A prodeltaic paleoenvironment agrees well with the shallow neritic findings of Gradstein (1978), but is much shallower than Miller and D'Eon's (1987) bathyal interpretation. The interpretation of core 1 provides strong evidence that deposition was in a shelfal setting.

Capping the top of the Cartwright Formation, the lithostratigraphic boundary is adjusted in the present study match the top of this interval where there is a noticeable change in the lithology and corresponding paleoenvironment at 3038.9 m. Also at this depth, the lithostratigraphic boundary with the overlying Kenamu Formation is marked by gamma-ray, sonic velocity, and resistivity log increases (Fig. 16). The Cartwright Formation thus extends from 3770.4–3038.9 m (Table 26). This prodeltaic interval is latest Thanetian (Late Paleocene) to Ypresian (Early Eocene) according to Nøhr-Hansen et al. (2016). However, core 1 has been dated as Selandian to Thanetian (Middle to Late Paleocene) at the very base of the interval (Dafoe and Williams, 2020a), indicating a slightly older age for at least part of the interval.

Outer shelf

A shale succession with rare limestone or marlstone beds at the base and rare siltstone and sandstone beds in upper half of the interval extends from 3038.9 m to 2575.6 m (9970–8450 ft.). Shales are dark grey and contain limestone stringers, scattered fossil fragments (foraminifera, bivalve, and other indeterminate fragments), rare silt, possible rare coal stringers, and a rare micro-micaceous character. Marlstone and limestone interbeds are dark brown, calcareous, argillaceous, dense, and cryptocrystalline. Sandstone interbeds are light grey-brown, very fine-grained, silty, and argillaceous, and grey, argillaceous siltstone units contain sand grains.

The generally fine-grained nature of the shale, with the associated fossil suite suggests an outer shelf setting, with a slight shallowing-upward trend. Discrete, thin sandstone and siltstone interbeds could reflect storm deposits. The paleoenvironmental interpretation from the present study agrees relatively well with that of Gradstein (1978) in terms of his deep neritic to bathyal setting, but Miller and D'Eon (1987) suggested only bathyal conditions, despite the presence of relatively common fossil material. This thick shale interval comprises much of the Kenamu Formation and was interpreted as Ypresian (Early Eocene) by Nøhr-Hansen et al. (2016).

Middle to inner shelf

A shallowing trend is evident in the interval spanning 2575.6 m to 2476.8 m (8450–8126 ft.), where sandy shale contains sandstone and rare limestone interbeds. Brown-grey, slightly micaceous, silty, and increasingly sandy upward (very fine-grained) shale includes siltstone stringers. Sandstone interbeds are light brown, very fine-grained, silty, and argillaceous, and further characterized by dolomite cement, subangular grains, and a well sorted nature. Medium to dark brown, silty, very fine sandy, argillaceous limestone includes rare indeterminate fossil fragments. The gamma-ray log shows subtle coarsening-upward trends into thin sandstone units, including the thicker overlying sandstone described below (Fig. 16).

The increase in sand content upwards within the unit and coarsening-upward profile implies some degree of progradation. The dominance of shale, however, is interpreted to reflect shallowing from a middle to inner shelf setting. Such a proximal setting was not previous interpreted, only bathyal water depths (Gradstein, 1978; Miller and D'Eon, 1987). Such a distal marine setting is not typical for the upper part of the Kenamu Formation (Balkwill and McMillan, 1990; Dickie et al., 2011; Dafoe, Dickie et al., in press) and is inconsistent with the sedimentological findings of the present study. Within the

Kenamu Formation, this sandy shale interval was determined to be Ypresian (Early Eocene) in age by Nøhr-Hansen et al. (2016), although others place it in the Middle Eocene (Fenton and Pardon, 2007; Ainsworth et al., 2016).

Lower shoreface

A thin interval from 2476.8 m to 2463.4 m (8126–8082 ft.) includes very fine-grained, well sorted, brown to light grey, silty, argillaceous, friable sandstone that contains subangular grains and dolomite cement. As described above, there is a coarsening-upward trend noted in the gamma-ray log from the underlying deposits into this interval of the well (Fig. 16).

The coarsening-upward gramma-ray profile, very fine-grained nature, and high sonic velocity suggests well cemented sandstones deposited in a lower shoreface paleoenvironment. Wave or storm energy could explain the lack of fossil material encountered, but the interval is also rather thin and possibly poorly represented in the cuttings descriptions used in the present study. This shallow marine setting was not documented in previous studies by Gradstein (1978) and Miller and D'Eon (1987), where they reported bathyal water depths, with turbidites explaining sandstone accumulations. Lithologically, there is little evidence to suggest that a turbidite succession is not possible, but the coarsening-upward nature would appear to indicate progradation rather than the fining-upward profile typically seen in turbidity current deposits. Forming part of the upper Kenamu Formation, Nøhr-Hansen et al. (2016) gave a Ypresian (Early Eocene) age for this sandstone, but a Lutetian–Bartonian (Middle Eocene) age may also be possible (Fenton and Pardon, 2007; Ainsworth et al., 2016).

Inner shelf or prodelta

The interval spanning 2463.4 m to 2392.7 m (8082–7850 ft.) is characterized by sandy shale with sandstone beds. Shales are grey, silty, sandy (very fine-grained), and slightly micaceous, and contain dolomitic sandstone stringers, rare dark brown marlstone, and rare bivalve shell fragments. Sandstone units are brown, very fine-grained, argillaceous, silty, and well sorted, with dolomite cement and subrounded grains. The gamma-ray log is somewhat ragged, but shows a coarsening-upward trend into the overlying interval described below (Fig. 16).

The lack of fossil abundance and diversity combined with an overall coarsening-upward profile and dominance of fine-grained lithologies suggest inner shelf to prodeltaic conditions. A shallow marine setting was not previously indicated by Gradstein (1978) nor Miller and D'Eon (1987), whom interpreted deep neritic to bathyal water depths. However, the shallow marine setting is in accord with the typical character of the upper Kenamu Formation (Balkwill and McMillan, 1990; Dickie et al., 2011; Dafoe, Dickie et al., in press). Lying near the top of the Kenamu Formation, this shale succession is Ypresian (Early Eocene) to Lutetian–Bartonian (Middle Eocene) according to Nøhr-Hansen et al. (2016), or possibly restricted to the Lutetian–Bartonian (Middle Eocene; Fenton and Pardon, 2007; Ainsworth et al., 2016).

Distal delta front

The base of the interval from 2392.7 m to 2268.7 m (7850–7443 ft.) is characterized by a relatively abrupt contact to the overlying heterolithic sandstones with lesser sandy shale. Sandstone units are light grey, very fine- to fine-grained, silty, argillaceous, friable, micaceous, and well sorted, with subrounded grains. Grey, silty, very fine-grained sandy, soft shale is interbedded with the sandstone and includes rare fossil fragments and rare limestone stringers. Four main coarsening-upward units with a ragged gamma-ray log profile typifies the interval.

The gamma-ray profile, heterolithic nature of the strata, and lack of fossils may indicate a storm-dominated inner shelf or distal delta front setting. Sidewall core indicate the presence of black shale partings in sandstone intervals, which would be more consistent with deltaic conditions, where hyperpycnal flows sourced from fluvial discharge typically remain unbioturbated (MacEachern et al., 2005). This interval forms part of the Kenamu Formation and the base of the Leif Member, which is adjusted slightly from the findings of Moir (1989) to 2392.7 m (Table 26). A Lutetian–Bartonian (Middle Eocene) age was assigned by Nøhr-Hansen et al. (2016), consistent with other studies (Fenton and Pardon, 2007; Ainsworth et al., 2016).

Inner shelf or prodelta

Between the depths of 2268.7 m and 2241.8 m (7443–7355 ft.) is an interval of dark grey, silty, sandy, soft, slightly micaceous shale, with dark brown limestone stringers and rare fossil fragments (bivalve). The gamma-ray log indicates a sharp base and top to the interval and coarsening-upward nature into the overlying sandstone interval (*see* below; Fig. 16).

The sandy nature of the shale and association with adjacent shallow marine settings (*see* below) suggests an inner shelf or prodelta setting. The lack of fossil abundance and diversity could indicate brackish conditions related to fluvial influx. Deep neritic to bathyal water depths were previously interpreted for this part of Karlsefni A-13 (Gradstein, 1978; Miller and D'Eon, 1987), but the consistently sandy nature of the shale is not congruent with discrete, fining-upward turbidity current deposits as interpreted by Miller and D'Eon (1987). This thin shale unit falls within the Leif Member of the Kenamu Formation (reflecting an atypical lithology) and is, according to Nøhr-Hansen et al. (2016) and Ainsworth et al. (2016), Lutetian–Bartonian (Middle Eocene) in age.

Lower shoreface

A sandstone-dominated interval with rare shale beds is present from 2241.8 m to 2190.9 m (7355–7188 ft.). The sandstone is brown to light grey to white, very fine- to fine-grained, well sorted, silty, argillaceous, friable, locally calcareous, and coarsening-upward, with interbedded shale, subrounded grains, and scattered fossil fragments (foraminifera, indeterminate shell material, and gastropod). Rare shale interbeds are dark grey, silty, sandy, and micro-micaceous, and contain rare foraminifera. The gamma-ray log highlights three main, roughly coarsening-upward units (Fig. 16).

The overall grain size, rounding, and dominance of sandstone suggests a return to lower shoreface deposition. The presence of some fossil content indicates possible normal-marine conditions, but the interbedding of shale could indicate some storm or deltaic influence. As seen in underlying intervals, a deep neritic to bathyal interpretation was given by Gradstein (1978) and Miller and D'Eon (1987), settings that are inconsistent with the Leif Member (Umpleby, 1979; McWhae et al., 1980; Dickie et al., 2011; Dafoe, Dickie et al., in press). The interval further caps the Leif Member of the Kenamu Formation, which is proposed in the present study to range from 2392.7–2191 m, modifying Umpleby's (1979) and McWhae et al.'s (1980) original type section (Table 26). The high sonic velocity indicates a well-cemented sandstone, with a sharp contact to the overlying Mokami Formation shale. The resulting Kenamu Formation reference section is also slightly modified from that of McWhae et al. (1980): 3038.9–2191 m (Table 26). This lower shoreface interval is Lutetian–Bartonian (Middle Eocene) based on the findings of Nøhr-Hansen et al. (2016) and Ainsworth et al. (2016).

Outer shelf to upper slope

Spanning the depths from 2190.9 m to 2151.9 m (7188–7060 ft.) is a silty, micaceous, dark grey shale containing rare limestone stringers.

The overall grain size, silty nature, and lack of fossil material suggests a distal marine setting consistent with the outer shelf to upper slope. The interpretation from the present study agrees well with previous work: deep neritic to bathyal water depths (Gradstein, 1978; Miller and D'Eon, 1987). This thin interval lies at the base of the Mokami Formation and records the typical transgressive episode at the base of the formation (Dafoe, Dickie et al., in press). Nøhr-Hansen et al. (2016) gave a Lutetian–

Bartonian (Middle Eocene) age, similar to that of Fenton and Pardon (2007), but older than the Rupelian (Early Oligocene) of Ainsworth et al. (2016).

Middle shelf

An interval of silty and sandy shale persists from 2151.9 m to 2042.2 m (7060–6700 ft.). This brown-grey to dark grey, silty, very fine sandy, slightly micaceous shale contains limestone stringers, scattered fossil fragments (bivalve and foraminifera), and rare pyrite. Rare limestone interbeds are dark brown, sandy, silty, and argillaceous.

The sandy nature of the shale and fossil content is interpreted to reflect a middle shelf setting. Miller and D'Eon (1987) suggested outer to inner shelf conditions for part of the interval, but primarily bathyal depths. Similarly, Gradstein (1978) interpreted a sharp contrast between marginal marine and bathyal settings, with the boundary found within the interval described herein. These sudden changes in water depth do not agree well with the lithological evidence, and the gradual change in water depth as reported in the present study appears to be more plausible. This part of the Mokami Formation is Lutetian–Bartonian (Middle Eocene) according to Nøhr-Hansen et al. (2016), but was suggested to be Rupelian by Ainsworth et al. (2016).

Inner shelf to prodelta

A thick interval of heterolithic shale or claystone with common sandstone and siltstone beds characterizes Karlsefni A-13 from 2042.2 m to 1511.8 m (6700–4960 ft.). Shale or claystone units are grey to brown grey, sandy (very fine-grained), silty, soft, partly micaceous, locally carbonaceous, and locally fissile, with sandstone stringers, localized fossil fragments (bivalve, foraminifera, locally common indeterminate shell material, and scaphopod), scattered lignite and coal, rare pyritized lignite, and rare siderite nodules. Sandstone units are light grey to brown to white and salt-and-pepper, fine- to medium-grained, silty, argillaceous, friable, and locally calcareous, becoming coarse-grained at the top of the interval, with subangular to subrounded clasts, moderate to well sorting, localized dark chert grains, and rare very coarse-grained sand grains and pebbles (quartz) increasing in abundance towards the top of the overall interval. Rare siltstones are grey, very argillaceous, sandy, friable, and slightly carbonaceous. In the well logs, the gamma-ray profile is ragged, but shows some thin, coarsening-upward successions (Fig. 16).

The coarsening-upward nature and presence of coarse-grained material, lignite, and coal implies a nearshore proximal setting. The fossil content is taken to indicate a more marine setting at the base, becoming brackish upwards in the interval. Accordingly, the paleoenvironment is interpreted as representing inner shelf to prodeltaic conditions. Previous authors documented similar marginal marine to inner shelf settings and brackish conditions, but also proposed some nonmarine units (Gradstein, 1978; Miller and D'Eon, 1987). The fossil content, however, appears to negate possible nonmarine deposition. This interval forms a significant part of the Mokami Formation and was found to be Lutetian–Bartonian (Middle Eocene) to Oligocene based on the findings of Nøhr-Hansen et al. (2016), but Ainsworth et al. (2016) gave only a Rupelian–Chattian (Early–Late Oligocene) age.

Estuarine or lagoonal

A thick interval of heterolithic claystone with thin sandstone beds, lesser limestone and rare siltstone occurs between the depths of 1511.8 m and 805.6 m (4960–2643 ft.). Grey sandy, silty, partly calcareous, locally shaly, locally micaceous, locally carbonaceous claystone includes sandstone stringers, limestone stringers, common fossil fragments throughout (bivalve, indeterminate shell material, and lesser gastropod), scattered siltstone stringers, scattered lignite, rare siderite nodules, rare pyrite, rare plant remains, and is locally coquina-like. Sandstone units are white, very fine- to medium-grained, argillaceous, friable, clayey, and locally calcareous, with subrounded grains, and moderate sorting, rare indeterminate shell and bivalve fragments, and rare black chert grains. Brown, argillaceous, sandy, and friable siltstones, and dark grey-brown, silty, argillaceous limestones with rare very fine-grained sand grains are also present. In contrast to the underlying interval (*see* above), these strata do not show clear trends in the gamma-ray profile other than a heterolithic, or ragged character (Fig. 16).

The overall heterolithic nature of this interval combined with common lignite and an abundance of primarily bivalve shell material suggests an estuarine or lagoonal setting, where brackish conditions hampered a diverse suite of marine fauna, but the sheltered setting resulted in a thriving, opportunistic population (Clarkson, 1998). Gradstein (1978) suggested marginal marine to inner neritic conditions, within range of the present study, and Miller and D'Eon (1987) similarly indicated brackish or marginal marine to inner shelf deposition including estuarine settings, but also possibly deltaic conditions. This interval forms part of the upper portion of the Mokami Formation. Nøhr-Hansen et al. (2016) indicated an Oligocene to Miocene age, but Ainsworth et al. (2016) only gave a Rupelian–Chattian (Early–Late Oligocene) age.

(?)Lagoonal

A thin interval from 805.6 m to 734.6 m (2643–2410 ft.) is composed of brown-grey, sandy (very fine- to medium-grained), silty, partly micaceous claystone bearing rare lignite and rare pyrite.

The lack of fossil material suggests a change from the underlying paleoenvironmental setting below, possibly becoming more restricted marine and the presence of lignite implies continued shoreline proximity. Accordingly, a more restricted, lagoonal setting is proposed. Both Gradstein (1978) and Miller and D'Eon (1987) interpreted inner shelf or inner neritic conditions, within range of the present study, but they did not report restricted marine conditions. This claystone succession forms the top of the Mokami Formation as defined in the present study at 734.6 m. This revised lithostratigraphic boundary is based on both the lithological change and associated decrease in the gamma-ray, sonic velocity, and resistivity log values. The age of this interval was given as Miocene by Nøhr-Hansen et al. (2016), but a younger Late Miocene–(?)Pliocene age was proposed by Ainsworth et al. (2016).

Shoreface

An overall coarsening-upward sandstone and conglomerate interval that is slightly heterolithic at the base is found between 734.6 m and 597.4 m (2410–1960 ft.). Sandstones are white to light yellow in colour, fine- to very coarse-grained, very clayey, friable, and are sometimes loose consolidated, with subrounded grains, moderate to poor sorting, common bivalve fragments, pebbles (igneous, quartz, white and dark chert, siderite, and limestone), rare lignite, and rare *Otionella* (shallow marine) bryozoan. Conglomerates are white to light grey to yellow, sandy, and unconsolidated, with subrounded to well rounded quartz and dark chert pebbles, common fossil fragments (bivalve), rare pyrite, rare igneous pebbles, and rare lignite. Grey, silty, sandy (fine- to medium-grained) claystone also contains rare quartz pebbles, rare bivalve fragments, and rare lignite. In general, there are localized abundances of bivalve fragments within the interval. The gamma-ray log is characterized by a ragged profile that is subtly coarsening-upward (Fig. 16).

The coarse-grained nature of the strata and presence of fossil and terrestrial material suggests a high-energy shoreface setting. This is further supported by the grain rounding. Similar settings were proposed by Miller and D'Eon (1987) as inner shelf, deltaic, and distributary bars, and Gradstein (1978) also found the paleoenvironment to be inner neritic. This coarse-grained succession forms the base of the Saglek Formation in Karlsefni A-13. Nøhr-Hansen et al. (2016) indicated a Miocene to Pliocene–Pleistocene age for the interval, in good agreement with the designation of Ainsworth et al. (2016).

Shoreface

The uppermost interval in Karlsefni A-13 between the depths 597.4 m and 533.4 m (1960–1750 ft.) is primarily composed of sandstone with some conglomerate at the very top. Light yellow to white, unconsolidated, overall coarse-grained, moderately to poorly sorted sandstone includes varicoloured igneous, metamorphic, quartz, siderite, black chert, and limestone pebbles, as well as subrounded to well rounded grains, scattered bivalve shell fragments, rare siderite sandstone stringers, rare lignite, and rare coal. Conglomerate units include white to pink quartz, varicoloured igneous pebbles, siderite, limestone, and rare metamorphic pebbles, with rare bivalve shell material and sideritized sandstone.

The grain size, coarsening-upward character, and presence of shell material and coal and lignite suggests a proximal setting within a shoreface paleoenvironment. Miller and D'Eon (1987) indicated a similar delta front setting and the inner neritic paleoenvironment of Gradstein (1978) is also comparable with the results of the present study. This part of the Saglek Formation continues to 505 m at the top of the electric logs. Accordingly, the Saglek Formation is modified from that of Moir (1989) to 734.6–505 m (Table 26).

Lithostratigraphy

Based on the discussion around lithostratigraphic refinements to the framework of Moir (1989) in Karlsefni A-13, the lithostratigraphic picks from the present study are summarized in Table 26. Modifications to the type and reference sections are also indicated.

Lithostratigraphic unit	Moir (1989)		The present study		Type or reference section
	Base (m)	Top (m)	Base (m)	Top (m)	
Saglek Fm	724	287	734.6	505	None
Mokami Fm	2191	724	2191	734.6	None
Kenamu Fm (Leif Mb)	2393	2191	2392.7	2191	Type section from 2394–2191 m of Umpleby (1979) and McWhae et al. (1980) is modified to 2392.7–2191 m
Kenamu Fm	3036	2191	3038.9	2191	Reference section from 3036–2191 m of McWhae et al. (1980) is modified to 3038.9–2191 m
Cartwright Fm	3796	3036	3770.4	3038.9	None
Markland Fm	4129	3796	4134.6	3770.4	None
Unnamed Precambrian	4149	4129	4149	4134.6	None

Table 26: Lithostratigraphic assignment for Karlsefni A-13 from the present study and compared to that of Moir (1989). Fm=Formation; Mb=Member.

LEIF E-38

The Leif E-38 well is situated in a proximal setting in the southern part of the Hopedale Basin (Fig. 1). The samples from Leif E-38 are described in the Tennaco Oil and Minerals Ltd. (1972) report, including cuttings, sidewall core, and petrographic descriptions. The Canadian Stratigraphic Service Ltd. Tenneco et al Leif E-38 log (log EC-32) was also utilized to develop the interval descriptions below. This log has the most extensive set of information, which encompass detailed lithological, grain size, grain rounding, and sample descriptions for most of the well. Figure 17 is the well plot that shows key well logs, lithology, grain size, rock colour, ages, and paleoenvironmental and lithostratigraphic information. In the present study, the ages of Williams (1979h) are used, and the paleoenvironments described below are summarized in Table 27. These settings are also compared in the descriptions below to the interpretations of Gonzalez et al. (1971) whom used microfauna and to those of Miller and D'Eon (1987). The modified lithostratigraphic assignments from the present study are also indicated in Figure 17 and in Table 28 as compared to those of Moir (1989).

Base (m)	Top (m)	Paleoenvironment
1084	1005.9	MIDDLE SHELF
1005.9	662.3	INNER SHELF
662.3	432.2	INNER SHELF TO LOWER SHOREFACE
432.2	344.4	SHOREFACE

Table 27: Paleoenvironmental determinations for Leif E-38 from the present study.

Middle shelf

The base of Leif E-38 includes an overall claystone-dominated interval with limestone and marlstone and lesser sandstone and siltstone beds from 1084 m to 1005.9 m (3558–3300 ft.). Grey-brown claystone is sandy, silty, soft, micaceous, and slightly calcareous, and further includes thin siltstone stringers, pyrite, limestone stringers, rare fossil fragments (bivalve and indeterminate fossil material), and rare sandstone stringers. Limestone and marlstone units are dark grey, sandy, and argillaceous, with pyrite, interbedded claystone, rare dark chert, and rare indeterminate fossil fragments. Dark grey to brown, argillaceous, calcareous, very fine-grained sandstone includes subangular grains and moderate sorting.

The overall heterolithic nature, incorporation of sand grains, and presence of fossil material reflects a middle shelf paleoenvironment. This setting is slightly shallower than that of previous studies, which found outer neritic or outer shelf to bathyal water depths (Gonzalez et al., 1971; Miller and D'Eon (1987). The distribution of sand grains within the claystone and commonality of bivalve fragments appears to support a shelfal rather than a deep-water setting. The Mokami Formation includes this claystone-dominated interval, which is Early Miocene in age according to Williams (1979h).

Inner shelf

The interval from 1005.9 m to 662.3 m (3300–2173 ft.) includes claystone with sandstone, siltstone, and rare limestone or marlstone beds. Brown claystones are silty, locally sandy, soft, micaceous, and slightly calcareous. They further contain pyrite, common fossil fragments throughout (scaphopod are locally abundant, bivalve, gastropod, indeterminate shell material, ostracod, worm tubes, echinoderm, bryozoan (more common near the top of the interval, and possible *Otionella*), and fish remains), very coarse-grained sand grains in the upper portion of the interval, rare coal fragments, and rare carbonaceous plant remains (but these are more common at the top of the interval). Sandstone are brown to grey to white, very fine- to fine-grained, silty, calcareous, and locally coarse-grained, with muscovite, chlorite, pyrite, feldspar, fossil fragments (bivalve), shale stringers, and rare glauconite. In addition, the sandstones are composed of subangular grains and are well sorted becoming moderately to poorly sorted with subrounded to rounded grains. Siltstone units are brown, argillaceous, sandy, calcareous, and micaceous.

The diverse suite of fossils, indications of terrestrial influx, and coarse-grained nature indicates normal-marine conditions within an inner shelf setting. This interpretation is generally similar to the inner to middle shelf and sublittoral paleoenvironments postulated by previous authors (Gonzalez et al., 1971; Miller and D'Eon, 1987). This thick interval forms a significant part of the Mokami Formation in the well, and Williams (1979h) gave an age of Early to Middle–Late Miocene.

Inner shelf to lower shoreface

Spanning the depths of 662.3 m to 432.2 m (2173–1418 ft.) is a succession of heterolithic claystone and lesser sandstone and limestone or marlstone. Brown claystone units are soft, micaceous, and silty and further include carbonaceous plant remains, fossil fragments throughout (bivalve, gastropod, bryozoan, fish remains, echinoderm, ostracods, worm tubes, and solitary corals), sandstone stringers, very coarse-grained sand grains near the top of the interval (but these may be related to cavings; *see* below), and locally common pyrite. Limestones and marlstones are brown, argillaceous, sandy, and silty, with fossil fragments and rare chert. Brown to dark grey sandstone units are very fine- to coarse-grained, argillaceous, calcareous, glauconitic, silty, and micaceous, with chlorite, marlstone stringers, very coarse-grained sand grains, pebbles near the top of the interval, rare fossil fragments (bivalve and other), and rare feldspar. Overall, the gamma-ray log suggests a subtle coarsening-upward trend, but a ragged log character is prevalent (Fig. 17).

The lithology and abundant and diverse fossil suite represent continued inner shelf deposition, but the heterolithic nature could be related to storm-dominated conditions that result in fluctuating storm sandstones and fair-weather mudstone intervals. Subtle coarsening upward could also indicate lower shoreface deposition at the top of the interval. Inner shelf or sublittoral settings were also generally indicated by Gonzalez et al. (1971) and Miller and D'Eon (1987). This claystone succession represents the upper part of the Mokami Formation as defined in the present study. It is included in the Mokami Formation rather than the Saglek Formation, as was proposed by Moir (1989), based on the dominance of claystone rather than sandstone (Fig. 17). Thus, the Mokami Formation extends from 1084–432.2 m (Table 28). The age of this succession is Middle–Late Miocene to Pliocene–Pleistocene (Williams, 1979h).

Shoreface

The uppermost interval in Leif E-38 between 432.2 m and 344.4 m (1418–1130 ft.) is a sandstone and conglomerate interval with interbedded claystones. White, mostly coarse-grained, poorly sorted, unconsolidated sandstones include rounded and lesser subrounded grains, polished grains, feldspar, very coarse-grained sand grains, fossil fragments (echinoderm plates, bivalve, gastropod, and bryozoan), and rare glauconite. Conglomerate is white to red and/or orange, unconsolidated, and sandy, with igneous pebbles, limestone pebbles, quartz pebbles, frosted pebbles, fossil fragments (bivalve, echinoderms plates, foraminifera, and scaphopod), weathered feldspar, claystone interbeds, and rare chert. Brown claystone units are silty, very sandy, and micaceous, and include very coarse-grained sand grains, rare bivalve fragments, and rare glauconite.

The coarse grain size and presence of weathered and frosted grains suggests a nearshore, high-energy setting. This, combined with the abundance and diversity of fossil material and grain rounding is consistent with a normal marine, shoreface setting. Both Gonzalez et al. (1971) and Miller and D'Eon (1987) proposed inner shelf or sublittoral settings, in good agreement with the present study. This interval is equated with the Saglek Formation in this well, which extends to 334.4 m at the top of the electric logs, rather than to 204 m within the cased portion of the well as proposed by Moir (1989; Table 28). Williams (1979h) reported a Pliocene–Pleistocene age for the shoreface succession, younger than other ages for the Saglek Formation intersected in nearby wells (e.g. North Leif I-05, *see* below).

Lithostratigraphy

Based on the discussion around lithostratigraphic refinements to the framework of Moir (1989) in Leif E-38, the lithostratigraphic picks from the present study are summarized in Table 28. There are no type or reference sections for this well.

Lithostratigraphic unit	**Moir (1989)**		**The present study**		**Type or reference section**
	Base (m)	**Top (m)**	**Base (m)**	**Top (m)**	
Saglek Fm	596	204	432.2	334.4	None
Mokami Fm	1084	596	1084	432.2	None

Table 28: Lithostratigraphic assignment for Leif E-38 from the present study and compared to that of Moir (1989). Fm=Formation.

LEIF M-48

Nearby to Leif E-38 is the Leif M-48 well in the Hopedale Basin (Fig. 1). The well history report for Leif M-48 includes both sidewall core and cuttings descriptions (Corgnet and McWhae, 1973b) utilized in the present study. In addition to this, detailed descriptions of the lithology, grain size, grain rounding, and sample descriptions from the Canadian Stratigraphic Service Ltd. Eastcan et al. Leif M-48 log (log EC-71) were used to compile the below descriptions. The well plot is shown in Figure 18 and includes key well logs, lithology, grain size, rock colour, ages, and paleoenvironmental and lithostratigraphic information. The ages of Williams (1979i) for the lower part of the well are in close agreement with those of Bujak Davies Group (1989e) and Fenton and Pardon (2007), but ages in the upper part of the well are based on those of Bujak Davies Group (1989e), which fit the lithostratigraphic framework established by McWhae et al. (1980), Dickie et al. (2011), and Dafoe, Dickie et al. (in press) for these formations. Table 29 summarizes the paleoenvironmental interpretations from the present study, and these are further compared in the below descriptions with results from Miller and D'Eon (1987) and Bujak Davies Group (1989e), the latter derived from micropaleontological and palynological results. The lithostratigraphy from the present study and those of Moir (1989) are compared in Figure 18 and Table 30.

Below the sedimentary succession, the Alexis Formation basalts extend from 1879–1839.5 m at the base of this well. This assignment differs only slightly from that of Moir (1989), but is based on the clear lithological and log change at 1839.5 m (Fig. 18; Table 30).

Base (m)	Top (m)	Paleoenvironment
1839.5	1819.7	OUTER SHELF
1819.7	1804.4	UPPER SLOPE
1804.4	1722.1	OUTER TO MIDDLE SHELF
1722.1	1692.6	PRODELTA
1692.6	1666.7	DELTA FRONT
1666.7	1380.8	OUTER SHELF
1380.8	1298.5	PRODELTA
1298.5	1257.3	DELTA FRONT
1257.3	1222.3	PRODELTA
1222.3	1158.3	OUTER SHELF
1158.3	1005.9	MIDDLE SHELF
1005.9	582.8	INNER SHELF (STORM-DOMINATED)
582.8	454.2	LOWER SHOREFACE (STORM-DOMINATED)
454.2	388.9	SHOREFACE
388.9	381.0	INNER SHELF

Table 29: Paleoenvironmental determinations for Leif M-48 from the present study.

Outer shelf

The base of the sedimentary section in Leif M-48 includes a thin interval of silty shale from 1839.5 m to 1819.7 m (6035–5970 ft.). The brown-grey to green-grey shale is silty, partly sandy, and micaceous, with limestone stringers, fossil fragments (foraminifera and (?)worm tube), rare glauconite, and rare pyrite.

The fossil and silt content along with limestone suggests an outer shelf paleoenvironment, possibly with reducing conditions accounting for the localized greenish colouration (Myrow, 2003).

Slightly deeper bathyal settings were previously proposed by Miller and D'Eon (1987) and Bujak Davies Group (1989e).

Lying above the Alexis Formation basalts, this silty shale interval forms the base of the Markland Formation. Both Williams (1979i) and Bujak Davies Group (1989e) gave a Maastrichtian age, with Fenton and Pardon (2007) suggesting late Maastrichtian.

Upper slope

From 1819.7 m to 1804.4 m (5970–5920 ft.) is a succession of green-grey, fissile, partly silty, micro-micaceous shale, with very rare (?)worm tube fragments.

The overall lack of fossil material and silt content suggests an upper slope-equivalent setting beyond the shelf edge, and the green colouration may again indicate reducing conditions (Myrow, 2003). This is similar to the bathyal settings of Miller and D'Eon (1987) and Bujak Davies Group (1989e), although the latter authors indicated lower bathyal water depths. Also within the Markland Formation, this shale interval is Maastrichtian (Williams, 1979i; Bujak Davies Group, 1989e) to late Maastrichtian (Fenton and Pardon, 2007).

Outer to middle shelf

Spanning the depths of 1804.4 m to 1722.1 m (5920–5650 ft.) is a silty and fossil fragment-bearing shale. Grey to green or brown-grey shale is silty and micaceous, and includes fossil fragments (foraminifera, possible worm tubes, and other indeterminate fragments), rare pyrite, rare glauconite, rare sand grains increasing in abundance upwards, and rare pyritized possible worm tubes. Dark brown, silty, argillaceous limestone is also rarely present.

The increase in silt and sand content upwards suggests shallowing, and the dominance of foraminifera is consistent with a shelfal setting. Accordingly, the paleoenvironment is interpreted as outer shelf shallowing upward to middle shelf. This interval spans the upper part of the Markland Formation and lower Cartwright Formation, with a Maastrichtian to Late Paleocene (Thanetian) age (Williams, 1979i; Bujak Davies Group, 1989e; Fenton and Pardon, 2007). The top of the Markland Formation is well defined by an increase in the gamma-ray, sonic, and resistivity logs into the overlying Cartwright Formation, with the boundary at 1780 m (Table 30).

Prodelta

A thin interval that consists of shale with thin sandstones is present between 1722.1 m and 1692.6 m (5650–5553 ft.). Dark grey-brown shale is silty, sandy (very sandy near the top of the interval), slightly micaceous, and slightly calcareous, and is further characterized by limestone nodules, scattered foraminifera, and rare pyrite. Sandstones are well sorted and fine-grained, with subrounded clasts. Overall, quartz pebbles and fossil fragments are found at the base of unit, and rare glauconite is present. The gamma-ray log further shows a subtle coarsening-upward character into the overlying sandstone.

The increase in sand content upwards suggests shallowing and progradation in a marine setting based on the fossil suite. The pebble and fossil lag at base of the interval could indicate erosion or reworking. The paleoenvironment is interpreted as prodeltaic partly based on the interpretation of the overlying unit, as well as the limited fossil abundance and diversity that imply brackish conditions. This shallow marine setting was not observed in previous studies as bathyal water depths were reported (Miller and D'Eon, 1987; Bujak Davies Group, 1989e). This discrepancy is possibly due to the thin nature of the shallow marine interval, including that of the sandstone interval above (*see* below). This sandy shale unit caps the top of the Cartwright Formation, and the age is likely Early Eocene (Williams, 1979i), but possibly Thanetian (Late Paleocene; Fenton and Pardon, 2007). The reference section for the Cartwright Formation is thus modified slightly to 1780–1692.6 m from the original designation of McWhae et al. (1980; Table 30).

Delta front

Spanning the interval from 1692.6 m to 1666.7 m (5553–5468 ft.) is a sandstone succession with shalier intervals and one prominent limestone bed. Sandstones are white to brown, very fine- to fine-grained, argillaceous, and friable, and also contain dark brown shale stringers, very coarse-grained sand grains near the top of the interval, subrounded to well rounded grains, and are well to moderately sorted. Interstratified shale is dark brown, silty, and fissile, with very fine- to fine-grained sand. Limestone is brown, sandy, silty, and argillaceous. In the gamma-ray log, a subtle coarsening-upward profile is noted, with low API values also recorded for the limestone. The top of unit is marked by a thin siderite with pyrite and glauconite and is sandy, argillaceous and calcareous.

In general, the sandy nature, coarsening-upward character, and presence of shale stringers is typical of a delta front setting. A lack of fossil detritus and the general grain rounding supports this interpretation. This type of shallow marine setting was not reported by Miller and D'Eon (1987), nor by Bujak Davies Group (1989e) as they interpreted bathyal water depths. Dafoe, Dickie et al. (in press) confirmed the shallow marine nature of the Gudrid Formation and suggested that paleoenvironmental interpretations of thin sandstones in some wells could be skewed where cuttings from overlying deep-water intervals contaminated the successions. The top of the interval is consistent with the transgressed horizon that is typically seen at the Gudrid to Kenamu formation boundary (Dickie et al., 2011; Dafoe, Dickie et al., in press). The upper Gudrid Formation lithostratigraphic assignment is modified from that of Moir (1989) to extend from 1692.2–1666.7 m (Table 30). Williams (1979i) and Bujak Davies Group (1989e) indicated an Early Eocene age for this interval.

Outer shelf

A thick shale persists from 1666.7 m to 1380.8 m (5468–4530 ft.). The thick brown shale is silty, micaceous, and fissile, and includes brown argillaceous limestone stringers, scattered siderite nodules, fossil fragments that increase in abundance within the upper part of interval (foraminifera, scaphopod, and gastropod), rare sand grains, rare pyrite, rare carbonaceous inclusions, and rare glauconite. Rare interbeds of marlstone or limestone are dark brown, calcareous, silty, and argillaceous.

The silty shale with foraminifera and scaphopod fragments suggests an outer shelf paleoenvironment. Miller and D'Eon (1987) and Bujak Davies Group (1989e) both indicated bathyal settings, but the upper bathyal to outer neritic conditions postulated by the latter author for part of the interval are in good agreement with the setting proposed herein. The increase in fossil content and silt content upward would agree with the slight shallowing noted by Bujak Davies Group (1989e). This shale forms a significant portion of the Kenamu Formation, and was found to be Early Eocene to Middle–Late Eocene by Williams (1979i), but possibly only ranging into the Middle Eocene (Bujak Davies Group, 1989e; Fenton and Pardon, 2007), as would be consistent with the regional understanding of the Kenamu Formation (Dickie et al., 2011; Dafoe, Dickie et al., in press). The type section of the Brown Mudstone Member of the Kenamu Formation was defined in this part of the well by McWhae et al. (1980), but is modified here to 1666.7–1380.8 m (Table 30).

Prodelta

Spanning the depths of 1380.8 m to 1298.5 m (4530–4260 ft.) is a claystone with thin sandstone intervals increasing in abundance upward. Brown, silty, very fine-grained sandy, slightly calcareous, slightly micaceous claystone includes locally common fossil fragments (foraminifera and indeterminate shell material) and rare pyrite. Sandstone interbeds are white to light brown, very fine- to fine-grained, well sorted, silty, argillaceous, and friable, with subrounded grains, rare coarse-grained quartz sand grains, rare muscovite, and rare scaphopod and indeterminate shell fragments. The overall gamma-ray log exhibits cleaning upward, with discrete coarsening-upward units (Fig. 18).

The coarsening upward nature and dominance of claystone, combined with the nature of the overlying sandstone (*see* below), and locally common, but limited fossil diversity suggests a prodeltaic paleoenvironment. A shallow marine setting was not reported by previous authors as they interpreted outer neritic to upper bathyal conditions, with turbidites explaining the presence of sandstones (Miller and D'Eon, 1987; Bujak Davies Group, 1989e). As this interval coarsens upward into the overlying shallow marine sandstone interval, such a deep-water interpretation is inconsistent with the sedimentological findings. This sandy claystone interval forms part of the upper Kenamu Formation and is of Middle–Late Eocene age according to Williams (1979i), but may be restricted to the Middle Eocene based on the findings of Bujak Davies Group (1989e) and Fenton and Pardon (2007).

Delta front

Strata composed of coarsening- and cleaning-upward sandstone with some shale beds is present from 1298.5 m to 1257.3 m (4260–4125 ft.). White to light brown, very fine- to fine-grained, argillaceous, silty, friable sandstone is locally poorly consolidated, with argillaceous grains (possible mudstone rip-up clasts), subrounded grains, a well sorted character, rare muscovite, rare glauconite, rare dark chert grains, and rare brown shale partings. Brown shale units are silty, sandy (very fine-grained), slightly calcareous, and slightly micaceous. The gamma-ray log shows three main coarsening-upward units (Fig. 18).

The grain rounding and sorting combined with shale partings and argillaceous grains are interpreted to represent a delta front setting. Shoreface settings tend to have cleaner sands and less interbedding, as well as blockier gamma-ray profiles (McCubbin, 1982). The lack of fossil detritus further attests to brackish conditions during deposition. These sandstones were interpreted by Miller and D'Eon (1987) to indicate turbidite deposition at bathyal depths, and Bujak Davies Group (1989e) also found an outer neritic to upper bathyal setting. The evidence above does not support such a deep-water setting, and contamination by cavings from overlying shales could explain the settings interpreted by previous authors. This sandstone interval forms the Leif Member of the Kenamu Formation, with a Middle–Late (Williams, 1979i) or Middle Eocene age (Bujak Davies Group, 1989e), the latter age preferred in the present study. The Leif Member reference section proposed by McWhae et al. (1980) is refined here to 1298.5–1257.3 m to match the paleoenvironmental changes and the sharp base and top of the sandstone-dominated interval (Fig. 18; Table 30).

Prodelta

From 1257.3 m to 1222.3 m (4125–4010 ft.) is a succession composed of very sandy shale with thin sandstones. Medium to dark brown, silty, sandy to very sandy (very-fine grained), slightly calcareous shale includes rare gastropod and indeterminate shell fragments. Sandstone interbeds are white, well sorted, very fine- to fine-grained, silty, argillaceous, with friable brown shale stringers and subrounded grains. Gamma-ray character is ragged, but shows a subtle fining-upward trend (Fig. 18).

The overall similarity to the sandy shale unit below 1298.5 m suggests deepening from the delta front setting back to prodeltaic conditions. A low diversity fossil assemblage supports a prodeltaic interpretation, as does the heterolithic nature and ragged gamma-ray log profile. A fining-upward trend would appear to indicate the onset of relative sea-level rise and continued deepening. Like other intervals at the top of the Kenamu Formation, this shallow marine setting was not seen in previous studies (Miller and D'Eon, 1987; Bujak Davies Group, 1989e). Bathyal water depths are not supported by the consistently sandy nature of the strata, nor by the types of fossils encountered. This sandy shale interval lies above the Leif Member and represents a slight deepening at the top of the Kenamu Formation. The type section of the formation is revised in the present study from 1666.7–1222.3 m, differing only slightly from that of McWhae et al. (1980; Table 30). While Williams (1979i) gave an Early

Oligocene age, the Middle Eocene interpretation of Bujak Davies Group (1989e) fits better within the regional understanding of the Kenamu Formation discussed in Dafoe, Dickie et al. (in press).

Outer shelf

The succession from 1222.3 m to 1158.3 m (4010–3800 ft.) consists of claystone or shale that is grey-brown to brown-grey, calcareous, and silty, and further contains dark grey-brown marlstone stringers and very rare very fine-grained sand grains.

The silty and calcareous character of the claystone is indicative of an outer shelf setting. The lack of fossil detritus is unusual, but the colour change to dominantly grey further indicates a change in the depositional regime, perhaps related to water chemistry. This setting matches closely with that of Miller and D'Eon (1987) and Bujak Davies Group (1989e) where they reported outer shelf or outer neritic to bathyal paleoenvironments. This claystone marks the base of the Mokami Formation and a transgression above the underlying Kenamu Formation. Williams (1979i) proposed an Oligocene age, but Bujak Davies Group (1989e) and Fenton and Pardon (2007) suggested Middle–Late Eocene ages, consistent with the base of the Mokami Formation as defined in Dickie et al. (2011) and Dafoe, Dickie et al. (in press).

Middle shelf

The interval from 1158.3 m to 1005.9 m (3800–3300 ft.) includes shale or claystone with marlstone or limestone interbeds. The claystone and shale units are grey-brown, partly calcareous at the base, silty, and sandy (increasingly sandy upward), with dark grey-brown marlstone stringers, fossil fragments present in the uppermost part of interval (foraminifera and indeterminate shell material), and rare sandstone stringers near the top of the interval. Rare marlstone and limestone beds are dark grey-brown, silty, and sandy (very fine-grained), with shale stringers.

The sandier upwards nature suggests progressive shallowing, which is also indicated by an increase in fossiliferous detritus upwards. The degree of silt and sand content within the shale and claystone is interpreted to reflect a middle shelf setting. The mix of foraminifera and shell material agrees well with this paleoenvironmental setting. This interpretation is slightly shallower than the outer shelf and outer neritic to bathyal water depths of Miller and D'Eon (1987) and Bujak Davies Group (1989e). This part of the Mokami Formation was found to be Late Eocene by Bujak Davies Group (1989e), an age that is preferred over the Early Miocene determination of Williams (1979i).

Inner shelf (storm-dominated)

A claystone and shale-dominated unit with sandstone and lesser siltstone interbeds is prevalent from 1005.9 m to 582.8 m (3300–1912 ft.). Grey-brown, silty, very fine-grained sandy, slightly micaceous, slightly calcareous claystone and shale contain common to locally abundant fossil fragments (10% of the rock in places; bivalve, scaphopod, (?)*Orthoceras*, foraminifera, gastropod, worm tubes, and bryozoa), locally common sandstone stringers, very coarse-grained sand grains in the upper half of unit, rare quartz pebbles, and rare pyrite. Grey, well sorted, very fine-grained, locally glauconitic, argillaceous, silty, very calcareous sandstone also includes shale stringers and subangular grains. Siltstone units are, grey, sandy (very fine-grained), argillaceous, and calcareous. Rare coaly material is locally present in the interval. A ragged profile is seen in the gamma-ray log and porosity logs further suggest the alternation of lithologies (Fig. 18).

The lithology is more heterolithic than expected for an inner shelf setting, but could be explained by alternating storm and fair-weather conditions. The diverse fossil content, however, confirms normal marine salinity and an inner shelf setting. Prograding middle shelf and middle to outer neritic conditions were postulated by previous workers (Miller and D'Eon, 1987; Bujak Davies Group, 1989e). The sand and fossil content is, however, suggestive of shallower shelf deposition as indicated in the present study. This thick, heterolithic interval forms part of the Mokami Formation, and was assigned a Late Eocene to Early Oligocene age by Bujak Davies Group (1989e), an age that is preferred over the Early Miocene to Pliocene determination of Williams (1979i).

Lower shoreface (storm-dominated)

Spanning the depths of 582.8 m to 454.2 m (1912–1490 ft.) is a succession of very heterolithic sandstone, claystone or shale, siltstone, and marlstone. Sandstone units are grey, very fine- to fine-grained, silty, calcareous, argillaceous, slightly micaceous, and well sorted, with shale stringers, subangular grains, fossil fragments ((?)*Orthoceras* and bivalve), and argillaceous grains. Claystone or shale interbeds are grey-brown, silty, slightly calcareous, rarely sandy, and further include fossil fragments throughout (bivalve, gastropod, (?)*Orthoceras*, indeterminate shell material, foraminifera, and scaphopod), pyrite, and rare carbonaceous plant remains. Medium to dark grey, sandy, argillaceous, calcareous siltstone also contains shale stringers. Dark grey-brown marlstone is silty and partly sandy, with fossil fragments ((?)*Orthoceras*, bivalve, and gastropod).

The variety and abundance of fossil material implies normal marine salinity and a shallow shelf setting. The lithology is consistent with a lower shoreface setting, but the heterolithic nature may indicate storm-dominance and alternating fair-weather mudstones and storm sandstones. Similar settings in the inner to middle shelf range were reported by previous authors (Miller and D'Eon, 1987; Bujak Davies Group, 1989e) and are in good agreement with the present study. This interval caps the top of the Mokami Formation as defined here. Moir (1989) included this heterolithic interval in the Saglek Formation, but the sandstone content is less than 50% of the total interval, so it is better placed within the Mokami Formation similar to Leif E-38. Accordingly, the Mokami Formation extends from 1222.3–454.2 m according to the present study (Table 30). Bujak Davies Group (1989e) gave an Early–Late Oligocene age for this lower shoreface interval, an age that is preferred over the Pliocene–Pleistocene findings of Williams (1979i).

Shoreface

Between 454.2 m and 388.9 m (1490–1276 ft.) is a sandstone and conglomerate interval. These rocks are to brown and unconsolidated, with fine- to coarse-grained sandstone, varicoloured igneous pebbles, moderate to well sorting, a partly argillaceous character, subrounded to rounded and rare subangular to angular clasts, pyrite, rare indeterminate shell fragments throughout, and rare dark brown limestone pebbles. The gamma-ray log character highlights the presence of the conglomeratic intervals within an overall blocky log character (Fig. 18).

The grain size, log character, low diversity fossil suite, and shale/limestone fragments indicates a high-energy, shoreface setting is most likely. Similar inner shelf or neritic settings were proposed by Miller and D'Eon (1987) and Bujak Davies Group (1989e), with a possible deltaic setting indicated by the former author. These strata form part of the Saglek Formation in Leif M-48, and an Early Miocene age was given by Bujak Davies Group (1989e) and is preferred over the Pliocene–Pleistocene age of Williams (1979i).

Inner shelf

A thin interval at the very top of Leif M-48 from 388.9 m to 381.0 m (1276–1250 ft.) is composed of brown-grey claystone that is silty and sandy (very fine-grained), with rare indeterminate shell fragments. While the lithology appears to be finer-grained, a low gamma-ray log signature continues from the underlying coarse-grained strata (Fig. 18).

There is limited information from this thin interval, but the mixed lithology likely indicates a return to inner shelf conditions. Miller and D'Eon's (1987) inner shelf interpretation is similar to the present study. These finer-grained strata are part of the Saglek Formation, with the top of the formation considered to coincide with the end of the lithological and log information at 381 m (Table 30), but this part of the well has no biostratigraphic control (Fig. 18).

Lithostratigraphy

Based on the discussion around lithostratigraphic refinements to the framework of Moir (1989) in Leif M-48, the lithostratigraphic picks from the present study are summarized in Table 30. Revisions to the type and reference sections are also indicated in Table 30.

Lithostratigraphic unit	Moir (1989)		The present study		Type or reference section
	Base (m)	Top (m)	Base (m)	Top (m)	
Saglek Fm	590	202	454.2	381	None
Mokami Fm	1222	590	1222.3	454.2	None
Kenamu Fm (Leif Mb)	1298	1257	1298.5	1257.3	Reference section from 1298–1257 m of McWhae et al. (1980) is modified to 1298.5–1257.3 m
Kenamu Fm (Brown Mudstone Mb)	--	--	1666.7	1380.8	Type section from 1666–1381 m of McWhae et al. (1980) is modified to 1666.7–1380.8 m
Kenamu Fm	1666	1222	1666.7	1222.3	Type section from 1666–1222 m of McWhae et al. (1980) is modified to 1666.7–1222.3 m
Gudrid Fm (upper)	1693	1666	1692.6	1666.7	None
Cartwright Fm	1780	1693	1780	1692.6	Reference section from 1780–1695 m of McWhae et al. (1980) is modified to 1780–1692.6 m
Markland Fm	1839	1780	1839.5	1780	None
Alexis Fm	1879	1839	1879	1839.5	None

Table 30: Lithostratigraphic assignment for Leif M-48 from the present study and compared to that of Moir (1989). The type section for the Brown Mudstone Member is shown on Figure 18, partly overlapping the Kenamu Formation type section. Fm=Formation; Mb=Member.

NORTH BJARNI F-06

Situated near the Bjarni wells in the central region of the Hopedale Basin is the North Bjarni F-06 well (Fig. 1). Samples from North Bjarni F-06 are documented in the well history report by Duff (1981a), which includes cuttings descriptions, a core description, and sidewall core descriptions. The Canadian Stratigraphic Service Ltd. Petro-Canada North Bjarni F-06 log (log EC-154) further includes detailed information regarding the lithology, grain size, grain rounding, and sample descriptions that were used in the present study. Some of these data are shown in the well plot in Figure 19, which includes key well logs, lithology, grain size, rock colour, ages, and paleoenvironmental and lithostratigraphic information. The biostratigraphic interpretations from Bujak Davies Group (1989e) and Ainsworth et al. (2016) are similar and are both used in the present study, with some consideration of the work by Fenton and Pardon (2007). Ages from palynomorph biostratigraphy and paleoenvironmental interpretations are provided for core 1 from the Bjarni Formation by Dafoe and Williams (2020a). Paleoenvironmental interpretations in the present study are summarized in Table 31 below. In the descriptions below, these interpretations are also compared with those of Miller and D'Eon (1987) and Ainsworth et al. (2014), with the latter presumably based on both the micropaleontology and palynology conducted in their study. The lithostratigraphic refinements to the original work by Moir (1989) are also shown in Figure 19 and in Table 32.

Base (m)	Top (m)	Paleoenvironment
2812	2618	NONMARINE FLUVIAL OR ALLUVIAL
2618	2424	DELTAIC
2424	2397	OUTER SHELF
2397	2289	SLOPE
2289	2200	OUTER SHELF TO UPPER SLOPE
2200	2119	SLOPE
2119	1700	OUTER SHELF
1700	1400	MIDDLE SHELF
1400	1250	OUTER SHELF
1250	852	INNER SHELF TO PRODELTA
852	425	SHOREFACE

Table 31: Paleoenvironmental determinations for North Bjarni F-06 from the present study.

Nonmarine fluvial or alluvial

At the base of North Bjarni F-06 from 2812 m to 2618 m is a succession of sandstone with thin interbeds of shale, resulting in an overall heterolithic character where the two lithologies alternate. The dominant sandstone lithology is light grey to white, medium- to coarse-grained, composed of subangular grains, and moderately sorted. Sandstones also include scattered very coarse-grained sand grains throughout and common feldspar, chert, and kaolinite. They also possess a calcareous cement, frosted to vitreous quartz, scattered pebbles (feldspar, chert, and quartz), and rare coal fragments. Shale interbeds are grey, silty, and locally sandy. The ragged gamma-ray log character confirms a heterolithic lithology, but the API values of the sandstones are high, as is typical for some Bjarni Formation sandstones with elevated feldspar content (Umpleby, 1979).

The overall lack of fossil material and abundance of kaolinite suggests a nonmarine setting, possibly alternating between fluvial and floodplain deposition or the result of mixed alluvial sedimentation. The gamma-ray log character does not support a typical fining-upward fluvial profile, but this could reflect a more braided character to the fluvial channels. Miller and D'Eon (1987) inferred a possible nonmarine braided fluvial setting, and Ainsworth et al. (2014) also supposed a nonmarine to transitional setting. These strata comprise part of the Bjarni Formation that may be as old as Aptian to early–middle Albian in age (Bujak Davies Group, 1989e; Fenton and Pardon, 2007; Ainsworth et al., 2014).

Deltaic

In the interval from 2618 m to 2424 m is a sandstone succession with interbeds of claystone and limestone. Sandstone units are 3–25 m thick, light grey to white, fine- to coarse-grained, locally shaly, and moderately to poorly sorted. They further contain subangular grains, calcareous cement, feldspar, chert, abundant very coarse-grained sand grains, scattered feldspar pebbles, glauconite at the top of the interval, and rare kaolinite. Thin, less common, grey silty shale interbeds and occasional white and sandy limestones are also present.

These sandstone-dominated strata resemble the underlying interval, but the presence of limestone beds throughout and glauconite near the top of the interval are suggestive of marine deposition. The interpretation of core 1 (2458.0–2452.0 m) by Dafoe and Williams (2020a) is deltaic, possibly river-influenced. Thicker sandstone beds within the overall interval, the heterolithic character, and the lack of fossil detritus is consistent with deltaic deposition throughout the entire interval. There is a lack of plant and coal detritus typical of deltaic settings, but this material is also lacking in the underlying nonmarine strata and could be due to a lack of established vegetation during the early syn-rift phase. The deltaic interpretation of the present study agrees well with the deltaic interpretation of Miller and D'Eon (1987) and the nonmarine-transitional setting of Ainsworth et al. (2014), although the former authors indicated an onset of shallow marine conditions deeper in the well.

This interval caps the top of the Bjarni Formation and the lithostratigraphic boundary is adjusted slightly from that of Moir (1989) to range from 2812–2424 m (Table 32). The top is picked based on the pronounced log change at a decrease in sonic velocity and resistivity, as well as the gamma-ray log. In existing biostratigraphic studies, a major unconformity at about 2424 m is also noted by all previous authors, with some variation likely due to limitations of the cutting samples. Ainsworth et al. (2016) gave an Aptian/(?)early–middle Albian to late Albian age, but near the top of the interval the early Albian or older age of core 1 (Dafoe and Williams, 2020a), would suggest that middle and late Albian strata are not likely present. Furthermore, the Turonian–Coniacian age of Bujak Davies Group (1989e) is also too young and does not agree with the framework outlined by Dafoe, Dickie et al. (in press).

Outer shelf

A thin interval of sandstone and overlying silty shale occurs between the depths of 2424 m to 2397 m. The sandstone resembles the underlying interval and is cream to white, white to light grey and silty, with feldspar, very coarse-grained sand grains, and chert. This interval is, however, unique in its highly glauconitic character. The sandstone is capped by a dark grey, silty shale that includes coarse- to very coarse-grained sand grains, disseminated pyrite, glauconite, siderite, and indeterminate fossil fragments.

Combined with the unconformity described above, the glauconitic nature of the sandstone is suggestive of marine transgression (cf. Amorosi, 2003) with the sand likely sourced and reworked from the Bjarni Formation. The silty shale with fossil fragments is interpreted to reflect outer shelf deposition based on the general lack of disseminated sand grains. Deeper-water, bathyal settings were proposed by Miller and D'Eon and Ainsworth et al. (2014), and are only slightly deeper than the setting indicated herein.

This interval forms the base of the Markland Formation and was found to be Santonian and Maastrichtian by Ainsworth et al. (2014), but Fenton and Pardon (2007) interpreted Coniacian to early

Campanian and late Maastrichtian strata. It is unclear if missing section is indicated by the findings of Bujak Davies Group (1989e) as their Turonian–Coniacian unit covers the very base of this interval, followed by Campanian and Maastrichtian rocks. A condensed section could be present here, but this is not clear from the lithological or log data. The prevalence of glauconite, however, does indicate low sedimentation rates. In summary, a Campanian–Maastrichtian age is likely, but possible Santonian strata may also be present.

Slope

A relatively characterless, homogeneous shale is found between 2397 m and 2289 m. This grey to dark grey, fissile shale contains siderite stringers, rare pyrite, rare limestone stringers, and glauconite at top of the interval.

The lack of fossil detritus, silt, and sand is interpreted to reflect slope-equivalent water depths. A slope setting agrees well with the bathyal settings previously proposed (Miller and D'Eon, 1987; Ainsworth et al., 2014). This homogeneous shale comprises the top of the Markland Formation in the well, which extends from 2424–2289 m according to the present study (Table 32), with the top picked at a major log break in the gamma-ray and resistivity logs. The age of the slope-equivalent interval was found to be Maastrichtian and Selandian by Ainsworth et al. (2014) and similarly Campanian, Maastrichtian and Late Paleocene by Bujak Davies Group (1989e), both suggesting missing Danian section, which could be explained by a condensed section or limited sample intervals through that part of the well. However, Fenton and Pardon (2007) identified a Danian interval. Regardless, Danian and early Selandian uppermost Markland Formation mudstones agree well with the framework proposed by Dafoe, Dickie et al. (in press).

Outer shelf to upper slope

An interval of fossil and silt-bearing shale occurs from 2289 m to 2200 m. The dark grey shale is partly silty, fissile, locally calcareous, and micro-micaceous, with prominent brown siderite, scattered fossil debris (bivalve and indeterminate shell material), and rare pyrite. Silty, dark brown limestone is rare.

Rare silt and fossil material suggests shallowing from the underlying slope interval to near the shelf edge between an outer shelf and upper slope-equivalent setting. This slight shallowing was not noted by Miller and D'Eon (1987) and Ainsworth et al. (2014) as they reported bathyal water depths, but the present interpretation is within range of these previous results.

The base of this interval coincides with the onset of Cartwright Formation. It is further proposed in the present study that the top of this interval coincides with the top of the Cartwright Formation (2289–2200 m), which presents a different interpretation than Moir (1989; Table 32). This revised lithostratigraphic designation agrees well with the lithological change into the overlying interval that is characterized by a return to homogeneous shale, as well as the decrease in the resistivity log into the overlying Kenamu Formation. A deepening at the base of the overlying Kenamu Formation (*see* below) is also in good agreement with the stratal relationships outlined in Dickie et al. (2011) and Dafoe, Dickie et al. (in press). A Middle–Late Paleocene (Selandian–Thanetian) to Ypresian (Early Eocene) age is generally agreed upon for this interval of the well as indicated by several studies (Bujak Davies Group, 1989e; Fenton and Pardon, 2007; Ainsworth et al., 2014).

Slope

Spanning the depths of 2200 m to 2119 m is a grey-brown, fissile, rarely silty shale containing siderite stringers, scattered pyrite, and occasional dark brown limestone stringers.

The general lack of fossils and rare silt suggests a distal marine setting and a return to a slope-equivalent paleoenvironment; although true slope settings developed during the Kenamu Formation

(Dickie et al., 2011), it is unclear if the shelf edge was established at the onset. This setting is equivalent to the bathyal water depths proposed by previous studies (Miller and D'Eon, 1987; Ainsworth et al., 2014). In the present study, this slope interval is placed at the base of the Kenamu Formation, and a Ypresian (Early Eocene) age is well constrained by Bujak Davies Group (1989e), Fenton and Pardon (2007), and Ainsworth et al. (2014).

Outer shelf

Another silty shale with limestone beds persists from 2119 m to 1700 m. The shale to claystone units are grey, silty throughout, calcareous, and rarely sandy, with siltstone stringers, scattered fossil fragments throughout (foraminifera, rare gastropod, and other indeterminate material), siderite, rare limestone, rare pyrite, and rare carbonaceous flakes. Dark brown, argillaceous limestone is slightly silty.

The influx of silt and fossil fragments suggests shallowing to outer shelf conditions. This shallowing was not noted previously, as Miller and D'Eon (1987) and Ainsworth et al. (2014) reported continued bathyal or upper bathyal conditions, respectively. This succession is part of the Kenamu Formation and was found to be Ypresian (Early Eocene) to Lutetian–Bartonian (Middle Eocene) by Ainsworth et al. (2014), which is in good agreement with other biostratigraphic studies (Fig. 19).

Middle shelf

Brown-grey claystone with rare siltstone and limestone occurs between 1700 m and 1400 m. The brown-grey claystone is silty throughout, locally sandy, micro-micaceous, and locally calcareous and includes limestone stringers, scattered fossil fragments (foraminifera, scaphopod, indeterminate shell material, gastropod, and mollusc), rare siderite, rare very coarse-grained sand grains, rare pyrite, and plant remains and chert pebbles at the top of the unit. Brown-grey, sandy, argillaceous siltstone is also locally present.

Overall the interval is sandier upward, with the plant remains near the top of the interval suggesting shallowing, but within a middle shelf setting based on the overall lithology. The diversity of fossil material further supports such a paleoenvironmental interpretation. Sand content within this interval was explained by Miller and D'Eon (1987) as derived from turbidity current deposits, and the outer shelf to bathyal settings of those authors and of Ainsworth et al. (2014) do not agree well with the observations presented above or with the general understanding of the upper part of the Kenamu Formation (Balkwill and McMillan, 1990; Dickie et al., 2011; Dafoe, Dickie et al., in press).

Spanning the top of the Kenamu Formation and into the lowermost Mokami Formation, this interval contains the prominent log change typical for the top Kenamu Formation (increase in the gamma-ray and decrease in sonic velocity and resistivity logs; Fig. 18). Accordingly, the Kenamu Formation is defined herein from 2200 m to 1480 m (Table 32). It is unclear why significant marine flooding at the Kenamu to Mokami formation boundary that is typically seen in Labrador Shelf wells (Dickie et al., 2011; Dafoe, Dickie et al., in press) is not observed in North Bjarni F-06, but deepening is seen within the overlying interval of the Mokami Formation (*see* below).

Outer shelf

In the interval from 1400 m to 1250 m is a succession of grey-brown, soft, silty throughout, calcareous throughout, micro-micaceous claystone that further contains rare siderite, rare limestone stringers, rare fossil fragments (indeterminate shell material and rare crinoid), and rare siltstone stringers.

The fine-grained nature, incorporation of silt, and limited fossil suite suggests deepening back to outer shelf conditions. This interpretation is similar to that of Ainsworth et al. (2014), and Miller and D'Eon (1987) whom reported outer shelf conditions for part of the interval, but shallowing to inner–middle or outer shelf. Forming part of the Mokami Formation in North Bjarni F-06, this interval is

Bartonian–Priabonian (Middle–Late Eocene) to Rupelian (Early Oligocene) according to Ainsworth et al. (2014), and similar ages were interpreted by Bujak Davies Group (1989e), with Fenton and Pardon (2007) finding only Upper Eocene strata.

Inner shelf to prodelta

Silty and sandy claystone dominates the well from 1250 m to 852 m. This silty and sandy brown claystone is micro-micaceous and calcareous, with common fossil fragments (indeterminate shell material), scattered small pebbles, scattered chert pebbles, locally common lignite, rare pyritic fossils, rare carbonaceous material, and wood fragments near the top of the interval. Thin, fine- to medium-grained, argillaceous brown sandstone beds near top of interval contain pebbles, chert, pyrite, and siderite.

The abundance of fossil material and presence of wood, lignite, and sand indicates shallowing to inner shelf conditions relative to the underlying interval. The low diversity of fossil material could indicate some prodeltaic influence. Similar inner to middle shelf and inner to outer neritic settings were suggested by previous workers, including possible prodeltaic conditions (Miller and D'Eon, 1987; Ainsworth et al., 2014). The top of the Mokami Formation is defined in the present study to correspond to the top of the interval at 852 m, slightly higher than that of Moir (1989) and where it better aligns with the lithological change and decrease in gamma-ray log signature (Fig. 19; Table 32). Ainsworth et al. (2014) gave a Rupelian to Chattian (Early–Late Oligocene) age for these strata.

Shoreface

The uppermost interval in North Bjarni F-06 from 852 m to 425 m is sandstone-dominated. The sandstone is light brown to grey, moderately and lesser poorly sorted, medium- to primarily coarse-grained, with subrounded grains and very coarse-grained sand grains and pebbles throughout (chert and quartz) that increasing in abundance upward, in addition to rare plant remains, rare siderite, rare hornblende, rare feldspar, rare wood, rare glauconite, rare pyrite, and feldspar is more common at the top of the interval. Some conglomeratic intervals are present, as well as rare claystone and limestone beds at the base of the interval. A clear, coarsening-upward profile is shown in the gamma-ray log, with a generally sustained blocky log character for much of the interval (Fig. 19).

The blocky gamma-ray signature, coarsening-upward nature, and grain size are consistent with a shoreface succession. The sharp base and mature nature of the sandstone (subrounded grains and less feldspar) further support a shoreface settings deposited under high-energy conditions with ample wave reworking. Previous studies found similar inner shelf settings including deltaic conditions (Miller and D'Eon, 1987; Ainsworth et al., 2014), but the log character appears to support a shoreface paleoenvironment where fines remain in suspension due to wave reworking. Here, this interval is equated with the Saglek Formation, which continues upward in the well to the top of the electric logs at 407 m (Table 32). Bujak Davies Group (1989e) placed this interval in the Early Oligocene, Early–Middle Miocene and Late Miocene, in reasonable agreement with the lithostratigraphic framework proposed by Dafoe, Dickie et al. (in press).

Lithostratigraphy

Based on the discussion around lithostratigraphic refinements to the framework of Moir (1989) in North Bjarni F-06, the lithostratigraphic picks from the present study are summarized in Table 32. There are no type or reference sections in this well.

Lithostratigraphic unit	Moir (1989)		The present study		Type or reference section
	Base (m)	Top (m)	Base (m)	Top (m)	
Saglek Fm	857	262	852	407	None
Mokami Fm	1480	857	1480	852	None
Kenamu Fm	2059	1480	2200	1480	None
Cartwright Fm	2289	2059	2289	2200	None
Markland Fm	2423	2289	2424	2289	None
Bjarni Fm	2812	2423	2812	2424	None

Table 32: Lithostratigraphic assignment for North Bjarni F-06 from the present study and compared to that of Moir (1989). Fm=Formation; Mb=Member.

NORTH LEIF I-05

Near the Leif wells in Hopedale Basin is the North Leif I-05 well (Fig. 1). The well history report for North Leif I-05 (Duff, 1981b) includes conventional core, cuttings, and sidewall core descriptions that were used in the present study. In addition to this, the PetroCan North Leif I-05 log (log EC-159) from Canadian Stratigraphic Service Ltd. includes detailed information regarding the lithology, grain size, grain rounding, and sample descriptions. Core study by Dafoe and Williams (2020a) presented new age and paleoenvironmental interpretations for cores 1 and 2 of the Bjarni Formation. The well plot in Figure 20 includes key well logs, lithology, grain size, rock colour, ages, and paleoenvironmental and lithostratigraphic information. The age constraints from Dafoe and Williams (2020b) are used in the present study, and paleoenvironmental interpretations determined herein are summarized in Table 33 below. Miller and D'Eon (1987) and Dafoe and Williams (2020b) provide paleoenvironments of deposition that are compared in the discussions below, with those of the latter study based on palynomorphs. The lithostratigraphic assignments of Moir (1989), Dafoe and Williams (2020b), and from the present study are shown in Figure 20 and in Table 34.

The basalts at the very base of North Leif I-05 are not described in the present study, but these form part of the Alexis Formation. Lying above the basalts of the Alexis Formation as shown in Figure 20, the interval from 3469 m to 3444 m appears to be volcanic rock to weathered volcanic rock based on cuttings and sidewall core, rather than sedimentary as indicated. The gamma-ray log shows continued low API values for this part of the section that are in the same range of values as the underlying basalt, in addition to the continued green rock colour. Accordingly, these rocks are considered to be basaltic and also part of the Alexis Formation.

Base (m)	Top (m)	Paleoenvironment
3444	3432	TUFFACEOUS VOLCANIC ROCKS
3432	3394	SUBAERIAL VOLCANICLASTIC ROCKS
3394	3354	NONMARINE FLUVIAL
3354	2820	MARINE EMBAYMENT WITH DELTAIC PULSES
2820	2776	MIDDLE SHELF
2776	2724	OUTER SHELF
2724	2610	OUTER SHELF
2610	2400	UPPER SLOPE
2400	2350	OUTER SHELF
2350	2220	MIDDLE SHELF
2220	2141	SHOREFACE OR DELTA FRONT
2141	2080	OUTER SHELF TO SLOPE
2080	1698	OUTER SHELF
1698	1588	MIDDLE TO INNER SHELF
1588	1476	LOWER SHOREFACE
1476	1330	OUTER SHELF
1330	1230	MIDDLE SHELF
1230	547	INNER SHELF
547	425	DELTA FRONT

Table 33: Paleoenvironmental determinations for North Leif I-05 from the present study.

Tuffaceous volcanic rocks

From 3444 m to 3432 m is an interval of light green to white, feldspathic, and kaolinitic volcanic rocks (as noted from sidewall core) and in contrast to what is shown in the Canstrat lithology data in Figure 20. The gamma-ray log shows an increase in API values relative to the underlying basalts (Fig. 20).

The coloration and weathered nature of this interval (with feldspar weathering to kaolinite) is suggestive of subaerial tuffaceous accumulations. Miller and D'Eon (1987) proposed tuff and (?)welded tuff between 3444 m to 3394 m, and a nonmarine setting in good agreement with the present study. Nonmarine to marginal marine conditions were suggested for this interval by Dafoe and Williams (2020b) as part of a thick Lower Cretaceous succession at the base of North Leif I-05, but also in good agreement with the present findings. This tuffaceous interval forms part of the Alexis Formation, albeit with an atypical lithology. Dafoe and Williams (2020b) gave an Aptian age for this part of the well, but considering the lithology this age could also be derived from sedimentary cavings from the overlying Bjarni Formation.

Subaerial volcaniclastic rocks

Spanning the depths from 3432 m to 3394 m is a succession that appears to be clastic on the Canstrat lithology log (Fig. 20), but other evidence suggests volcaniclastic accumulation. The shales are dark grey, fissile, and silty, with carbonaceous plant fragments, coal fragments, and pyrite. Cherts are described as white to light green, very calcareous, argillaceous, pelitic, and grading to limestone, with trace glauconite. Sidewall core indicate light green to white, very fine-grained to granular, poorly sorted, very soft, very kaolinitic becomingly shaly sandstone with green clasts and subangular grains (3425 m, 3415 m, 3400 m; Duff, 1981b).

The sidewall core descriptions imply subaerial, weathered volcanic rocks mixed with clastic sediments, as do the detailed cuttings descriptions, which is consistent with the texture and colouration of the rock. This lithology is also atypical for the Alexis Formation, but perhaps reflects some interbedding and a transition between the Alexis and Bjarni formations. Like that of the underlying interval, Miller and D'Eon (1987) proposed tuff and (?)welded tuff and a nonmarine setting, in reasonable agreement with the present results. Dafoe and Williams (2020b) included this interval in their nonmarine to marginal marine succession, also in reasonable agreement with the present study. This interval marks the top of the Alexis Formation (Table 34), well defined by a striking lithological and log change at 3394 m, as was recognized by Moir (1989) and Dafoe and Williams (2020b). The latter authors found the volcaniclastic rocks to be Aptian in age.

Nonmarine fluvial

The strata from 3394 m to 3354 m incorporate a somewhat fining-upward unit of sandstone and thin shales. Light grey, green to white and brown, silty, siliceous and calcareous sandstones contain green chert, shale stringers, feldspar, and glauconite. Dark grey shales with coal seams, and rare grey argillaceous siltstones are also present. Duff (1981b) further reported conglomerate with weathered porphyritic and amygdaloidal fragments, as well as chert (agate), and feldspars weathered to kaolinite. The gamma-ray log confirms a subtle, fining-upward trend (Fig. 20).

The fining-upward profile with the presence of coal is suggestive of a fluvial channel setting. The weathered nature of clasts also indicates nonmarine conditions. However, glauconite would imply a marine setting, but green-coloured clasts could be misinterpreted as glauconite and rather sourced from nearby exposed volcaniclastic and or basalt intervals, as was noted by Duff (1981b). Miller and D’Eon (1987) indicated similar nonmarine, possible fluvial settings. The setting postulated in the present study also fits with the generalized interpretation of Dafoe and Williams (2020b): nonmarine to marginal marine. This interval comprises the base of the Bjarni Formation and is Aptian to early Albian according to Dafoe and Williams (2020b).

Marine embayment with deltaic pulses

A thick succession of primarily dark grey shales with occasional siltstone and sandstone beds is found from 3354 m and 2820 m. Dark grey (rarely green), fissile, silty shale is characterized by common carbonaceous plant remains throughout, common fossil fragments throughout (bivalve, *Inoceramus*, gastropod, agglutinated foraminifera, indeterminate shell material, and possible scaphopod), occasional sandstone stringers, scattered coal flakes, rare pyrite, rare mica, rare quartz sand grains or pebbles, and rare glauconite pellets. Brown-grey sandstone is very fine- to fine-grained, silty, argillaceous, and well sorted, with kaolinite, siderite, subangular grains, carbonaceous flakes, glauconite, rare feldspar, and rare chert. Brown, argillaceous, shaly siltstone is also sandy, with pyrite. Glauconite is also present at the top of the unit within sandstones there. Sandstone intervals show clear low API spikes in the gamma-ray log, within thin, coarsening-upward units (Fig. 20).

The overall lithology, diversity and abundance of marine fossils, and abundance of carbonaceous plant remains suggests shallow-marine conditions. Cores 1 and 2 (3117.1–3110 m) were interpreted as river-dominated distal delta front and prodelta deposits with a highly brackish signature (Dafoe and Williams, 2020a). Here, the fossil content from cuttings contrasts with the interpretation from the cores, suggesting that salinity fluctuations may have taken place within a marine embayment. Thin sandstones would thus appear to reflect occasional deltaic influxes (bayhead delta) into a restricted marine bay setting, representing periods during which riverine influx may have temporarily reduced salinity. Dafoe and Williams (2020b) found a similar nonmarine to marginal marine setting, but indicated neritic deposition near the top of the interval. Miller and D'Eon (1987) generally interpreted marginal marine deposition including brackish conditions, embayment or lagoon and possible deltaic or tidal settings, in reasonable agreement with the present study.

These strata form the Snorri Member of the Bjarni Formation, a more shale-dominated succession compared to the typical Bjarni Formation sandstones. The lithostratigraphic boundaries remain the same as those proposed by Moir (1989) and Dafoe and Williams (2020b; Table 34). The top of the Bjarni Formation (and Snorri Member) is based on the increase in gamma-ray and decrease in sonic velocity and resistivity logs at 2820 m. The Bjarni Formation lithostratigraphic assignment is also unchanged from the original work of Moir (1989; Table 34). An early Albian to Albian age was proposed by Dafoe and Williams (2020b) for this embayment interval in the well.

Middle shelf

A thin interval of fossiliferous claystone persists from 2820 m to 2776 m. The grey to brown claystone is soft and micaceous, with interbedded marlstone and limestone, common fossil fragments (abundant indeterminate shell material, bivalve, and gastropod) and rare glauconite pellets. Grey-brown marlstone, and white limestone, with a rhythmic, argillaceous and fossiliferous (bivalve and gastropod) character are also present.

The fine-grained lithology and carbonate content, together with the fossil suite implies a middle shelf setting. It is unclear why the sand content is so limited, but the interval contrasts with the overlying strata that are more limited in their fossil content (*see* below). Miller and D'Eon (1987) proposed a similar possible inner shelf setting, and Dafoe and Williams (2020b) found neritic deposition within this interval, both in good agreement with the present study. Marking the base of the Markland Formation, this claystone is Cenomanian–Turonian based on the findings of Dafoe and Williams (2020b).

Outer shelf

In the interval spanning 2776 m to 2724 m is a succession of silty and locally sandy claystone and shale. Brown, silty, micaceous, and slightly calcareous claystone dominates. Brown-grey, silty, soft shale, with thin brown sandstone interbeds is also present. Benthonic foraminifera and very small pyritized bivalves are found in this interval, as well as pyrite, rare glauconite, and possible localized reduction zones.

The overall lack of fossil material, with silt and minimal sand content suggests a likely distal marine settings. This, combined with glauconite and pyritized fossils suggests low sedimentation rates and possible reducing conditions consistent with the outer shelf (Amorosi, 2003; Wilkin, 2003). While Miller and D'Eon (1987) proposed possible inner shelf conditions, Dafoe and Williams (2020b) indicated an outer neritic to open ocean setting, which is in general agreement with the interpretation here. This interval forms part of the Markland Formation, and the age was given as Cenomanian–Turonian by Dafoe and Williams (2020b).

Outer shelf

Another interval of partly silty and partly sandy claystone dominates the well from 2724 m to 2610 m. The dark grey shale to claystone (some green in colour) is silty, with carbonaceous plant remains throughout, sandy stringers, common fossil fragments (foraminifera (agglutinated, benthonic, large globular, and siliceous forms), ostracod, and spicules), scattered pyrite, and rare mica. Rare, brown, silty, glauconitic, argillaceous, sideritized sandstone is also present, especially at the base of the overall interval.

The abundance of benthonic foraminifera and lack of shelly fossil material suggests a more distal marine setting. This, and the influx of both silt, and to a lesser degree, sand suggests outer shelf conditions. This is slightly shallower than the open ocean and bathyal settings of previous studies (Miller and D'Eon, 1987; Dafoe and Williams, 2020b).

Comprising part of the Markland Formation, this claystone interval corresponds to the age determinations of Cenomanian–Turonian, Campanian and early Maastrichtian of Dafoe and Williams (2020b). However, it is suggested in the present study that the break between the Cenomanian–Turonian and Campanian from Dafoe and Williams (2020b) is likely at 2724 m where there is a clear lithological change and prominent log break (decrease in gamma-ray, sonic velocity and resistivity logs). In Dafoe and Williams' (2020b) study, the palynological samples were restricted to 10 m regular intervals, but here the boundary can be slightly refined to better fit the unconformity picked from the log data. Accordingly, there is a major unconformity in the Markland Formation with much of the Upper Cretaceous missing, a break in section variously noted by other biostratigraphic studies of the well (Fig. 20).

Upper slope

In North Leif I-05 from 2610 m to 2400 m is an interval of relatively homogeneous shale. The dark grey to grey fissile, micaceous shale contains calcareous stringers, pyrite, siderite, scattered carbonaceous plant remains throughout, scattered fossil fragments (foraminifera, rare indeterminate shell material, benthonic foraminifera, and pyritized globular calcareous foraminifera), rare siltstone beds, and very rare very fine-grained sandstone beds with glauconite.

This characteristically shale-dominated interval has a general lack of fossil diversity and is dominated by foraminifera. The fine-grained lithology and limited silt and sand content suggests a distal marine setting. In contrast to under- and overlying intervals, this interval is interpreted to reflect upper slope-equivalent water depths. The glauconitic sandstone beds are likely from turbidity flows with glauconite formation indicating low sedimentation rates following emplacement (Amorosi, 2003). Similar paleoenvironments were interpreted by Miller and D'Eon (1987) and Dafoe and Williams (2020b) as bathyal and outer neritic to open ocean, respectively. This part of the Markland Formation is early late Maastrichtian to late Danian (Early Paleocene) in age according to Dafoe and Williams (2020b).

Outer shelf

A thin interval of slightly sandy and silty shale occurs between the depths of 2400 m and 2350 m. Grey shale is fissile, micaceous, and slightly silty, with carbonaceous plant remains throughout, fossil fragments throughout (bivalve and foraminifera), pyrite, glauconite pellets, scattered sandstone beds, and rare floating quartz grains.

This shale interval reflects a slight shallowing relative to the underlying interval to outer shelf conditions. This interpretation is based on the increase in silt and sand and the presence of non-foraminiferal fossil fragments indicating a slight increase in proximity to the shoreline. This setting agrees relatively well with the outer neritic to open ocean interpretation of Dafoe and Williams (2020b), but is slightly shallower than the bathyal interpretation of Miller and D'Eon (1987). Capping the top of the Markland Formation, this interval is Selandian (Middle Paleocene) in age according to Dafoe and Williams (2020b). Moir (1989) brought the Markland Formation up to 2340 m, but it was restricted by Dafoe and Williams (2020b) to 2348 m based on the prominent log break in the gamma-ray log at that depth. Based on the intervals described here, a further adjustment to the top of the Markland Formation is proposed at 2350 m, which matches better with the breaks in the sonic velocity and resistivity logs, as well as the paleoenvironmental changes proposed herein (Table 34).

Middle shelf

From 2350 m to 2220 m is a shale succession with some thin sandstone intervals. The grey, fissile, and silty shale includes, sandstone stringers, common fossil fragments throughout (foraminifera, siliceous agglutinated foraminifera, pyritized fossil material, benthonic foraminifera, calcareous foraminifera, bivalve, and gastropod), rare pyrite at the base of the interval, and rare coal near the top of the interval. Brown sandstone is very fine- to fine-grained, calcareous or dolomitic, silty, and moderately to well sorted, with glauconite, feldspar, chert, and subangular grains.

The silt and sand content in this interval, combined with the high-diversity of fossil forms, but dominance of foraminifera, is representative of middle shelf deposition. The neritic interpretation of Dafoe and Williams (2020b) is in close agreement, but the bathyal setting of Miller and D'Eon (1987) is significantly deeper than expected based on the evidence listed above. This interval is correlated with the Cartwright Formation, which is slightly modified from Dafoe and Williams (2020b) to 2350–2220 m and below the prominent sandstones of the Gudrid Formation (*see* below; Table 34). As discussed by these authors, the lower Gudrid Formation of Moir (1989) does not appear to be present (Fig. 20).

Shoreface or delta front

An overall heterolithic sandstone succession with shale interbeds, but coarsening-upward character extends from 2220 m to 2141 m. Brown to grey, and white sandstone is very fine- to fine-grained, but mostly medium- and coarse-grained at the top of the interval. The sandstone grains are subangular to subrounded, becoming rounded near the top of the interval. Furthermore, the sandstone is well or poorly sorted, calcareous, and slightly dolomitic, with glauconite throughout, chert throughout, feldspar throughout, shaly beds throughout, fossil fragments throughout (foraminifera and bivalve), pyrite common near the top of the interval, and very coarse-grained sand grains present near the top of the interval. Shales are dark grey, sandy, and silty, with carbonaceous plant remains and fossil fragments (foraminifera, benthonic foraminifera, calcareous benthonic foraminifera, and indeterminate shell material). The gamma-ray log shows a generally coarsening-upward profile (Fig. 20).

The coarse-grained nature of the sandstone, rounded grains, coarsening-upward profile, and fossil content are interpreted to represent a shoreface setting. However, the slightly heterolithic character could indicate a possible delta front setting (perhaps more wave-dominated). It is unclear why there is an abundance of foraminifera, however, cavings from overlying deep-water strata could account for this discrepancy. Dafoe and Williams (2020b) found a similar inner neritic setting, but the bathyal water depths proposed by Miller and D'Eon (1987), with turbidites explaining the presence of sand, is inconsistent with the evidence above and may be related to the presence of possible caved foraminifera. Similar cavings of overlying deep-marine shales into the samples representing the Gudrid Formation have been suggested for other wells (Dafoe and Williams, 2020a). This sandstone succession corresponds to the early Ypresian (Early Eocene) upper Gudrid Formation of Dafoe and Williams (2020b). It is unclear why Moir (1989) extended the Gudrid Formation from 2228–2124 m as this places the formation boundaries beyond the prominent well log breaks and definitive sandstone interval (Fig. 20).

Outer shelf to slope

At a depth of 2141 m to 2080 m is a dark grey, fissile, hard, silty shale that further includes limestone stringers, rare siltstone beds, rare pyrite, and rare fossil debris.

The fine-grained lithology and lack of sand and fossil content suggests a more distal marine setting, perhaps near the shelf edge between outer shelf and slope-equivalent water depths. The interpretation here is similar to the bathyal and outer neritic settings of previous studies (Miller and D'Eon, 1987; Dafoe and Williams, 2020b). This shale interval characterizes the base of the Kenamu Formation and was found to be early Ypresian to Ypresian (Early Eocene) by Dafoe and Williams (2020b).

Outer shelf

A thick interval of shale with occasional marlstone and limestone beds near the base and siltstone and sandstone beds near the top is present from 2080 m to 1698 m. Dark grey to brown shale and claystone is fissile, micaceous, silty, and slightly calcareous, with siltstone stringers, scattered fossil fragments (foraminifera, locally abundant indeterminate fossil debris, indeterminate shell material, and benthonic foraminifera), pyrite, rare marlstone, and rare siderite nodules. Limestone and marlstone units are dark brown, argillaceous, and shaly, and include rare pellets and rare fossil fragments that become more abundant near top of unit (foraminifera). Siltstone is brown, argillaceous, and slightly calcareous, and rare calcareous, glauconitic, silty sandstone includes feldspar grains.

The slight increase in fossil fragments and silt and sand content upward in the interval indicates shallowing, but the overall grain size and dominance of foraminifera implies outer shelf conditions. This is similar to the outer neritic to inner neritic settings of Dafoe and Williams (2020b), but is slightly shallower than the bathyal setting reported by Miller and D'Eon (1987). This thick interval makes up much of the Kenamu Formation, and, according to Dafoe and Williams (2020b), is Ypresian (Early Eocene) to Bartonian (Middle Eocene) in age.

Middle to inner shelf

An interval composed of sandy siltstone, shale, and silty sandstone is present from 1698 m to 1588 m. Brown, argillaceous, sandy (very fine-grained), micaceous siltstone dominates the interval. Brown sandstone is very fine-grained, well sorted, dolomitic, silty, argillaceous, locally unconsolidated, and friable, with subangular grains, rare feldspar, and rare glauconite. Dark grey to brown, soft, sandy, micaceous, locally calcareous shale and claystone includes fossil fragments (foraminifera) and rare pyrite. The gamma-ray log shows some ragged character, but thin, coarsening-upward units are present (Fig. 20).

The heterolithic nature of the interval with dominance of silt and sand suggests a shallow shelf setting likely middle to inner shelf. The lack of fossil content is atypical and could indicate some brackish or prodeltaic influence. This setting matches well with the inner neritic of Dafoe and Williams (2020b), but is in contrast to the bathyal depths proposed by Miller and D'Eon (1987), where they explain the sand content as related to turbidite fan accumulations. Fining-upward turbidity current deposits are not noted in the present study. This heterolithic interval is part of the Kenamu Formation and is Bartonian (Middle Eocene) in age based on the findings of Dafoe and Williams (2020b).

Lower shoreface

Spanning the depths of 1588 m to 1476 m is a series of three coarsening-upward, stacked units of sandstone separated by shalier intervals. The sandstone is brown to white-grey (salt and pepper), very fine-grained, silty, well sorted, and locally dolomitic, with subangular grains, fossil fragments throughout (foraminifera, spicules, and bivalve), occasional feldspar, rare glauconite, and rare chert. Shales and claystones are brown to grey, soft, silty, slightly calcareous, and locally sandy, with rare foraminiferal fossil fragments and rare pyrite. The gamma-ray log confirms the coarsening-upward nature of the three units (Fig. 20).

The sandy nature of the strata, coarsening-upward character, and relatively diverse fossil assemblage suggests shallow, normal marine conditions. However, the finer-grained nature of the sandstone and interbedding with shales indicates a lower shoreface paleoenvironment is most likely. It is unclear why foraminifera are relatively prevalent, but the genera are not described in the original well reports and logs, and there could also be cavings from the overlying, deeper-water interval (*see* below). The interpretation from the present study agrees well with the setting proposed by Dafoe and Williams (2020b) as inner neritic, but is again much shallower than Miller and D'Eon's (1987) bathyal setting with turbidite fan accumulations. The evidence, particularly the coarsening-upward sandstone units, does not agree with such a distal marine setting.

These strata comprise the Leif Member of the Kenamu Formation, as described by Dafoe and Williams (2020b), where they extended the Leif Member up section in the well to include the entire sandstone-dominated succession (Fig. 20; Table 34). These authors further gave a Bartonian (Middle Eocene) age for the Leif Member, with its top ending in the later part of the Bartonian, in good agreement with the lithostratigraphic framework of Dickie et al. (2011) and Dafoe, Dickie et al. (in press) for the Kenamu Formation. The Kenamu Formation also follows that of Dafoe and Williams (2020b) and extends from 2141–1476 m (Table 34).

Outer shelf

A claystone interval characterizes North Leif I-05 from 1476 m to 1330 m. This brown to dark grey claystone is silty, micaceous, and slightly calcareous, with rare fossil fragments (foraminifera), rare marlstone beds and limestone beds, rare pyrite, and a blocky gamma-ray log character (Fig. 20). Brown limestone is both sandy and argillaceous.

The silty and calcareous nature of the claystone, with only foraminifera present suggests an outer shelf paleoenvironment. Dafoe and Williams (2020b) interpreted a shallower, inner shelf setting, but Miller and D'Eon (1987) found similar outer shelf to bathyal conditions; accordingly, the interpretation from the present study falls within range of previous work. Located at the base of the Mokami Formation, this claystone interval is latest Bartonian (Middle Eocene) to Priabonian (Late Eocene) according to Dafoe and Williams (2020b).

Middle Shelf

An interval of sandy and calcareous claystone persists from 1330 m to 1230 m. This brown to dark grey claystone is silty, micaceous, soft, and notably sandy (very fine-grained), and further contains fossil fragments throughout (bivalve, gastropod, indeterminate debris, and echinoid spicules), scattered marlstone beds and limestone beds that increase in abundance upward, rare pyrite, and rare carbonaceous flakes. Brown limestone and marlstones are sandy, argillaceous, and locally dolomitic, with rare pyrite.

There is evident shallowing relative to the underlying claystone as seen with the addition of sand, increase in calcareous content, and significant fossil abundance and diversity. The interpretation here is of a middle shelf succession, which lies between the outer shelf to bathyal settings proposed by Miller and D'Eon (1987) and inner shelf setting of Dafoe and Williams (2020b). These strata are from within the Mokami Formation and are Priabonian (Late Eocene) according to Dafoe and Williams (2020b).

Inner shelf

A substantial succession of silty and sandy to very sandy claystone with occasional sandstone and limestone beds spans the depths of 1230 m to 547 m. Claystone is brown to grey, sandy (very fine-grained), silty, micaceous, and slightly calcareous, with common fossil fragments throughout (bivalve are most common, ostracod, gastropod, foraminifera, echinoid spicules, and indeterminate shell debris), rare chert grains, rare very coarse-grained sand grains, rare carbonaceous or lignite flakes, and rare glauconite near the top of the interval. Sandstone beds are brown to white, very fine- to fine-grained, calcareous, moderately to well sorted, glauconitic, and shaly, with subangular to subrounded grains, occasional chert, rare feldspar, rare carbonaceous flakes, rare pyrite, rare very coarse-grained sand grains, and rare fossil fragments (bivalve). Brown limestone to marlstone is sandy, hard, and argillaceous, with rare indeterminate fossil fragments.

The sandy nature of the claystone and presence of lignite and diverse fossil suite, with an upward increase in these elements indicates shallowing in an inner shelf setting. This agrees well with the inner to middle shelf interpretations of both Miller and D'Eon (1987) and Dafoe and Williams (2020b). This interval forms the top of the Mokami Formation, which is retained here as originally defined by Moir (1989) from 1476–547 m (Table 34). A Priabonian (Late Eocene) to Rupelian (Early Oligocene) age was postulated by Dafoe and Williams (2020b).

Delta front

The uppermost interval in North Leif I-05 comprises a sandstone-dominated succession from 547 m to 425 m, with some claystone intervals. White sandstone is very fine- to coarse-grained, moderately to poorly sorted, friable, argillaceous, and unconsolidated, and also contains subrounded to rounded grains, very coarse-grained sand grains throughout, pebbly horizons (quartz), scattered fossil fragments (indeterminate shell material, bivalve), shale/limestone fragments, rare glauconite, rare pyrite, and rare siderite. Claystone units are brown-grey, soft, very sandy, and silty, with bivalve fragments, rare carbonaceous flakes, and rare very coarse-grained sand grains. The log character confirms a ragged, slightly heterolithic character to the interval (Fig. 20).

Overall there is a coarse-grained, but heterolithic character to the interval. This, combined with the limited fossil content and rounding of grains suggest a nearshore, high-energy, delta front setting. This sandstone-dominated succession defines the Saglek Formation in the well, and a Rupelian (Early Oligocene) and Early Miocene age were reported by Dafoe and Williams (2020b). The top of the Saglek Formation was refined by Dafoe and Williams (2020b) to be in accord with the top of the electric log recordings at 396 m (Table 34).

Lithostratigraphy

Based on the discussion around lithostratigraphic refinements to the framework of Moir (1989) and Dafoe and Williams (2020b) in North Leif I-05, the lithostratigraphic picks from the present study are summarized in Table 34. There are no type or reference sections in this well.

Lithostratigraphic unit	Moir (1989)		Dafoe and Williams (2020b)		The present study		Type or reference section
	Base (m)	Top (m)	Base (m)	Top (m)	Base (m)	Top (m)	
Saglek Fm	547	319	547	396	547	396	None
Mokami Fm	1476	547	1476	547	1476	547	None
Kenamu Fm (Leif Mb)	1586	1524	1588	1476	1588	1476	None
Kenamu Fm	2124	1476	2141	1476	2141	1476	None
Gudrid Fm (upper)	2228	2124	2220	2141	2220	2141	None
Cartwright Fm	2326	2228	2348	2220	2350	2220	None
Gudrid Fm (lower)	2340	2326	--	--	--	--	None
Markland Fm	2820	2340	2820	2348	2820	2350	None
Bjarni Fm (Snorri Mb)	3354	2820	3354	2820	3354	2820	None
Bjarni Fm	3394	2820	3394	2820	3394	2820	None
Alexis Fm	3513	3394	3513	3394	3513	3394	None

Table 34: Lithostratigraphic assignment for North Leif I-05 from the present study and compared to that of Moir (1989) and Dafoe and Williams (2020b). Fm=Formation; Mb=Member.

OGMUND E-72

At the northernmost end of the Hopedale Basin is the Ogmund E-72 well (Fig. 1). In this well, the cuttings, conventional core, and sidewall cores are described in Dungan (1980b) in the well history report, which was used to build the interval descriptions in the present study. Furthermore, the detailed information from Canadian Stratigraphic Service Ltd. Petro-Canada Ogmund E-72 log (log EC-149) includes further descriptions of the lithology, grain size, grain rounding, and sample descriptions that were utilized in the present study. Three conventional core intervals were also studied by Dafoe and Williams (2020a), two from the Bjarni Formation, and one from the Gudrid Formation, with new age constraints and paleoenvironmental interpretations. The well is presented in Figure 21 and includes key well logs, lithology, grain size, rock colour, ages, and paleoenvironmental and lithostratigraphic information. Biostratigraphic results from Ainsworth et al. (2014) best fit the lithostratigraphic model for the Cretaceous and early Cenozoic in Dafoe, Dickie et al. (in press) and are generally used here, with some insights from other studies. The paleoenvironmental interpretations of the present study are summarized in Table 35 and are compared in the descriptions below with those of Miller and D'Eon (1987) and Ainsworth et al. (2014), the latter of which is presumably based on both the micropaleontology and palynology conducted in their study. The lithostratigraphic assignments of Moir (1989) and from the present study are summarizes in Table 36 and in Figure 21.

Base (m)	Top (m)	Paleoenvironment
3094	3039	NONMARINE ALLUVIAL FAN
3039	2947	NONMARINE FLUVIAL
2947	2836	NONMARINE LACUSTRINE
2836	2592	DELTA PLAIN
2592	2200	DELTA FRONT
2200	1846	PRODELTA
1846	1787	DELTA FRONT
1787	1712	PRODELTA
1712	1608	DELTA FRONT
1608	1587	INNER SHELF
1587	1458	SHOREFACE
1458	1356	MIDDLE SHELF
1356	1240	MIDDLE TO OUTER SHELF
1240	892	MIDDLE SHELF
892	608	INNER SHELF
608	430	DELTA FRONT

Table 35: Paleoenvironmental determinations for Ogmund E-72 from the present study.

Nonmarine alluvial fan

Despite the Canstrat lithology log that shows a prominent igneous rock succession (Fig. 21), the interval from 3094 m to 3039 m is described as a pebble conglomerate in the well history report (Dungan, 1980b), and this agrees with sidewall core descriptions at three different depths and with core 3 from 3094.05–3093 m (Dafoe and Williams, 2020a). Based on these samples, the sandstone matrix is white to light grey, fine- to very coarse-grained, very poorly sorted, and kaolinitic, with angular to subrounded grains, some mica, and rock fragments. Dafoe and Williams (2020a) described core 3 as a matrix-supported conglomerate with a fine- to coarse-grained sandstone matrix and subangular to rounded pebbles comprising feldspar, granite, quartzite, volcanic rock, and sandstone. Accordingly, the gamma-ray log shows relatively consistent low API values suggestive of coarse-grained, clastic rock (Fig. 21).

The gamma-ray log values for this part of the well are in line with the overlying sandstones and the nature of core 3 confirms a sedimentary origin. Dafoe and Williams (2020a) interpreted core 3 to reflect a high-energy shoreface or delta front setting based on the presence of dinoflagellates that indicated a marginal marine setting. From the sedimentology, however, an alluvial setting was found to be most likely. Given the nonmarine settings interpreted for the overlying intervals (*see* below), a marine setting at the base of the syn-rift succession is unlikely. Perhaps there was contamination in the core samples from Dafoe and Williams (2020a). Based on the coarse-grained nature, poor sorting and kaolinitic character, an alluvial fan setting is suggested for this interval.

This interval is found at the base of the Bjarni Formation, and this part of Ogmund E-72 is either Barremian–early Aptian (Ainsworth et al., 2014) or late Aptian–(?)early Albian (Nøhr-Hansen et al., 2016). However, Nøhr-Hansen et al. (2016) did not find any Barremian rocks in their study of wells along the Labrador margin, with Aptian as the oldest strata they identified based on a revised palynomorph events chart. Fenton and Pardon (2007) gave a similar Aptian–Albian age, and core 3, found at the base of the interval, was reported to be Aptian (Dafoe and Williams, 2020a), so a Barremian age is unlikely.

Nonmarine fluvial

A sandstone-dominated, but heterolithic interval with interbedded shale and siltstone prevails between the depths of 3039 m and 2947 m. Sandstones are grey to white, fine- to medium-grained, moderately sorted, siliceous, argillaceous, and slightly calcareous, and contain subangular grains, chert grains, very coarse-grained sand grains in the lower half of the interval, silt in the upper half of the interval, rare mica, rare glauconite, rare chlorite, and rare thin coal stringers. Shales are dark grey to grey, slightly silty, with thin siltstone stringers, and rare coal stringers at the base of the interval. Grey siltstone also contains shale stringers. The ragged gamma-ray log does not clearly define coarsening- or fining-upward trends; however, in the grain size log, there is a general fining-upward character from more medium-grained (with very coarse-grains) to lower medium-grained above (Fig. 21).

The presence of chlorite grains in the sandstone calls into question if this mineral could be glauconite (and thus indicating a marine setting) as chlorite is micaceous and could be difficult to identify in sandstone cuttings. The presence of coaly intervals indicates that either fluvial or marginal marine conditions are possible. While the interpretation is not fully clear, a fluvial succession with some degree of channel abandonment and flood plain development is the most plausible interpretation. Miller and D'Eon (1987) also suggested a fluvial setting, particularly braided fluvial, and Ainsworth et al. (2014) indicated continued nonmarine deposition, both in line with the present study. This interval forms part of the Bjarni Formation, with an age that could be as old a Barremian–early Aptian or late Aptian–(?)early Albian (Ainsworth et al., 2014; Nøhr-Hansen et al., 2016), but a Barremian age is not likely (*see* above discussion).

Nonmarine Lacustrine

Spanning the depths of 2947 m to 2836 m is a thick grey shale interval with interspersed siltstone beds. The shale abruptly overlies the sandstone below and is grey and silty, with siltstone stringers and a slightly sandy character near the top of the interval. Siltstone units are thin, grey, and argillaceous and include shale stringers, rare sand grains, and rare mica.

The consistent nature of the lithology, with a complete lack of fossil material, pyrite, and siderite suggests a lacustrine setting, reflecting flooding of the underlying fluvial succession. Miller and D'Eon (1987) found a similar lacustrine paleoenvironment for much of the interval and nonmarine conditions were also confirmed by Ainsworth et al. (2014). This part of the Bjarni Formation is shale-dominated and typical of the Snorri Member. In the present study, the base and top of the member are refined to 2947–2836 m at the log breaks between the shale and over- and underlying sandstone intervals (Fig. 21; Table 36). As with the underlying two intervals, the strata area either Barremian–early Aptian (Ainsworth et al., 2014) or late Aptian–(?)early Albian (Nøhr-Hansen et al., 2016), with a preference for the latter age.

Delta plain

From 2836 m to 2592 m are strata composed of heterolithic sandstone, siltstone, and shale, with coaly horizons. Light grey to white, very fine- to coarse-grained (variable), siliceous, slightly silty, calcareous, moderately to locally well sorted, and micaceous sandstone contains subangular grains, localized pyrite, localized interbedded coal, localized glauconite, minor chlorite, minor kaolinite, and rare chert grains. Siltstone units are grey and slightly bituminous locally, with sandstone stringers, interbedded shale, minor mica, rare carbonaceous flakes, and rare pyrite. Grey shale with coal parting is sandy and includes localized carbonaceous flakes, and rare mica. Black coal is rare and locally shaly. In the gamma-ray log, a ragged character is superimposed on some roughly coarsening-upward units (Fig. 21).

The abundance of coal suggests development of swampy or marshy settings with glauconite- and pyrite-bearing intervals indicating shallow marine deposition. Some sandstones are blockier, but most are thinly bedded, and the succession is overall heterolithic and would be best described as representing a delta plain paleoenvironment, possibly with some distributary channel development. Miller and D'Eon (1987) found similar delta plain to delta front settings, but Ainsworth et al. (2014) indicated only nonmarine deposition. This interval forms part of the Bjarni Formation, and is as old as Barremian–early Aptian or late Aptian–(?)early Albian (Ainsworth et al., 2014; Nøhr-Hansen et al., 2016), with a preference for the latter age.

Delta front

The strata between 2592 m and 2200 m are composed of an overall coarsening-upward succession that is sandstone-dominated, with siltstone beds and rare claystone beds. Sandstones are grey to white, fine- to medium-grained, moderately sorted, silty, calcareous, siliceous, micaceous, and argillaceous, and contain subangular grains, scattered feldspar grains, scattered pyrite, scattered chert grains, localized very coarse-grained sand grains, rare chlorite, rare kaolinite, and rare carbonaceous flakes near the top of the interval. Siltstones are grey to grey-brown and sandy, and grey, sandy, and silty claystone is also present. In general, two siltier units break up the interval into three sandstone-dominated successions, but the gamma-ray profile is rather blocky for the entire interval (Fig. 21).

A blocky gamma-ray profile is typical of a shoreface succession, but evidence from core 2 (2240–2234 m) indicates that, at least in part, this unit is representative of wave-influenced deltaic deposition (Dafoe and Williams, 2020a). A wave-influenced delta can resemble shoreface strata as wave action mitigates the environmental stresses associated with fluvial discharge, specifically fines are kept in suspension resulting in a more sandstone-dominated interval and blockier log signature compared to a river-dominated delta (Bhattacharya and Walker, 1991). The presence of pyrite and lack of fossils is consistent with a deltaic setting, but the lack of organic detritus, coal, and glauconite, as was seen in the underlying interval, is curious. From the log character and the nature of core 2, it would appear that the entire interval reflects a delta front setting. Miller and D'Eon (1987) assigned a nonmarine, alluvial fan paleoenvironment, but Ainsworth et al. (2014) indicated a nonmarine to transitional setting for much of this same interval, the latter interpretation in reasonable agreement with the present study.

This sandstone-dominated interval makes up part of the Bjarni Formation and is late Aptian–(?)early Albian to middle Albian according to Nøhr-Hansen et al. (2016). Ainsworth et al. (2014) suggested an age as old as Barremian–early Aptian to late Aptian–late Albian, but it is unclear why they did not include any middle Aptian in their assessment. Fenton and Pardon (2007) suggested only late Albian strata, but core 2 represents strata near the top of the interval and is early and middle-late Albian (Dafoe and Williams (2020a), which corresponds best with the findings of Ainsworth et al. (2014) from cuttings.

Prodelta

A siltstone- and claystone-dominated interval with sandstone units persists from 2200 m to 1846 m. Siltstones are grey, sandy, argillaceous, and micaceous. Grey, sandy, silty, micaceous claystone includes rare carbonaceous flakes. Grey to white sandstone becomes grey-brown near the top of the interval and is fine- to medium-grained, moderately sorted, calcareous, argillaceous, and slightly silty. The sandstone also contains subangular grains, very coarse-grained sand grains in the upper half of the interval, and rare quartz pebbles. Black coal further occurs near the base of the interval, and rare sandy marlstone is present. A ragged gamma-ray profile, with both coarsening- and fining-upward trends is seen in Figure 21.

Based on the underlying core 2 interpretation from Dafoe and Williams (2020a) and similar lithological characteristics for this interval (but finer-grained), a prodeltaic setting is interpreted, with sandstone intervals likely representing distal delta front progradation. The lack of fossils further supports this interpretation, as does the presence of coal indicating continued nearshore conditions. This setting is deeper than recognized by Ainsworth et al. (2014), as they reported continued nonmarine to transitional settings at this depth in the well. Furthermore, Miller and D'Eon (1987) suggested nonmarine conditions from alluvial fan to lacustrine. Relying on the interpretation of core 2 in the underlying interval, a prodeltaic setting is more plausible.

These strata form part of the Bjarni Formation and are middle Albian to Cenomanian in age according to Nøhr-Hansen et al. (2016), but recent work by Dafoe, Dickie et al. (in press) suggested that the Bjarni Formation excludes Cenomanian strata. According, the late Aptian–late Albian ages of Ainsworth et al. (2014) are in better agreement with the regional lithostratigraphic framework, but Aptian strata are unlikely based on Dafoe and Williams' (2020a) Albian age assignment for core 2 (*see* above).

Delta front

Thinly bedded sandstone characterizes the interval spanning 1846 m to 1787 m. The sandstone is fine- to medium-grained and coarsens upward to medium-grained with very coarse-grained sand grains and rare pebbles. The sandstone is also grey to brown, argillaceous, partly calcareous, and moderately sorted, with subangular grains, shale stringers, and carbonaceous flakes in the upper half of the interval. Siltstone units are grey, argillaceous, calcareous, and sandy, and rare brown claystone is further present. A slightly ragged character is observed in the gamma-ray log (Fig. 21).

The sandstones resemble those in the underlying succession from 2592–2200 m, with a continued heterolithic character. The lithology, coarsening-upward nature, and presence of carbonaceous flakes are consistent with a return to a delta front setting. A lack of fossil material further confirms continued brackish conditions. The interpretation from the present study agrees well with the nonmarine to transitional conditions postulated by Ainsworth et al. (2014), but contrasts with the nonmarine conditions of Miller and D'Eon (1987). The sandy, heterolithic character is not consistent with a lacustrine setting as suggested by the latter authors. This interval is attributed to the Bjarni Formation and is again late Aptian–late Albian based on the findings of Ainsworth et al. (2014), but is likely restricted to the Albian based on the age of the underlying core 2 (*see* above).

Prodelta

A thin interval of heterolithic claystone, sandstone, and lesser siltstone comprises 1787 m to 1712 m. Claystones are brown, sandy, and silty. Light grey, medium-grained, moderately sorted, argillaceous, partly calcareous, and partly silty sandstones include subangular grains and rare chert pebbles. Siltstones are brown and sandy.

In general, there is notable similarity to underlying strata, and the fine-grained nature and lack of fossils suggests a return to prodeltaic deposition. This setting agrees reasonably well with the nonmarine to transitional interpretation of Ainsworth et al. (2014), but not with the nonmarine lacustrine to alluvial fan interpretation of Miller and D'Eon (1987). Such nonmarine settings are atypical of the upper Bjarni Formation (*see* Dafoe, Dickie et al., in press). Capping the top of the Bjarni Formation, this interval is late Aptian–late Albian based on Ainsworth et al. (2014), but likely Albian as discussed above in relation to core 2 results. This interval caps the top of the Bjarni Formation, the extent of which remains unchanged from Moir (1989) from 3094–1712 m (Table 36), as there is are prominent log decreases in the sonic velocity and resistivity at 1712 m (Fig. 21).

Delta front

Sandstone-dominated strata are present between the depths of 1712 m and 1608 m. White to light grey sandstone and thin shale and siltstone beds characterize this interval. The sandstone is fine- to coarse-grained, moderately to poorly sorted, partly argillaceous, and partly calcareous, with subangular to rounded grains, scattered very coarse-grained sand grains, and rare chert grains and pebbles. Shale to claystone is grey and sandy, with siltstones being grey and argillaceous. Notably the gamma-ray log shows a ragged, but coarsening-upward succession (Fig. 21).

The gamma-ray profile, dominance of sandstone, heterolithic lithology, and lack of fossils suggests delta front progradation. The log break and missing section implied by biostratigraphic studies between this and the underlying interval (*see* below) indicates that there is no affinity to the underlying deltaic strata. A delta front setting is similar to the inner neritic interpretation of Ainsworth et al. (2014), but the alluvial fan setting of Miller and D'Eon (1987) does not appear to be consistent with the observations noted above, nor with paleoenvironments typically found in the Markland Formation (*see* Dafoe, Dickie et al. in press).

This interval is Late Cretaceous in age, but with poor agreement between studies (Fig. 21). Based on a Late Cretaceous age, the sandstones would be characterized as the Freydis Member of the Markland Formation. The late Campanian age of Nøhr-Hansen et al. (2016) fits the understanding of the upper Freydis Member in Dafoe, Dickie et al. (in press), with cavings likely accounting for the Late Campanian age determined below 1712 m. Ainsworth et al. (2014) gave a much broader (?)Turonian–Campanian age, and Fenton and Pardon (2007) suggested Campanian to Maastrichtian strata. Based on the above, a Campanian age is most likely and in good accord with other Freydis Member sandstones along the Labrador Shelf (Dafoe, Dickie et al., in press). This lithostratigraphic assignment of the present study differs from that of Moir (1989), as the Markland Formation and respective Freydis Member are herein suggested to extend from 1712–1608 m (Fig. 21; Table 36).

Inner shelf

A thin interval of shale and siltstone is present between 1608 m and 1587 m. Shale is grey and silty and the siltstone is argillaceous, sandy, and brown-grey. The gamma-ray log indicates a general coarsening-upward trend within the interval and further coarsening-upward into the overlying sandstones above (*see* below; Fig. 21).

The fine-grained nature of the strata, but lack of fossils is unusual for normal marine deposition, but the clear lithological and well log association with the overlying interval suggests an inner shelf setting. This agrees with the inner neritic interpretation of Ainsworth et al. (2014), but is slightly deeper than the beach to alluvial fan successions proposed by Miller and D'Eon (1987).

This interval stands out as a thin, finer-grained section that is assigned in the present study to the Cartwright Formation (Table 36). The boundary between the Markland (Freydis Member) and Cartwright formations is picked at 1608 m, where it corresponds to a prominent shale break and general change in log character, especially of the gamma-ray log. This interval further exemplifies strong affinity to the overlying interval in that they form a clear coarsening-upward succession in the well (Fig. 21). Accordingly, the age of this interval is tied to that of the overlying Gudrid Formation sandstones, with revision of that unit based on core 1 (1556–1546 m) analyzed by Dafoe and Williams (2020a) where they found a basal Ypresian (Early Eocene) age, consistent with upper Gudrid Formation sandstones (McWhae et al., 1980; Dafoe and Williams, 2020a; Dafoe, Dickie et al., in press). Based on the consistent log and lithological characteristics, the Gudrid Formation appears to extend down to 1587 m at the top of this interval (*see* below). However, the basal Ypresian age of core 1 indicates that the mostly Late Cretaceous ages for the lower part of the Gudrid Formation, and this Cartwright Formation interval are possibly inaccurate. As a result, the base of the Cenozoic should extend further down in the well. Extensive reworking of the Freydis Member sandstones during regression and development of the Cartwright and Gudrid formations may have resulted in reworking of Cretaceous microfossils. Dafoe and Williams (2020a) also noted reworked Cretaceous forms in their analyses of core 1. Accordingly, the interval from 1608–1587 m is possibly Paleocene. Paleocene ages were noted by both Ainsworth et al. (2014) and Nøhr-Hansen et al. (2016) from higher up in the well just above the core 1 sample.

Shoreface

Between the depths of 1587 m and 1458 m is a slightly heterolithic, but coarsening- and cleaning-upward interval dominated by sandstone. Sandstones are clearly separated by siltstone and shale units, with limestone and fossil content more prevalent at the top of the overall interval. Sandstones are white to light grey, argillaceous, calcareous, and partly silty, with limestone stringers, scattered very coarse-grained sand grains throughout, rare chert pebbles and grains, rare glauconite, and rare pyrite. The sand grains are more rounded and more poorly sorted at the base of the succession. Grey-brown siltstone is sandy and argillaceous, and includes sandstone stringers and rare pyrite. Grey silty shale occurs locally, and limestone is cream to white and sandy, with rare indeterminate fossil fragments. The gamma-ray log confirms a coarsening-upward succession, with a blocky to ragged character (Fig. 21).

The blocky gamma-ray signature, coarsening-upward character, and evidence of fossil detritus are interpreted to reflect shoreface deposition. The rounding of grains further supports a high-energy setting with ample wave reworking, and interbedded fossiliferous limestones also suggest more normal-marine conditions. A shoreface or delta front setting was also proposed for the core 1 interval (Dafoe and Williams, 2020a). In terms of previous paleoenvironmental assessments, the marginal marine (beach) to possible inner shelf (shoreface) settings interpreted by Miller and D'Eon (1987) agree well with the present study. The inner neritic setting of Ainsworth et al. (2014) also agrees, but these authors further indicated upper bathyal conditions not supported by the above description.

As explained for the underlying inner shelf interval, this interval is considered to form the Gudrid Formation in the present study based primarily on the age of core 1 (Dafoe and Williams, 2020a), the sandstone-dominated lithology, and Ypresian (Early Eocene) ages noted by several studies of the cuttings (Fenton and Pardon, 2007; Nøhr-Hansen et al., 2016). Due to the uncertainties here, distinction of the lower and upper Gudrid Formation cannot be undertaken for this interval, but as described above, the age is thought to be basal Ypresian and in better agreement with the upper Gudrid Formation (*see* Dafoe, Dickie et al., in press). The lithostratigraphic assignment of the Gudrid Formation is modified from Moir (1989) to extend from 1587–1458 m (Table 36), with the upper boundary clearly demarcated by an increase in the gamma-ray and resistivity values, but decrease in sonic velocity (Fig. 21).

Middle shelf

Between the depths of 1458 m and 1356 m is a claystone succession with rare limestone, sandstone, and siltstone interbeds. This unit sits sharply above the underlying sandstones. Claystone to shale is brown, sandy, and silty, with limestone stringers, rare mica, and rare pyrite. Limestone units are brown, argillaceous, and slightly sandy. Brown, argillaceous, slightly sandy, calcareous siltstone contains rare indeterminate shell fragments. Finally, brown, argillaceous, very fine-grained, well-sorted sandstone possesses subangular grains.

The fine-grained nature, but presence of sand is interpreted to indicate a middle shelf setting. A lack of fossil abundance and diversity is unusual and could be related to the transgressive nature of the base of the Kenamu Formation. More distal, outer shelf or outer neritic to upper bathyal settings were previous reported (Miller and D'Eon, 1987; Ainsworth et al., 2014), but the dispersion of sand is not consistent with turbidite fan accumulations as previously proposed. This interval marks the base of the Kenamu Formation and is Ypresian (Early Eocene) according to Nøhr-Hansen et al. (2016), as well as Fenton and Pardon (2007).

Middle to outer shelf

Claystone with rare limestone and siltstone persists from 1356 m to 1240 m. Brown, silty, locally sandy claystone includes scattered fossil fragments (indeterminate shell material and bivalve) and rare siltstone stringers. Limestone units are brown, argillaceous, and sandy.

The claystone becomes sandier upwards and more fossil debris is present suggesting shallowing upward from outer to middle shelf conditions. This setting agrees reasonably well with previous studies which interpreted outer shelf or outer neritic to upper bathyal conditions (Miller and D'Eon, 1987; Ainsworth et al., 2014). Within the Kenamu Formation, this finer-grained interval is Ypresian (Early Eocene) and Bartonian (Middle Eocene) according to Nøhr-Hansen et al. (2016), although Ainsworth et al. (2014) also gave a Lutetian (Middle Eocene) age for part of this interval. An unconformity or condensed Lutetian interval as suggested by the findings of Nøhr-Hansen et al. (2016) are not seen in the lithological or log data.

Middle shelf

A thick claystone-dominated interval with siltstone, limestone, and sandstone beds occurs between the depths of 1240 m and 892 m. Claystone is sandy and silty throughout, brown, with scattered fossil fragments (indeterminate shell material, scaphopod, bivalve, and foraminifera) that are locally abundant, especially near the top of the interval. Brown to brown-grey, argillaceous, sandy siltstone includes rare indeterminate shell fragments. Sandstones are brown, very fine- to fine-grained, silty, argillaceous, and moderately sorted, with subrounded grains. Brown, argillaceous, sandy limestone also occurs.

The abundance of scaphopods and shell fragments combined with the sandy nature of the claystone suggests a middle shelf paleoenvironment. Previous studies indicated outer shelf to inner shelf conditions (Miller and D'Eon, 1987; Ainsworth et al., 2014) in good agreement with the present study's results.

This interval spans the top of the Kenamu Formation and base of the Mokami Formation as defined in the present study, with the lithostratigraphic boundary of Moir (1989) at 1121 m retained (Table 36). There appears to be no break or significant change in lithology at this lithostratigraphic boundary, with only a slight reduction in the sonic velocity and resistivity logs. Since this interval and the overlying interval are dominated by claystone rather than sandstone, they are considered herein to be part of the Mokami Formation, rather than the Saglek Formation as suggested by Moir (1989; Fig. 21). The strata in this interval are Bartonian–(?)Priabonian (Middle–Late Eocene) based on the findings of Nøhr-Hansen et al. (2016), but could be as young as Rupelian (Early Oligocene; Ainsworth et al., 2014).

Inner shelf

The interval from 892 m to 608 m in Ogmund E-72 is a heterolithic claystone (50%), sandstone (35%), and siltstone (15%) interval. The claystone component is brown, silty, and sandy, with fossil fragments throughout (indeterminate shell material and bivalve) and rare limestone stringers. Light brown to white sandstone is argillaceous, fine- to medium-grained, moderately sorted, and silty, and further contains subrounded grains, fossil fragments throughout (indeterminate shell material, foraminifera, and bivalve), scattered very coarse-grained sand grains, rare dark chert grains, rare quartz pebbles, and rare chlorite. Siltstone units are grey-brown and sandy.

The heterolithic nature of the strata and fossil abundance (mostly bivalve) suggests a shallowing to an inner shelf setting, possibly under storm-dominated conditions where fair-weather mudstones alternate with storm-generated sandstone deposits. These strata comprise the upper part of the Mokami Formation, defined in the present study from 1121–608 m based on the dominant claystone lithology (Fig. 21; Table 36). This inner shelf interval is possibly Bartonian–(?)Priabonian (Middle–Late Eocene) according to Nøhr-Hansen et al. (2016), but may also extend into the Rupelian (Early Oligocene), Chattian (Late Oligocene) and possibly Miocene (Bujak Davies Group, 1989f; Ainsworth et al., 2014).

Delta front

The uppermost part of Ogmund E-72 from 608 m to 430 m comprises a sandstone- and conglomerate- dominated unit with claystone and rare siltstone interbeds. Sandstones are white to translucent to light grey, fine- to coarse-grained, moderately to poorly sorted, calcareous, and silty, with pebbles throughout (quartz and chert), subrounded to rounded grains, scattered fossil fragments that are locally common at the base (indeterminate shell material and bivalve), scattered very coarse-grained sand grains, and very rare carbonaceous flakes. Conglomerates are sandy and varicoloured, with igneous and quartz pebbles. Claystones are grey and sandy, and further contain fossil fragments near the base of the interval (bivalve). The gamma-ray log is somewhat ragged, but shows an overall coarsening-upward profile (Fig. 21).

The coarse-grained nature and abundance of shell fragments suggests shallow marine conditions, but interbedded claystones are more indicative of delta front deposition. The inner shelf to marginal marine settings of Miller and D'Eon (1987), including possible deltaic conditions agree well with the present results. This interval characterizes the Saglek Formation as defined in the present study, which extends from 608 m to 401 m at the top of the uppermost electric log signature (Fig. 21; Table 36).

Lithostratigraphy

Based on the discussion around lithostratigraphic refinements to the framework of Moir (1989) in Ogmund E-72, the lithostratigraphic picks from the present study are summarized in Table 36. There are no type or reference sections in this well.

Lithostratigraphic unit	Moir (1989)		The present study		Type or reference section
	Base (m)	Top (m)	Base (m)	Top (m)	
Saglek Fm	978	326	608	401	None
Mokami Fm	1121	978	1121	608	None
Kenamu Fm	1458	1121	1458	1121	None
Gudrid Fm*	1540	1458	1587	1458	None
Cartwright Fm	--	--	1608	1587	None
Markland Fm (Freydis Mb)	1712	1540	1712	1608	None
Bjarni Fm (Snorri Mb)	2948	2840	2947	2836	None
Bjarni Fm	3094	1712	3094	1712	None

Table 36: Lithostratigraphic assignment for Ogmund E-72 from the present study and compared to that of Moir (1989). *Moir's (1989) Gudrid Formation was reported as the informal upper member. Fm=Formation; Mb=Member.

POTHURST P-19

Located in a basinward setting on the Labrador Shelf in the southern Saglek Basin is the Pothurst P-19 well (Fig. 1). The well history reports for Pothurst P-19 only include cuttings descriptions for 547–3842 m (Steeves, 1982) and for 3610–3992 m (Steeves, 1983b), which were used to develop the descriptions of intervals below. The Canadian Stratigraphic Service Ltd. Petro-Canada Pothurst P-19 log (log EC-182) further includes detailed descriptions of the lithology, grain size, grain rounding, and sample descriptions also used in the present study. A detailed well plot is shown in Figure 22, with key well logs, lithology, grain size, rock colour, ages, and paleoenvironmental and lithostratigraphic information. The age framework of Williams (2017a) is used in the present study. Table 37 includes a summary of the paleoenvironments from the present study, which are compared with those of Miller and D'Eon (1987) and Ainsworth et al. (2014) in the text below. The latter study presumably based their paleoenvironments on both micropaleontology and palynology. The lithostratigraphic assignments of Moir (1989) and from the present study are further discussed below and compared in Figure 22 and in Table 38.

Base (m)	Top (m)	Paleoenvironment
3985	3674	SLOPE WITH TURBIDITE DEPOSITION
3674	3401	OUTER TO MIDDLE SHELF
3401	3306	OUTER SHELF TO UPPER SLOPE
3306	3246	PRODELTA
3246	3184	DELTA FRONT
3184	2956	PRODELTA
2956	2792	SHOREFACE OR DELTA FRONT
2792	2303	PRODELTA TO DISTAL DELTA FRONT
2303	2091	DELTA FRONT DISTRIBUTARY CHANNELS
2091	1967	PRODELTA
1967	1913	DELTA FRONT
1913	1838	PRODELTA
1838	1777	DELTA FRONT
1777	1593	PRODELTA
1593	1541	DELTA FRONT DISTRIBUTARY CHANNELS
1541	1450	PRODELTA
1450	1227	DELTA FRONT
1227	1154	PRODELTA
1154	1130	DELTA FRONT
1130	961	MIDDLE TO INNER SHELF
961	550	PRODELTA TO DISTAL DELTA FRONT

Table 37: Paleoenvironmental determinations for Pothurst P-19 from the present study.

Slope with turbidite deposition

At the base of the well, shale with siltstone and sandstone interbeds is present from 3985 m to 3674 m. The shales and/or claystones are brown-grey, locally sandy, and silty throughout, with rare ironstone nodules. Sandstone units are generally fining-upward and are light brown, fine- to medium-grained, well to moderately sorted, argillaceous, micaceous, slightly dolomitic, and partly silty. They further contain subangular to subrounded grains, scattered very coarse-grained sand grains, rare glauconite, rare chert, rare feldspar, rare pyrite, and rare carbonaceous flakes. Siltstone units are dark brown, argillaceous, and micaceous, with rare carbonaceous flakes. Rare dark brown limestone is also present. The gamma-ray log confirms the fining-upward nature of sandstone to siltstone and claystone intervals for part of the interval (Fig. 22).

The lack of fossil material, fining-upward character of sandstone intervals, and dominance of claystone suggests either deep-water or brackish conditions. Fining-upward sandstone into siltstone and claystone are interpreted here to indicate deposition by turbidity currents or debris flows. Shales are otherwise only silty and thus reflect deep-water conditions. Accordingly, a slope setting with turbidity current deposition is the most plausible, with coarser sand grains possibly indicating some sediment bypass on the shelf or proximity to a shelf-edge delta. A similar bathyal setting with turbidites was suggested by Miller and D'Eon (1987) and Ainsworth et al. (2014) also confirmed upper bathyal water depths, both in good agreement with the present study.

This interval forms the base of the Kenamu Formation penetrated in the well. Moir (1989) suggested a Gudrid Formation sandstone at the base of the well, but there is no evidence to indicate that this sandstone differs from the other sandstones in this same interval. Accordingly, the Gudrid Formation is not assigned here (Table 38), and the Lutetian (Middle Eocene) age of Williams (2017a) would be too young for that lithostratigraphic unit (*see* McWhae et al., 1980; Dickie et al., 2011; Dafoe, Dickie et al., in press). As shelf-slope conditions were established during deposition of the Eocene Kenamu Formation (Dickie et al., 2011), this interval is likely representative of a true slope environment. Williams (2017a) found the age of this interval to be Lutetian, but others indicated a slightly older Ypresian (Early Eocene) age (Bujak Davies Group, 1989g; Ainsworth et al., 2014).

Outer to middle shelf

Between the depths of 3674 m and 3401 m is an interval of claystone with occasional siltstone and sandstone intervals. Brown-grey, sandy, silty, claystone includes common fossil fragments at the base of the interval (scaphopod and foraminifera), rare ironstone fragments, and rare glauconite. Dark brown, argillaceous siltstone is slightly dolomitic and locally sandy, with sandstone stringers, rare pyrite, rare fossil fragments (scaphopod and foraminifera), and rare carbonaceous flakes. Sandstone units are brown, very fine- to fine-grained, well sorted, silty, argillaceous, and slightly dolomitic, with subangular grains, rare chert grains towards the top of the interval, and rare pyrite. Unlike the underlying interval, sandstone beds are thinner, such that the gamma-ray log does not show any definitive fining- or coarsening-upward trends (Fig. 22).

The increase in sand content upwards and interlamination described in the cuttings report, combined with the presence of scaphopods suggests shallowing relative to the underlying slope interval. An outer to middle shelf is interpreted here. While a similar outer shelf setting was postulated by Miller and D'Eon (1987), Ainsworth et al. (2014) interpreted continued upper bathyal deposition. Making up another significant part of the Kenamu Formation, this sandy claystone interval is Lutetian (Middle Eocene) according to Williams (2017a), and could range into the Bartonian (Ainsworth et al., 2014).

Outer shelf to upper slope

There is a distinct change back to silty shale with siltstone and sandstone intervals from 3401 m to 3306 m. Brown-grey, silty, shale is locally slightly sandy, with rare carbonaceous flakes. Siltstone units are dark brown, argillaceous, sandy, and micaceous, with rare carbonaceous flakes. Thicker sandstone units are notably fining-upward, but the sandstones are generally brown, very fine- to fine-grained, well sorted, argillaceous, and silty, and include chert grains and subangular clasts. The gamma-ray log confirms the fining-upward nature of the sandstones into the overlying siltstones and shales (Fig. 22).

The fine-grained nature of the strata, with fining-upward sandstone beds suggests a return to turbidite accumulations within an outer shelf to upper slope setting. Ainsworth et al. (2014) also gave an upper bathyal setting, and the outer shelf interpretation of Miller and D'Eon (1987) is also in relative agreement with the present study. This interval occurs near the top of the Kenamu Formation, and Williams (2017a) gave a Lutetian (Middle Eocene) age for this interval, but it could also include Bartonian (Middle Eocene) section (Ainsworth et al., 2014).

Prodelta

Spanning the depths of 3306 m to 3246 m is a succession of interbedded claystone and siltstone with rare sandstone. Sandy and silty brown to grey claystone or shale is the most abundant lithology. Siltstone units are brown, argillaceous, sandy, and micaceous, with rare carbonaceous flakes. Rare sandstone units are brown, argillaceous, and silty, with rare chert pebbles. Rare limestone, pyrite, and indeterminate shell fragments were also noted. The gamma ray log shows a generally coarsening-upward interval, but with some ragged character (Fig. 22).

The increase in sand content upwards within the interval suggests shallowing and progradation. The lack of fossil fragments aside from indeterminate shell material implies possible environmental stress such as in a prodeltaic setting, especially considering the nature of the overlying sandstone interval (*see* below). This further agrees with the introduction of rare pebbles indicating shoreline proximity, as well as the coarsening-upward gamma-ray profile. Deltaic conditions were suggested by Miller and D'Eon (1987) in either an outer or inner shelf setting; however, Ainsworth et al. (2014) found upper bathyal conditions. This discrepancy could be explained by the presence of a shelf-edge delta in which a mixed suite of shallow- and deep-water microfossils can be preserved (Emery and Myers, 1996). These strata comprise the uppermost claystone-dominated part of the Kenamu Formation as defined in the present study (Fig. 22), with a Lutetian (Middle Eocene) age postulated by Williams (2017a), but the Bartonian (Middle Eocene) age of Ainsworth et al. (2014) is preferred.

Delta front

A sandstone with rare siltstone intervals persists from 3246 m to 3184 m. The sandstone is light brown to grey, very fine- to coarse-grained, well to poorly sorted, argillaceous, locally silty, and locally dolomitic. The strata further contain subrounded clasts, dark chert grains throughout, very coarse-grained sand grains throughout, quartz pebbles in the lower half of the interval, scattered pyrite, a locally heavy oil stain, rare glauconite, and rare indeterminate shell fragments. An overall coarsening-upward profile is seen on the gamma-ray log, but there is a slightly ragged character (Fig. 22).

The ragged, but coarsening-upward character, dominance of sandstone, and presence of coarse-grained clasts suggests a delta front setting. The lack of terrigenous material is unusual, but grain rounding could be indicative of a more wave-influenced delta front, especially with a lack of fine-grained lithologies. A deltaic setting is further supported by the general lack of fossil material and diversity, implying brackish conditions. This interpretation agrees well with Miller and D'Eon's (1987) delta front interpretation, but not with the deep-water, upper bathyal conditions postulated by Ainsworth et al. (2014). The presence of a shelf-edge delta or cavings from the overlying succession could account for such a deep-water interpretation that does not appear to agree with the evidence presented above.

This sandstone-dominated succession forms the Leif Member of the Kenamu Formation as interpreted in the present study, from 3246–3184 m (Table 38). The member is restricted to the sandstone-dominated section of the Kenamu Formation where there is a distinct change in the gamma-ray (decrease) and resistivity (overall decrease) logs compared to the underlying interval. The Lutetian (Middle Eocene) age and thick Lutetian section of Williams (2017a) is atypical for the Leif Member and top Kenamu Formation (Dickie et al., 2011; Dafoe, Dickie et al., in press). Ainsworth et al. (2014) proposed a Lutetian–Bartonian (Middle Eocene) age, which is more consistent with the regional understanding of the member and formation and preferred in the present study.

Prodelta

The interval from 3184 m to 2956 m is composed of claystone with scattered siltstone interbeds. Brown-grey, sandy, silty claystone contains scattered fossil fragments (mostly scaphopod, as well as bivalve) and rare carbonaceous flakes. Siltstone units are brown to grey, argillaceous, sandy, and micaceous, with rare carbonaceous flakes and rare plant remains. Very rare brown argillaceous sandstone is also present. The gamma-ray log shows an overall, coarsening-upward, but ragged character (Fig. 22).

The generally sandy nature of the claystone and presence of scaphopods suggests shelfal conditions, but the lack of fossil diversity is unusual and is interpreted to indicate prodeltaic deposition in which brackish conditions hamper a diverse suite of marine life. This is further supported by the presence of plant material indicating shoreline proximity and the overall coarsening-upward gamma-ray profile. Ainsworth et al. (2014) interpreted outer neritic to upper bathyal settings, and Miller and D'Eon (1987) similarly suggested possible outer shelf conditions, but questioned the development of turbidites or a steep gradient shelf. The presence of a shelf-edge delta could explain the discrepancy between the present study and previous findings, with a mix of shallow and deeper water fossil assemblages, especially microfossils (Emery and Myers, 1996).

This claystone interval marks the base of the Mokami Formation in Pothurst P-19. Williams (2017a) gave this section of the well a Priabonian (Late Eocene) to Chattian (Late Oligocene) age, with missing or condensed Bartonian (Middle Eocene) section and condensed Priabonian and Rupelian (Early Oligocene) section. In contrast Ainsworth et al. (2014) documented the presence of Bartonian section, but lack of Priabonian rocks, with a reasonably thick Rupelian (Early Oligocene) interval. At the Kenamu–Mokami formation boundary there is clearly some degree of missing or condensed section, possibly related to the transgression typically seen at the base of the Mokami Formation (Dafoe, Dickie et al., in press). Despite this, a late Eocene to Late Oligocene age appears to be likely.

Shoreface or delta front

In the interval from 2956 m to 2792 m, sandstone is prevalent, with rare claystone, siltstone, and limestone intervals. Light brown to light grey sandstone is fine- to coarse-grained, argillaceous, locally silty, friable, and moderately to poorly sorted, and is also characterized by subrounded clasts, very coarse-grained sand grains throughout, dark chert grains throughout, quartz pebbles throughout, localized fossil fragments (bivalve), rare feldspar, rare pyrite, rare glauconite, and rare dolomite. Grey sandy and silty claystone, grey siltstone, and brown sandy and silty limestone are also present. The gamma-ray log signature is generally blocky for this interval, but also somewhat ragged (Fig. 22).

The presence of a limited fossil assemblage, coarse grain size, and some interbedded claystones suggest a shoreface to possible wave-dominated delta front setting. This interpretation is further supported by the grain rounding and limited fossil suite. This shallowing was not noted by previous studies where they interpreted outer shelf or outer neritic to upper bathyal conditions (Miller and D'Eon, 1987; Ainsworth et al., 2014), settings that are inconsistent with the coarse-grained to pebbly nature of the strata and dominance of bivalve fragments. Within the Mokami Formation, Williams (2017a) gave an age of Chattian (Late Oligocene) and Early Miocene for these shoreface strata; although other studies suggested older ages (Bujak Davies Group, 1989g; Ainsworth et al., 2014).

Prodelta to distal delta front

Heterolithic claystone, sandstone, and siltstone, with some generally coarsening-upward units occur from 2792 m to 2303 m. Claystones are most abundant and are grey, sandy, and silty, with scattered glauconite, rare fossil fragments (bivalve), rare siderite, and rare plant remains. Sandstones are light brown to grey, very fine- to coarse-grained, well to poorly sorted (mostly moderately), argillaceous, locally silty, and rarely calcareous, and also include subrounded to rare rounded clasts, common chert grains, common very coarse-grained sand grains, localized scattered quartz pebbles, rare feldspar grains, rare bivalve fragments, and rare mica. Argillaceous, sandy, grey siltstones contain rare plant remains or carbonaceous flakes and scattered bivalve fragments. The overall interval is sandiest at the top, with thicker sandstones showing coarsening-upward, gamma-ray trends (Fig. 22).

The mixed lithology with plant remains suggests terrestrial influx and shoreline proximity. The limited fossil content and diversity attests to a brackish-water setting. The varying degrees of claystone and sandstone implies changing prodeltaic to distal delta front conditions. Generally, Miller and D'Eon (1987) found similar inner shelf to marginal marine conditions and proposed possible deltaic sedimentation for part of the interval. Ainsworth et al. (2014) indicated more distal outer to middle neritic conditions. This interval forms part of the Mokami Formation, and was determined to be Late Miocene by Williams (2017a).

Delta front distributary channels

Sandstone-dominated strata between the depths of 2303 m and 2091 m include interbedded claystone units, with a conglomerate at the base of the interval. The light grey, argillaceous, sandy conglomerate is dominated by quartz pebbles. Sandstones are grey, very fine- to coarse-grained, argillaceous, and mostly moderately to poorly sorted, with mostly subrounded clasts, chert grains, very coarse-grained sand grains throughout, localized fossil fragments (bivalve), and rare quartz pebbles. Lesser claystones are grey, sandy, and silty, with common fossil fragments (bivalve and other indeterminate shell material), rare carbonaceous flakes, and rare siderite. These strata are characterized by blocky to mostly fining-upward intervals, with a slightly ragged gamma-ray profile (Fig. 22).

The thin conglomerate at the base of the interval likely represents an erosional lag. Accordingly, the coarse grain size, erosive base, and locally fining-upward trends are interpreted to reflect distributary channel migration and abandonment on the delta front. A low diversity fossil suite is again consistent with brackish conditions. The inner shelf setting postulated by Miller and D'Eon (1987) is similar, but they questioned the nature of the sandstones as possible bars or lower shoreface strata. The fossil content is, however, inconsistent with the typical fossil diversity seen within the inner shelf. The outer-middle neritic interpretation of Ainsworth et al. (2014) is also not supported by the observations listed above.

This sandstone-dominated succession is considered part of the Mokami Formation by both Moir (1989) and the present study. However, interbedding of Saglek Formation sandstones and Mokami Formation mudstones intervals could be more prevalent in this well than is shown in Figure 22. It is difficult to distinguish where the Mokami and Saglek Formation boundaries should be placed in Pothurst P-19 due to obvious interfingering of the units, but the major sandstone at 1450 m is considered to be the base of the Saglek Formation for simplicity (Fig. 22). The interval 2303–2091 m was given a Late Miocene age by Williams (2017a).

Prodelta

The interval between the depths of 2091 m and 1967 m is composed of claystone with siltstone interbeds. Grey claystone is sandy and silty, with ironstone fragments and fossil fragments throughout (indeterminate shell material and bivalve). Siltstone units are grey, argillaceous, sandy, and micaceous, and are further characterized by rare indeterminate shell fragments. The gamma-ray log shows a subtle coarsening-upward profile (Fig. 22).

The sandy and silty nature of this interval implies some degree of shoreline proximity, but the limited fossil diversity is interpreted to reflect a return to a prodeltaic paleoenvironment. The abundance of shell material could, however, indicate a more wave-dominated deltaic setting where brackish conditions are mitigated by wave activity (Bhattacharya, 2010). The subtle coarsening-upward profile hints towards progradation. As with the immediately underlying intervals, Ainsworth et al. (2014)

postulated a more distal middle to outer neritic setting, but the inner shelf to marginal marine interpretations of Miller and D'Eon (1987) also included a delta front setting that is in reasonable agreement with the present study. This Late Miocene to Early Pliocene (Zanclean) succession (Williams, 2017a) is part of the Mokami Formation.

Delta front

Spanning 1967 m to 1913 m is a coarsening-upward sandstone interval, with some raggedness in the gamma-ray log profile (Fig. 22). The sandstone is grey, very fine- to coarse-grained, well to poorly sorted, friable, argillaceous, and locally silty, and also includes fossil fragments throughout (indeterminate shell material), dark chert grains, very coarse-grained sand grains, subangular to subrounded clasts, rare feldspar, and rare mica.

The sharp base and top of the interval, coarsening-upward nature, poor degree of sorting, and monospecific fossil assemblage suggests delta front deposition. The abundance of fossil material could further indicate a wave-dominated delta in which wave activity mitigated brackish conditions and other stresses imparted by riverine discharge (Bhattacharya, 2010). Miller and D'Eon (1987) found a similar delta front setting, but Ainsworth et al. (2014) proposed a more distal neritic setting that is not in agreement with the evidence presented in above. This sandier interval forms part of the Mokami Formation, and was found to be Early Pliocene (Zanclean) in age by Williams (2017a).

Prodelta

Claystone with siltstone and rare sandstone is present from 1913 m to 1838 m. Grey, sandy, silty claystone contains localized indeterminate shell fragments, rare plant remains, and rare carbonaceous flakes. Lesser siltstone units are grey, argillaceous, sandy, and micaceous, with rare carbonaceous flakes and rare pyrite. Very rare sandstone is grey, argillaceous, silty, and friable, with very coarse-grained sand grains. Similar to some of the underlying intervals, a subtle coarsening-upward trend is seen in the gamma-ray log (Fig. 22).

The sandy nature of claystone, limited fossil diversity, and presence of terrigenous material suggests a return to prodeltaic conditions. This setting is in close agreement with the inner shelf interpretation of Miller and D'Eon (1987), but is again shallower than Ainsworth et al.'s (2014) middle to outer neritic paleoenvironment. Making up a part of the Mokami Formation, Williams (2017a) found this interval to be Early Pliocene (Zanclean) in age.

Delta front

Between 1838 m and 1777 m is sandstone with rare claystone interbeds. Grey, fine- to coarse-grained, well to poorly sorted, argillaceous, silty, friable sandstone includes subrounded clasts, fossil fragments throughout (indeterminate shell material), very coarse-grained sand grains throughout, rare pyrite, and rare chert. Claystone units are grey and sandy, with rare indeterminate shell fragments. A subtle coarsening-upward profile is seen in the gamma-ray log (Fig. 22).

The coarsening-upward nature is consistent with progradation, and the low diversity of fossils with some interbedded claystone is interpreted to reflect delta front conditions. The abundance of shell fragments, however, could again indicate some wave dominance and mitigation of freshwater influx (Bhattacharya, 2010). The deltaic interpretation is in close agreement with that of Miller and D'Eon's (1987) inner shelf to marginal marine settings (delta front bars). Ainsworth et al. (2014) indicated a more distal setting that does not appear to agree well with the descriptions of the rock presented above. This part of the Mokami Formation is Early Pliocene (Zanclean) according to Williams (2017a).

Prodelta

A relatively thick succession of claystone with common siltstone and rare sandstone interbeds occurs from 1777 m to 1593 m. Grey, sandy, silty claystone includes locally common fossil fragments (indeterminate shell material). Siltstones are grey, argillaceous, and sandy, with fossil fragments common in upper half of the interval (indeterminate shell material), and rare plant remains. Rare sandstones are grey, medium- to coarse-grained, moderately to poorly sorted, argillaceous, and silty, and include subrounded clasts, very coarse-grained sand grains, mica, and rare chert. In the gamma-ray log, the interval shows two main coarsening-upward units, the lowermost capped by a thin sandstone (Fig. 22).

Similar to some of the immediately underlying intervals, the sandy and silty nature suggests shoreline proximity, but within a prodeltaic setting. Fossil diversity is again dominated by shell fragments that are only locally common, perhaps indicating enhanced environmental stress relative to that seen in underlying intervals. The inner shelf to marginal marine settings, including deltaic deposits, of Miller and D'Eon (1987) are in good agreement with the present study, but these authors suggested more environmental fluctuation than noted herein. Like the underlying units of the Mokami Formation, Ainsworth et al. (2014) gave a middle–outer neritic setting based on their results from microfossils and palynomorphs. Located near the top of the Mokami Formation in Pothurst P-19, these strata are Early Pliocene (Zanclean) according to Williams (2017a).

Delta front distributary channels

The interval from 1593 m to 1541 m forms another sandstone-dominated interval with a fining-upward character and a sharp top and base (Fig. 22). The sandstone is light grey, coarse- to fine-grained, friable, argillaceous, and silty, with common fossil fragments (indeterminate shell material), mica, chert grains throughout, very coarse-grained sand grains near the base, and rare feldspar. The gamma-ray log shows a subtle fining-upward profile, as does the grain size log (Fig. 22).

The fining-upward character is interpreted to reflect a channelized succession that could be correlated with delta front distributary channels, especially considering the deltaic interpretations of the underlying intervals. Miller and D'Eon (1987) postulated possible delta front bars, but this does not appear to agree with the fining-upward profile, and Ainsworth et al. (2014) indicated middle-outer neritic settings that are far too distal to agree with the lithological information presented above. Lying within the Mokami Formation, the interval was found to be Early Pliocene (Zanclean) in age by Williams (2017a).

Prodelta

Claystone deposition characterizes the interval from 1541 m to 1450 m, with rare siltstone and sandstone units also present. The claystone is grey, silty, and sandy, and includes sandstone stringers, scattered glauconite, and rare indeterminate shell fragments. Sandstones are light grey, fine- to medium-grained, argillaceous, and silty, with mica, indeterminate shell fragments, scattered glauconite, and rare chert. Grey, argillaceous, sandy siltstone includes rare plant remains.

Similar to some of the immediately underlying intervals, the grain size, sandy nature and lack of abundance and diversity of fossils implies a prodeltaic paleoenvironment. Miller and D'Eon (1987) proposed a similar inner shelf setting, but the more distal shelf interpretation of Ainsworth et al. (2014) does not seem to fit with the descriptions above. Capping the top of the Mokami Formation, which is modified slightly relative to the findings of Moir (1989) at 1450 m (Table 38), this interval was determined to be Early Pliocene (Zanclean) by Williams (2017a).

Delta front

A thick sandstone that is overall coarsening-upward, with rare claystone and limestone intervals characterizes Pothurst P-19 from 1450 m to 1227 m. Light grey, fine- to coarse-grained (dominantly coarse-grained), argillaceous, poorly sorted sandstone includes very coarse-grained sand grains throughout, chert grains throughout, quartz pebbles mostly throughout, mica, feldspar, common fossil fragments throughout (indeterminate shell material and bivalve), and subrounded clasts. Rare claystones are grey and sandy, and contain bivalve fragments. Coal fragments are present at the very top of the interval. This thick sandstone shows a somewhat ragged, but overall coarsening-upward gamma-ray signature (Fig. 22).

The coarse grain size, presence of coaly material, low fossil diversity, interbedded claystones, ragged gamma-ray log profile, and presence of immature feldspar suggests a delta front setting. As with some of the immediately underlying intervals, the abundance of shell material could indicate a wave-dominated setting, where riverine influx is mitigated by wave action (Bhattacharya, 2010). This sandstone-dominated succession forms the base of the Saglek Formation defined here at 1450 m, only slightly deeper than that of Moir (1989; Table 38). Williams (2017a) gave an age of Zanclean (Early Pliocene) to Late Pliocene–Pleistocene for this delta front succession.

Prodelta

Spanning the depths of 1227 m to 1154 m is a claystone with scattered siltstone beds. Claystones are grey, sandy, and silty, and include fossil fragments throughout (bivalve, indeterminate shell material, and foraminifera). Grey, sandy siltstone, and rare light brown, argillaceous, silty, sandy dolostone are also present.

The presence of foraminifera suggests more normal marine conditions, but the lithology and dominance of shell material is consistent with the underlying prodeltaic intervals. This interpretation matches well with the inner shelf setting of Miller and D'Eon (1987), but they suggested offshore bars generated by storms. As before, the middle–outer neritic setting of Ainsworth et al. (2014) is more distal than interpreted here. This interval is finer-grained than typical Saglek Formation rocks of the Labrador margin (McWhae et al., 1980), but as indicated below, there could be more interfingering of Mokami Formation than is shown in Figure 22, but this relationship is not clear. These strata were considered Late Pliocene–Pleistocene by Williams (2017a).

Delta front

The interval from 1154 m to 1130 m is composed of grey, fine- to coarse-grained, argillaceous, partly silty, moderate to poorly sorted sandstone, with subrounded clasts, chert throughout, very coarse-grained sand grains throughout, fossil fragments throughout (indeterminate shell material and bivalve), and rare feldspar. The gamma-ray log is blocky, but the interval is rather thin for detailed log interpretation (Fig. 22).

The coarse-grained nature and limited fossil diversity are interpreted to reflect a delta front succession. Similar shallow marine settings were not observed in previous studies, which found inner shelf to middle-outer neritic paleoenvironments (Miller and D'Eon, 1987; Ainsworth et al., 2014). This thin interval of the Saglek Formation is Late Pliocene–Pleistocene according to Williams (2017a).

Middle to inner shelf

Claystone with rare siltstone characterizes 1130 m to 961 m in the well. The claystone is grey, sandy, and silty, with fossil fragments common throughout (foraminifera, bivalve, indeterminate shell material, and gastropod), sandstone stringers near the top of the interval, and rare coal fragments.

The fine-grained lithology, but sandy nature combined with the fossil diversity suggests more normal marine, middle to inner shelf conditions. This interpretation agrees reasonably with previous studies that reported inner shelf or middle–outer neritic conditions (Miller and D'Eon, 1987; Ainsworth et al., 2014). This part of the Saglek Formation is also Late Pliocene–Pleistocene according to Williams (2017a), but again represents an atypical lithology for the formation.

Prodelta to distal delta front

The uppermost interval in Pothurst P-19 from 961 m to 550 m includes an overall heterolithic succession of claystones with some siltstones capped by sandstones forming several units 10–100 m thick. Grey claystone is sandy, silty, and locally calcareous, with fossil fragments common throughout (bivalve and indeterminate shell material), rare pyrite, and rare ironstone nodules. Siltstones are grey, sandy, and argillaceous, and include fossil fragments (indeterminate shell material), rare plant remains, and rare coal stringers. Grey, very fine- to coarse-grained, argillaceous, well to poorly sorted sandstones include subangular to subrounded clasts, locally abundant very coarse-grained sand grains, locally common fossil fragments (bivalve), rare chert, and rare quartz pebbles. Conglomerate at the very top of the interval is grey and argillaceous, with quartz, igneous, limestone, dolomite, and granitic pebbles, as well as bivalve fragments. The gamma-ray log confirms a series of generally coarsening-upward claystone, siltstone, and sandstone units (Fig. 22).

The coarsening upward and sandy nature, with a lack of fossil diversity are interpreted to represent alternating prodelta to distal delta front settings developed during minor progradational events. Inclusion of coal and pebbles indicates enhanced periods of shoreline proximity. While in relative agreement with the inner shelf interpretation of Miller and D'Eon (1987), these authors suggested offshore bar development. The deeper, middle-outer neritic setting of Ainsworth et al. (2014), does not appear to agree with the lithological evidence above.

This part of the well forms the uppermost part of the Saglek Formation, which, in the present study, is extended to 528 m based on the uppermost gamma-ray log signature (Fig. 22). Moir (1989) extended the formation higher in the well where there is a resistivity log, but without any correlation to the resistivity of the underlying strata, it is unclear if the Saglek Formation should be continued into this part of the well. The conglomerate at the very top of the lithological information appears to indicate a return to coarse-grained deposition that is more typical for the Saglek Formation (McWhae et al., 1980). This interval was assigned a Late Pliocene to Pleistocene age by Williams (2017a).

Lithostratigraphy

Based on the discussion around lithostratigraphic refinements to the framework of Moir (1989) in Pothurst P-19, the lithostratigraphic picks from the present study are summarized in Table 38. There are no type or reference sections for this well.

Lithostratigraphic unit	Moir (1989)		The present study		Type or reference section
	Base (m)	Top (m)	Base (m)	Top (m)	
Saglek Fm	1449	362	1450	528	None
Mokami Fm	3184	1449	3184	1450	None
Kenamu Fm (Leif Mb)	3272	3184	3246	3184	None
Kenamu Fm	3976	3184	3985	3184	None
Gudrid Fm (upper)	3992	3976	--	--	None

Table 38: Lithostratigraphic assignment for Pothurst P-19 from the present study and compared to that of Moir (1989). Fm=Formation; Mb=Member.

RALEGH N-18

For the Ralegh N-18 well in the northern part of the Saglek Basin (Fig. 1), there are two key sources of geologic information that were used in the present study. The well history report by Canterra et al. (1982) includes sidewall core descriptions and cuttings descriptions for the well. These are significantly augmented by the Canterra Ralegh N-18 log (log EC-165) from the Canadian Stratigraphic Service Ltd., which includes detailed descriptions of the lithology, grain size, and grain rounding, as well as sample descriptions. Figure 23 shows the detailed well plot for Ralegh N-18 including: key well logs, lithology, grain size, rock colour, ages, and paleoenvironmental and lithostratigraphic information. Nøhr-Hansen et al. (2016) provides the most recent age framework for the well that is used here, in addition to some refinements by Williams (pers. comm., 2018) for the uppermost section. Paleoenvironments determined as part of the present study are summarized in Table 39 and compared with those of Miller and D'Eon (1987) and also with Bujak Davies Group (1989g) in the descriptions below, with the latter settings based on microfossils. Recent work by Dafoe, DesRoches et al. (in press) refined the lithostratigraphic interpretations developed by Moir (1987c) and these more recent interpretations are further locally modified in the present study (Fig. 23; Table 40).

Base (m)	Top (m)	Paleoenvironment
3833	3858	SUBAERIAL BASALT FLOW
3787	3833	SHELFAL
3677	3787	(?)MIDDLE SHELF
3552	3677	PRODELTA
3516	3552	DELTA FRONT
3484	3516	DISTRIBUTARY CHANNEL
3468	3484	INNER SHELF
3371	3468	SHELFAL
3166	3371	ESTUARINE
2752	3166	ESTUARINE
2241	2752	LAGOON TO MARSH
2032	2241	DELTA FRONT WITH DISTRIBUTARY CHANNELS
1755	2032	(?)FLUVIAL OR DELTAIC
1686	1755	INNER SHELF
1660	1686	OUTER SHELF
1514	1660	MIDDLE TO INNER SHELF
1456	1514	(?)TIDAL CHANNEL
1364	1456	LOWER SHOREFACE
1194	1364	SHOREFACE
795	1194	SHOREFACE

Table 39: Paleoenvironmental determinations for Ralegh N-18 from the present study.

Subaerial basalt flow

At the very base of Ralegh N-18 is a thin igneous interval between 3858 m and 3833 m. A sidewall core at 3835.9 m indicates green, friable to hard, weathered, microcrystalline, calcareous, very silty basalt. From cuttings, a similar description included: brown-green, igneous, slightly weathered, volcanic rock, possibly basalt, with hornblende, chlorite, and rare quartz grains.

The weathering and possible incorporation of silt or quartz grains suggests subaerial basalt flows, possibly combined with siliciclastic deposition. In contrast, Miller and D'Eon (1987) interpreted possible subaqueous flows or a possible intrusion, and Bujak Davies Group (1989g) gave a transitional to mid neritic interpretation. While a subaqueous basalt accumulation was determined for the Hekja O-71 well, there is a subaerially weathered top and possible subaerial intervals within the overall basalt (*see* Dafoe and Williams, 2020a). This unnamed basalt in Ralegh N-18 is at least as old as Thanetian (Late Paleocene) based on Nøhr-Hansen et al. (2016).

Shelfal

Lying above the basalt interval is a shale succession from 3833 m to 3787 m. The grey shale is slightly silty at the base, with rare pyrite also at the base. The shale is otherwise homogeneous and fissile.

The presence of silt and pyrite at the base of the interval may reflect a marine flooding event with reworking resulting in the incorporation of silt, and reducing conditions leading to the formation of pyrite (Wilkin, 2003). The homogeneous lithology and lack of fossils could indicate a distal marine or restricted marine setting, but there is a lack of terrestrial influx. Accordingly, the best interpretation is shelfal considering the overlying setting and general shallowing upward trend typical for the Cartwright Formation (*see* Dafoe, Dickie et al., in press). Miller and D'Eon (1987) postulated a possible inner shelf setting, and the transitional to mid-neritic setting of Bujak Davies Group (1989g) is in relative agreement with the present study. This part of the well was found to be Thanetian (Late Paleocene) by Nøhr-Hansen et al. (2016) and demarcates the base of the Cartwright Formation.

(?)Middle shelf

The interval spanning 3787 m to 3677 m includes shale with siltstone and rare limestone intervals. Near the base of the interval is brown argillaceous chert, with rare fractures, and chert inclusions are also present in the over- and underlying shale. Grey shale is brown, silty, and locally marly, with rare pyrite and rare siderite. Dark brown, argillaceous, silty limestone is present, as well as dark brown, argillaceous, slightly sideritic siltstone that includes rare plant remains and rare pyrite.

The chert layer at the base may be related to sourcing of silica from the unnamed basalts, but is likely diagenetic in origin (cf. Friedman, 2003). The silty nature suggests shallowing from the underlying unit to a possible middle shelf setting, but the lack of any fossil material is unusual, perhaps indicating reduced oxygenation or some brackish influence, especially considering the deltaic interpretation of the overlying strata (*see* below). Similar interpretations were made by previous authors: possible inner shelf (Miller and D'Eon, 1987) and transitional to mid neritic (Bujak Davies Group, 1989g). This part of the Cartwright Formation is Thanetian (Late Paleocene) in age based on the findings of Nøhr-Hansen et al. (2016).

Prodelta

A very heterolithic siltstone with shale and sandstone characterizes 3677 m to 3552 m. The dominant lithology is dark brown-grey, argillaceous, partly sandy, partly laminated siltstone that is interbedded with shale, and dolomitic, and includes mica, rare siderite, rare plant remains, and rare coal. Shale units are grey and silty. Sandstones are common at the top of the interval and are brown, very fine- to fine-grained, well sorted, argillaceous, dolomitic, and silty, with subangular clasts, pyrite, and rare very coarse-grained sand grains. This interval has a relatively ragged gamma-ray profile, but shows an overall decrease in API values upward, indicating progradation (Fig. 23).

The lack of fossil material and sandy nature, with suggestion of progradation, is interpreted to indicate a prodeltaic setting. A lack of fossil detritus supports this interpretation, as does the presence of some plant and coal material, the latter indicating shoreline proximity. Miller and D'Eon (1987) gave a similar inner–middle shelf setting and distal deltaic interpretation. In their interpretation, Bujak Davies Group (1989g) reported transitional to middle neritic conditions in reasonable agreement with the present study, but also mid to outer neritic conditions for the top of the interval. This unit forms the top of the Cartwright Formation as defined in the present study at 3552 m (Table 40). Moir (1987c) suggested a second interval of Cartwright Formation above the Gudrid Formation, but Dafoe, DesRoches et al. (in press) restricted the Cartwright Formation to the shalier succession below the Gudrid Formation. Here, the base of the Gudrid Formation is modified slightly from this earlier study to the base of the overlying sandstone-dominated, delta front succession (*see* below), which both lithologically and paleoenvironmentally better aligns with the nature of the Gudrid Formation, rather than the Cartwright (Fig. 23). The age of this prodeltaic interval is Thanetian (Late Paleocene) according to Nøhr-Hansen et al. (2016).

Delta front

A sandstone succession from 3552 m to 3516 m is characterized by brown, very fine- to fine-grained (rare medium-grained), well sorted, laminated, argillaceous, siliceous, micaceous, silty sandstone that is dolomitic at the base of the interval and glauconitic at the top of the interval, with subangular grains, scattered carbonaceous flakes, rare kaolinite at the top of the interval, and rare very coarse-grained sand grains. Similar to the underlying unit, the gamma-ray log is ragged, but shows a coarsening-upward profile (Fig. 23).

The sandy nature with carbonaceous flakes implies a shoreline proximal setting and the lack of fossils with a ragged, but coarsening-upward gamma-ray trend is consistent with a delta front paleoenvironment. A deltaic setting was also proposed by Miller and D'Eon (1987), but Bujak Davies Group (1989g) found mid to outer neritic conditions, possibly as a result of cavings from the base of the overlying Kenamu Formation (*see* below). This part of the well comprises the base of the Gudrid Formation of Thanetian (Late Paleocene) age according to Nøhr-Hansen et al. (2016).

Distributary channel

Spanning the depths of 3516 m to 3484 m is an interval of white to grey, coarse-grained to medium-grained, poorly to moderately sorted sandstone, with subangular to subrounded grains, kaolinite throughout, mica, very coarse-grained sand grains decreasing in prevalence upwards, rare quartz pebbles at the base, pyrite near the top of the interval, and glauconite at the top of the interval. The gamma-ray log exhibits a blocky, but subtle fining-upward succession (Fig. 23).

The gamma-ray log character, fining-upward nature, pebbly base, and presence of kaolinite suggest a near subaerial setting consistent with distributary channels. A similar delta front distributary channel interpretation was postulated by Miller and D'Eon (1987), but Bujak Davies Group (1989g) indicated a much more distal marine, mid to outer neritic setting that is not consistent with the observations described above. This interval forms the top of the Gudrid Formation, refined here to 3484 m based on the definitive log break at that depth (Table 40). As with the underlying intervals, this part of the well was found to be Thanetian (Late Paleocene) in age by Nøhr-Hansen et al. (2016), in general agreement with the lithostratigraphic framework of Dafoe, Dickie et al. (in press). The resulting Gudrid Formation extends from 3552–3484 m.

Inner shelf

An argillaceous, grey, dolomitic siltstone with pyrite and glauconite present throughout is found from 3484 m to 3468 m.

The glauconitic and fine-grained nature suggests transgressive flooding above the underlying deltaic succession and relatively low sedimentation rates (Amorosi, 2003). The prominence of silt implies an inner shelf succession, but the lack of fossil material is atypical and possibly related to the transgressive nature of the strata. The interpretation from the present study is shallower than the mid to outer neritic conditions proposed by Bujak Davies Group (1989g) and significantly shallower than Miller and D'Eon's (1987) bathyal to outer shelf interpretation. A dominance of silt in such distal marine settings is atypical. This thin interval forms the lowermost part of the Kenamu Formation in Ralegh N-18, and Nøhr-Hansen et al. (2016) assigned it a Thanetian (Late Paleocene) age.

Shelfal

The interval from 3468 m to 3371 m includes shale with siltstone increasing in abundance upward. Grey shale is partly silty, with pyrite. Siltstone units are grey, argillaceous, and slightly calcareous, and further contain rare pyrite and rare sand grains.

The fine-grained character, but siltier upwards nature suggests progressive shallowing, but with a consistently high gamma-ray log signature. The lack of fossils may indicate a restricted marine setting, but shelfal is more likely based on the abundance of pyrite and linkage to the underlying transgressive interval. Furthermore, previous studies have found inner to outer shelf or neritic settings in reasonable agreement with the present study (Miller and D'Eon, 1987; Bujak Davies Group, 1989g). Located near the base of the Kenamu Formation, this interval is Thanetian (Late Paleocene) according to Nøhr-Hansen et al. (2016), but an Early Eocene age is also possible (Bujak Davies Group, 1989g).

Estuarine

A heterolithic shale, siltstone, sandstone, and lesser limestone and marlstone interval characterizes the well from 3371 m to 3166 m. Shale dominates the interval and is grey, silty, and sandy, with ironstone fragments, rare ostracod fragments, rare siderite, and rare carbonaceous flakes. Light brown to white, fine- to coarse-grained, well to poorly sorted, locally calcareous, locally siliceous, slightly silty sandstone contains bivalve fragments, subangular to subrounded clasts, localized quartz pebbles, and rare coarse- to very coarse-grained sand grains. Siltstones are grey-brown, argillaceous, and sandy, with rare carbonaceous flakes. Brown, argillaceous, silty, slightly sandy limestone is also present, with rare pyrite. Marlstone is brown and silty, and black coal is found at the very base of the unit. The gamma-ray log confirms a heterolithic character based on the highly ragged profile (Fig. 23).

The overall heterolithic nature and ragged gamma-ray character indicates fluctuating depositional conditions. Rare fossil material, combined with carbonaceous material and coal at the base of the interval is interpreted to reflect a proximal, restricted marine setting. Estuarine conditions are most likely, as there are no indications of progradation, but rather a reduction in sand content upwards. The juxtaposition with shelfal deposition in the underlying interval is unusual, but implies a rapid shallowing. Miller and D'Eon (1987) gave a similar marginal marine lagoonal setting, but also found nonmarine conditions, with lacustrine and alluvial fan delta settings. Nonmarine settings were also interpreted by Bujak Davies Group (1989g), as well as transitional to inner neritic conditions, the latter in good agreement with the present study. This part of the well is from the Kenamu Formation and was found to be Thanetian (Late Paleocene) to Ypresian (Early Eocene) by Nøhr-Hansen et al. (2016).

Estuarine

Between the depths of 3166 m and 2752 m is a brown claystone with increasing siltstone upwards, rare sandstone and limestone beds, and rare green claystone. The brown claystone is silty and locally sandy. Sandstones are light brown, very fine- to medium-grained, well sorted, silty, siliceous, and argillaceous, and include subangular grains, mica, chert grains, pyrite, very coarse-grained sand grains, scattered glauconite, rare feldspar, and rare kaolinite. Limestone is light brown, sandy, silty, and argillaceous. Brown, argillaceous, sandy, locally calcareous, partly laminated siltstone contains mica, rare pyrite, and rare carbonaceous flakes.

The lack of fossils, but silty and sandy nature and laminated to interbedded character suggests continued fluctuating depositional conditions and likely brackish waters. The interval is again interpreted as estuarine, possibly from within the outer reaches of the estuary where marine sands and muds become intermixed (Clifton, 1982). However, Bujak Davies Group (1989g) suggested nonmarine conditions, as did Miller and D'Eon (1987), generally within a lacustrine setting. The inclusion of limestone intervals and proximity to the shallow marine Kenamu Formation strata in the nearby Hekja O-71 well (*see* above) suggests a marginal marine setting is more likely. Within the Kenamu Formation, this interval is Ypresian (Early Eocene) according to Nøhr-Hansen et al. (2016).

Lagoon to marsh

The interval from 2752 m to 2241 m in Ralegh N-18 includes interbedded siltstone and claystone, with sandstone, coal, and abundant carbonaceous flakes throughout. Siltstone units are brown, argillaceous, sandy, and calcareous, with common carbonaceous flakes, coal stringers, and rare pyrite. Brown, silty, sandy claystone includes common carbonaceous flakes. Sandstones are brown, very fine- to coarse-grained, well to poorly sorted, silty, calcareous, and argillaceous, and further incorporate carbonaceous flakes, subangular to subrounded grains, very coarse-grained sand grains near the top of the interval, and rare siderite. Black coal intervals are also present locally. Without specific trends, the gamma-ray log shows a highly ragged character (Fig. 23).

The degree of carbonaceous flakes and coaly horizons suggests a landward proximal setting, but the ragged gamma-ray character does not imply fluvial channel development. The interpretation is thus a lagoon to marsh setting, possibly becoming more enclosed from the underlying estuarine interval. Miller and D'Eon (1987), however, postulated a nonmarine, fluvial setting, and Bujak Davies Group (1989g) also gave a nonmarine interpretation. This interval forms the top of the fine-grained part of the Kenamu Formation. Nøhr-Hansen et al. (2016) gave a Ypresian (Early Eocene) to Lutetian (Middle Eocene) age for this interval.

(?)Bayhead delta

Heterolithic claystone and sandstone with lesser siltstone and dolostone dominates the interval from 2241 m to 2032 m. Claystones are brown, sandy, and silty, with scattered carbonaceous flakes. Light brown, very fine- to coarse-grained and coarsening-upward, well to poorly sorted, argillaceous, silty, locally dolomitic (base of interval) sandstone includes subangular grains becoming subrounded at the top of the interval, very coarse-grained sand grains common in the upper half of the interval, scattered carbonaceous flakes, rare chert grains, rare feldspar, rare quartz pebbles, and rare pyrite. Brown, argillaceous, sandy siltstone further includes carbonaceous flakes. Very rare dolostone is brown, sandy, and silty. Rare black coal is found near the base of the overall interval. The gamma-ray log is ragged in character, but the there is an overall coarsening-upward trend (Fig. 23).

The overall increase in sand content and grain size upward, but ragged gamma-ray log, with carbonaceous and coaly detritus suggests possible bayhead delta progradation. This is in accord with the lack of fossil material suggesting continued brackish conditions. Previous studies indicated nonmarine deposition for this interval, including fluvial, alluvial and delta plain settings (Miller and D'Eon, 1987; Bujak Davies Group, 1989g). Shallow marine strata present in the nearby Hekja O-71 and the underlying estuarine and lagoonal strata suggest that continued shallow marine deposition is more likely. These strata form the base of the Leif Member of the Kenamu Formation, and are Lutetian (Middle Eocene) according to Nøhr-Hansen et al. (2016).

Delta front with distributary channels

Spanning the depths of 2032 m to 1755 m is a thickly bedded sandstone succession with minor claystone and conglomerate units. The overall coarsening-upward sandstones are white to brown or grey, medium- to coarse-grained, poorly sorted, argillaceous, and friable, with subrounded to lesser rounded grains, very coarse-grained sand grains throughout, rare to common quartz pebbles, common dark chert grains at the top of the interval, scattered pyrite, rare dolomite cement, rare pyrite cement, rare chert, rare feldspar, rare siderite, and possible rare glauconite (reported in the well history). Claystones are brown, sandy, and silty, and contain pyrite and minor laminations. Light brown quartz pebble conglomerates are sandy and include pyrite. Overall, the interval has some ragged character, but a coarsening-upward profile, with subordinate coarsening-upward units and lesser fining-upward trends observed the gamma-ray log (Fig. 23).

Rounding of grains suggests significant reworking, and the possible presence of glauconite indicates a plausible marine setting, but this latter component is rare. The general progradational character is, however, interpreted to reflect delta front deposition, possibly with some distributary channel development accounting for the fining-upward trends. In contrast, Miller and D'Eon (1987) indicated nonmarine fluvial or delta plain deposition, and Bujak Davies Group (1989g) indicated only nonmarine deposition. It is unclear why these authors suggested a nonmarine paleoenvironment for much of the Kenamu Formation, but the lack of macrofossils could indicate a highly brackish setting.

This interval caps the top of the Leif Member of the Kenamu Formation as defined in the present study from 2241–1755 m. The sandstones in this delta front interval represent proximal settings in agreement with the paleoenvironmental framework developed for the member (Umpleby, 1979; McWhae et al., 1980; Dafoe, Dickie et al., in press), unlike the overlying succession which is more shelfal (*see* below). Accordingly, the top of the Leif Member is only extended to 1755 m (Table 40), and the delta front interval itself is Lutetian (Middle Eocene) in age according to Nøhr-Hansen et al. (2016). This age is, however, younger than expected for the top Kenamu Formation or Leif Member, which Dickie et al. (2011) and Dafoe, Dickie et al. (in press) placed in the late Bartonian. The Lutetian section of Nøhr-Hansen et al. (2016) is also anomalously thick in Ralegh N-18, and Dafoe, DesRoches et al. (in press) preferred the ages of Nøhr-Hansen (2004) and Bujak Davies Group (1989g) for the top of the Kenamu Formation, Middle–Late Eocene. The Kenamu Formation itself is defined in the present study between 3484 m and 1755 m (Table 40).

Inner shelf

Based by a thin limestone unit, the interval from 1755 m to 1686 m includes one sandier interval in an overall claystone-dominated succession. The limestone is light brown, sandy, and silty. Claystones are brown, sandy, and silty, with pyrite, fossil fragments throughout (indeterminate shell material and bivalve), and siltstone interbeds. Light brown, very fine- to fine-grained, well sorted, argillaceous, silty, calcareous sandstone includes mica, pyrite, subangular grains, rare indeterminate shell fragments, rare carbonaceous flakes, and rare glauconite.

In contrast to the underlying strata, the presence of fossil material and glauconite indicates a definitive marine setting. The grain size of the sandstone is also finer compared to the underlying interval, and coal and carbonaceous material are greatly reduced. Accordingly, this interval is interpreted as inner shelf, which is in good agreement with the marginal marine to inner shelf and transitional to inner neritic settings of previous authors (Miller and D'Eon, 1987; Bujak Davies Group, 1989g). Based on the significant lithological and paleoenvironmental differences between this and the underlying interval, it is considered here to be part of the Mokami Formation, with the base defined at 1755 m (Table 40). The boundary between the Kenamu and Mokami formations is exemplified in the change of character in the resistivity log and subtle decrease in sonic velocity (without considering the log character of the limestone bed). A Lutetian (Middle Eocene) age for these inner shelf strata was given by Nøhr-Hansen et al. (2016), but the Middle–Late Eocene ages of Nøhr-Hansen (2004) and Bujak Davies Group (1989g) are preferred in the present study.

Outer shelf

Between 1686 m and 1660 m is a light grey, silty claystone containing pyrite, scattered fossil fragments (bivalve and indeterminate shell material), and rare carbonaceous flakes.

The claystone notably lacks sand, but is silty with a low diversity fossil assemblage. It is interpreted here to indicate further marine flooding above the Kenamu Formation to an outer shelf paleoenvironment. This deepening was not noted by previous authors, whom reported marginal marine to inner shelf or transitional to inner neritic settings (Miller and D'Eon, 1987; Bujak Davies Group, 1989g). This discrepancy is possibly due to the thin nature of the interval in the cuttings records. This interval forms part of the Mokami Formation, and is Middle–Late Eocene based on the findings of Bujak Davies Group (1989g) and Nøhr-Hansen (2004), an age that is preferred over the Lutetian (Early Eocene) age of Nøhr-Hansen et al. (2016).

Middle to inner shelf

A return to claystone with siltstone and rare limestone and sandstone intervals is noted from 1660 m to 1514 m. Claystones are grey, sandy, and silty, with common fossil fragments throughout (bivalve and indeterminate shell material), sandstone stringers, and rare carbonaceous flakes. Light grey-brown, argillaceous, sandy, micaceous siltstones include pyrite and rare fossil fragments (bivalve and indeterminate shell material). Limestones are light brown, sandy, and silty, and sandstones are light brown, fine- to coarse-grained, and argillaceous, with very coarse-grained sand grains, rare pebbles, and rare indeterminate fossil fragments.

The degree of shell material and sandy nature of the claystone suggests a middle shelf setting shallowing to inner shelf upward. Previous authors found a slightly shallower, marginal marine to inner shelf setting, but did note a deepening near the top of this interval (Miller and D'Eon, 1987; Bujak Davies Group, 1989g). This interval lies at the top of the Mokami Formation and was assigned a Lutetian (Middle Eocene) to Priabonian (Late Eocene) age by Nøhr-Hansen et al. (2016), similar to other biostratigraphic studies. In the present study, the Mokami Formation is assigned to 1755–1514 m, with the upper boundary marked by the prominent lithological break and decrease in gamma-ray log values (Table 40).

(?)Tidal channel

A thin sandstone with a fining-upward gamma-ray log character (Fig. 23) and pebbly base occurs between 1514 m and 1456 m. Light grey, coarse-grained, poorly sorted, carbonaceous sandstone includes very coarse-grained sand grains at the base of the interval, quartz pebbles at the base of the interval, pyrite, subrounded grains, and scattered fossil fragments (bivalve and indeterminate shell material). This sandstone is sharply overlain by fine-grained sandstone that is light brown, well sorted, calcareous, silty, and argillaceous, with common fossil fragments (bivalve, indeterminate shell material, and gastropod), mica, pyrite, subrounded to subangular grains, and granitic fragments. Claystone units at the top of the interval are brown, sandy and silty with common fossil fragments (bivalve and indeterminate shell material).

The abundance and relative diversity of fossil material, combined with the obvious fining-upward profile suggests a marine channel, possibly a tidal channel, but this setting is hard to explain in light of the under- and overlying intervals. This paleoenvironmental interpretation is slightly shallower than the inner shelf settings of previous authors (Miller and D'Eon, 1987; Bujak Davies Group, 1989g). This sandstone interval marks the base of the Saglek Formation, which was interpreted by both Nøhr-Hansen et al. (2016) and Williams (pers. comm., 2018) as Priabonian (Late Eocene). This age is older than generally seen on the Labrador Shelf for the Saglek Formation (*see* Dafoe, Dickie et al., in press), a relationship that was recognized by Dafoe, DesRoches et al. (in press) and explained by the overall shallow nature of the northern part of the Saglek Basin and diachronous nature of the Saglek and Mokami formations (Balkwill and McMillan, 1990).

Lower shoreface

Spanning the depths between 1456 m and 1364 m is an interval of claystone that coarsens upward to sandstone, with an interbedded and heterolithic character. Brown, sandy, silty claystone includes scattered fossil fragments (bivalve, indeterminate shell material, and rare scaphopod). Sandstones are light brown to white and/or yellow, coarsening upward from very fine- to coarse-grained, well to poorly sorted, argillaceous, silty, and calcareous, with common fossil fragments (bivalve and indeterminate shell material), pyrite, very coarse-grained sand grains and chert pebbles increasing in abundance towards the top of the interval, mica, and subrounded grains. Brown siltstone is argillaceous, sandy, and calcareous, with pyrite, and bivalve and indeterminate shell fragments. The gamma-ray log shows an overall coarsening-upward trend, but a heterolithic nature (Fig. 23).

The log character, coarsening-upward trend, and the abundance and reasonable diversity of fossil detritus is interpreted to reflect normal marine conditions within the lower shoreface. Interbedding of sand and claystone may indicate some storm-influence. A lower shoreface setting agrees well with the inner shelf and inner neritic interpretations of both Miller and D'Eon (1987) and Bujak Davies Group (1989g), although the former authors further suggested delta front or open shelf conditions. This part of the Saglek Formation continues to be sandstone-dominated, with an Oligocene age according to Williams (pers. comm., 2018), as well as other studies (Bujak Davies Group, 1989g; Nøhr-Hansen, 2004).

Shoreface

Sandstone with two intervening claystone intervals, one at base and another within the sandstone, characterizes the well from 1364 m to 1194 m. Sandstones are light brown or white to yellow, medium- to mostly coarse-grained, poorly sorted, calcareous, argillaceous, and friable, with subrounded grains, very coarse-grained sand grains throughout, pebbles throughout (some conglomeratic intervals), common fossil fragments throughout (indeterminate shell material and bivalve), mica, rare pyrite, rare glauconite, and rare chert. Light brown claystone is sandy, with rare indeterminate shell and bivalve fragments. In contrast to the underlying strata, this interval has a relatively blocky gamma-ray signature (Fig. 23).

The coarse grain size, blocky gamma-ray signature, and degree of fossil material is most consistent with shoreface deposition. Similar settings were postulated by Miller and D'Eon (1987) including inner shelf to nonmarine with deltaic conditions prevailing. Bujak Davies Group (1989g) also suggested nonmarine to inner shelf settings, in good agreement with the present study. Within the Saglek Formation, this interval is Oligocene to Early Miocene in age according to Williams (pers. comm., 2018).

Shoreface

The uppermost interval in Ralegh N-18 from 1194 m to 795 m is a succession based by a thin claystone unit and dominated by coarse-grained sandstone with some conglomeratic units. The basal claystone is brown and sandy, with rare bivalve fragments. Sandstones are white to yellow, fine- to coarse-grained (mostly coarse-grained), calcareous, argillaceous, and friable, with fossil fragments common in the lower half (bivalve and indeterminate shell material), very coarse-grained sand grains throughout, quartz pebbles throughout, mica, rare glauconite near the top of the interval, and rare wood and coal near the top of the interval. Sand grains are stained red and/or orange locally, and dark and black mineral fragments are also present. Similar to the underlying interval, there is a blocky gamma-ray log character (Fig. 23).

The gamma-ray log profile, lithology, and fossil detritus imply continued shoreface deposition, but this succession may be separated from the underlying interval by a minor marine flooding represented by the basal claystone unit. Fossil material decreases upward as wood and coal become more prevalent, possibly indicating progressive shallowing to an upper shoreface paleoenvironment (Fig. 3). This interpretation agrees well with the inner shelf to nonmarine to marginal marine settings of previous authors (Miller and D'Eon, 1987; Bujak Davies Group, 1989g). This part of the well forms part of the upper Saglek Formation, which is extended here to 692 m at the top of the gamma-ray log; the formation thus extends from 1514–692 m (Table 40). Williams (pers. comm., 2018) gave an age of Early to Middle Miocene for this uppermost shoreface interval.

Lithostratigraphy

Based on the discussion around lithostratigraphic refinements to the framework of Moir (1987c) and Dafoe, DesRoches et al. (in press) in Ralegh N-18, the lithostratigraphic picks from the present study are summarized in Table 40. There are no type or reference sections for this well.

Lithostratigraphic unit	Moir (1987a)		Dafoe, DesRoches et al. (in press)		The present study		Type or reference section
	Base (m)	Top (m)	Base (m)	Top (m)	Base (m)	Top (m)	
Saglek Fm	1515	600	1515	692	1514	692	None
Mokami Fm	1720	1515	1720	1515	1755	1514	None
Kenamu Fm (Leif Mb)	2241	1720	2241	1720	2241	1755	None
Kenamu Fm	3331	1720	3485	1720	3484	1755	None
Gudrid Fm*	3515	3485	3515	3485	3552	3484	None
Cartwright Fm	3833	3331	3833	3485	3833	3552	None
Unnamed basalts*	3858	3833	3858	3833	3858	3833	None

Table 40: Lithostratigraphic assignment for Ralegh N-18 from the present study and compared to that of Moir (1987c) and Dafoe, DesRoches et al. (in press). *Moir (1987c) reported the Gudrid Formation as "Gudrid Tongue" and the unnamed basalts were listed as "Lower Cretaceous Basalt" by Moir (1987c) and "Basalts" by Dafoe, DesRoches et al. (in press). Fm=Formation; Mb=Member.

ROBERVAL C-02

The Roberval C-02 well is located in the southern portion of the Hopedale Basin (Fig. 1). A primary source of lithological information for this well is the well history report by Dungan (1980c), which summarizes cuttings, sidewall core, and conventional core descriptions. The Canadian Stratigraphic Service Ltd. Petro-Canada Roberval C-02 log (log EC-145) provides detailed information that was also compiled for the present study including: lithology, grain size, grain rounding, and sample descriptions. Roberval C-02 is shown in Figure 24 with the key well logs, lithology, grain size, rock colour, ages, and paleoenvironmental and lithostratigraphic information. The biostratigraphic interpretations from Williams (2017b) are used herein. The paleoenvironments from the present study are summarized in Table 41 and compared in the descriptions below with those of Miller and D'Eon (1987) and Doeven and McIntyre (1980), with the latter study presumably basing their interpretations on both the microfossils and palynomorphs that were listed in their study. Williams (2017b) also provided some paleoenvironmental constraints for the well, but these were loosely definitive without full coverage of the well, and somewhat similar to those of Miller and D'Eon (1987). In addition, the lithostratigraphic assignments from the present study are shown and compared against the work of Moir (1989) in both Figure 24 and Table 42.

The base of Roberval C-02 is defined by an interval of unnamed Precambrian basement rock from 2823–2803 m, with the top clearly indicated in the lithology column and sonic velocity, density, and resistivity logs, with notable decreases into the overlying sedimentary section (Fig. 24).

Base (m)	Top (m)	Paleoenvironment
2790	2803	OUTER SHELF
2482	2790	UPPER SLOPE
2196	2482	SHOREFACE
1986	2196	OUTER SHELF TO UPPER SLOPE
1716	1986	MIDDLE TO OUTER SHELF
1690	1716	INNER SHELF
1100	1690	MIDDLE SHELF
706	1100	INNER SHELF
550	706	SHOREFACE

Table 41: Paleoenvironmental determinations for Roberval C-02 from the present study.

Outer shelf

Lying above the Precambrian basement rock is a thin interval from 2803 m to 2790 m composed of dark grey silty and slightly sandy shale, with rare glauconite and rare mica.

The silty nature of the shale is consistent with an outer shelf setting. The lack of fossil material could be explained by the transgressive nature of this interval, and the presence of glauconite supports a period of low sedimentation rates during the onset of flooding (Amorosi, 2003). Miller and D'Eon (1987) also postulated a possible shelf setting or weathered basement interval, but Doeven and McIntyre (1980) indicated a slightly deeper, slope paleoenvironment. These strata form the base of the Markland Formation in the well. The silty shale is Campanian in age according to Williams (2017b).

Upper slope

A relatively homogeneous interval of shale extends from 2790 m to 2482 m and is truncated sharply above by the overlying sandstone (*see* below). The dark grey shale is hard and fissile, with scattered marlstone beds (brown-grey), scattered siderite bands, localized dolomite, rare silt, rare plant remains or carbonaceous material, rare limestone beds, and rare pyrite.

The consistent lithology, general lack of silt and sand, and rare presence of plant or carbonaceous material suggests a distal marine setting consistent with an upper slope-equivalent water depth. Similar slope and bathyal settings were reported by previous authors (Doeven and McIntyre, 1980; Miller and D'Eon, 1987). This interval makes up the remaining portion of the Markland Formation in the well, which is refined in the present study with a top at 2482 m based on the prominent log and lithology change there (Fig. 24; Table 42). Williams (2017d) gave Campanian, early Maastrichtian and Danian (Early Paleocene) ages for this interval with no late Maastrichtian identified, but an interpretation gap is present in his findings, possibly explaining this missing section (Fig. 24).

Shoreface

A prominent sandstone interval is found between the depths of 2482 m and 2196 m. The sandstone is light grey to white, gradually coarsening-upward from fine- to medium-grained to medium-grained, partly argillaceous, silty at the base of the interval, and moderately sorted. In addition, the sandstone is also characterized by subangular grains at the base of the interval, which transition upward to become mostly subrounded. Dolomite cement, feldspar grains, scattered chert grains, rare pyrite, and very rare kaolinite are also present, as well as glauconite throughout the interval, very coarse-grained sand grains throughout, and pebbles (quartz) that increase in abundance upward. The gamma-ray log is slightly ragged to blocky, and the grain size profile shows an upward thickening of beds (Fig. 24).

The overall sharp top and base of the sandstone succession is suggestive of sudden changes in the depositional setting. The grain rounding and general coarsening-upward and sorted nature of the sandstone, with glauconite confirms a shallow marine, shoreface unit that was likely deposited during a forced regression based on the sharp interval boundaries. Miller and D'Eon (1987) explained the presence of sandstone as related to the deposition of turbidite fans and channels with grain flows, and Doeven and McIntyre (1980) suggested slope conditions. Dafoe, Dickie et al. (in press) confirmed the shallow marine nature of the Gudrid Formation sandstones based on various lines of evidence, which is consistent with the interpretation in the present study. This sandstone forms the Gudrid Formation in the well, with a base defined here at 2482 m and the top at 2196 m where there is a decrease in gamma-ray and sonic velocity logs and increase in resistivity values (Fig. 24; Table 42). Whereas Moir (1989) indicated the presence of the upper Gudrid Formation, the present study suggests that both members are present and could be separated by a slight gamma-ray high at about 2310 m (Fig. 24). Williams (2017d) gave an age of Thanetian (Late Paleocene) to early Ypresian (Early Eocene) for these strata.

Outer shelf to upper slope

Shale and claystone dominate the interval from 2196 m to 1986 m. Dark brown shale at the very base of the interval is silty, micaceous, and dolomitic. Dark brown claystone is locally silty and calcareous to dolomitic, with scattered carbonaceous flakes and rare indeterminate shell fragments. Brown limestone and marlstone stringers are also scattered throughout the interval.

The grain size and commonality of carbonate beds, combined with rare terrigenous and fossil material suggests an uppermost slope-equivalent to outer shelf setting. It is unclear why there is not a more diverse and abundant fossil assemblage, especially of foraminifera, as is encountered elsewhere in such settings. Miller and D'Eon (1987) proposed bathyal water depths, while Doeven and McIntyre (1980) gave middle to deep neritic conditions, with the present study within range of these interpretations. This claystone interval forms the base of the Kenamu Formation, and Williams (2017b) indicated an early Ypresian (Early Eocene) to earliest Bartonian (Middle Eocene) age.

Middle to outer shelf

Spanning the interval from 1986 m to 1716 m is dark brown claystone, with lesser siltstone and scattered limestone and dolostone stringers. Claystones are brown, silty, and commonly locally sandy (very fine-grained), with fossil fragments scattered throughout the interval (common indeterminate shell material, common bivalve, and common foraminifera). Brown friable, and sandy siltstone and brown argillaceous limestone and dolostone are also present. The gamma-ray log shows subtle coarsening-upward units, but these are poorly defined (Fig. 24).

The increase in silt and sand relative to the underlying interval suggests shallowing to outer shelf conditions at the base of the interval and to middle shelf at the top of the interval. The mix of shell fragments and foraminifera are further consistent with this interpretation. Similar shallow to deep neritic settings were proposed by Doeven and McIntyre (1980), but Miller and D'Eon (1987) interpreted continued bathyal deposition with turbidites explaining the presence of sandstones. The relatively diverse and abundant fossil assemblage described above is inconsistent with such a distal marine setting, and the coarsening-upward character is atypical for deposits of turbidity currents that tend to fine upward. This interval forms the upper part of the fine-grained portion of the Kenamu Formation, and a Bartonian age was provided by Williams (2017b).

Inner shelf

Interbedded sandstone and siltstone with rare limestone persists in a thin interval from 1716 m to 1690 m. Dark brown siltstone is sandy, argillaceous, partly shaly, friable, and interbedded with sandstone. Sandstone units are brown-grey, very fine-grained, well sorted, argillaceous, friable, and rarely dolomitic, with subangular grains. Brown, sandy, argillaceous limestone caps the overall sandy succession.

The dominance of sandstone and siltstone and their interbedding is suggestive of an inner shelf, possibly lower shoreface setting. The lack of fossil material may also indicate riverine influence and brackish conditions consistent with a distal deltaic conditions. The inner shelf interpretation agrees well with the shallow to middle neritic setting reported by Doeven and McIntyre (1980), but not with the bathyal water depths postulated by Miller and D'Eon (1987). As with the Gudrid Formation, Dafoe, Dickie et al. (in press) confirmed a shallow marine origin for the Leif Member. In the present study, this interval (1716–1690 m) defines the Leif Member of the Kenamu Formation, thus restricting the original designation of Moir (1989; Table 42). The inner shelf interval is also Bartonian in age based on the findings of Williams (2017b). Accordingly, the overall Kenamu Formation extends from 2196 m to 1690 m, in according with the findings of Moir (1989; Table 42).

Middle shelf

Claystone with rare siltstone, dolostone, and limestone beds characterizes the interval from 1690 m to 1100 m. Grey-brown, silty, partly to commonly sandy (very fine-grained), dolomitic claystone includes fossil fragments throughout (indeterminate shell material, foraminifera, and bivalve), rare mica, rare carbonaceous flakes, rare coal, and rare plant remains near the top of the interval. Dark brown limestone and dolostone units are both argillaceous and silty. Siltstones are brown, argillaceous, sandy, and dolomitic, with foraminifera present.

The consistent presence of silt and sand throughout the interval, combined with a relatively diverse and abundant fossil assemblage is suggestive of middle shelf deposition. In general, this setting reasonably agrees with the inner to outer shelf or neritic settings of previous studies, but not with the bathyal depths that were also reported (Doeven and McIntyre, 1980; Miller and D'Eon, 1987). Marking the base of the Mokami Formation in Roberval C-02, this interval is latest Bartonian to Rupelian according to Williams (2017b).

Inner shelf

From 1100 m to 706 m is a sandy, silty claystone interval. Brown claystone is silty and sandy, with scattered very coarse-grained sand grains, common fossil fragments (indeterminate shell material, cephalopod, gastropod, bivalve, and foraminifera), pyrite in the upper portion of the interval, rare carbonaceous flakes, rare sideritized pellets, rare mica, rare quartz pebbles (possible cavings), and rare lignite. Brown, sandy, argillaceous siltstone is rare, as well as brown, argillaceous dolostone.

The fine-grained nature of the interval combined with consistent presence of sand, coarse grains, and the fossil diversity and abundance is interpreted to reflect an inner shelf paleoenvironment. This agrees well with the inner to middle shelf and shallow neritic interpretations of Doeven and McIntyre (1980) and Miller and D'Eon (1987). This succession marks the top of the Mokami Formation, which is defined here at 706 m at the major lithological and log change into the overlying Saglek Formation (Fig. 24). Williams (2017b) gave a Rupelian (Early Oligocene) age for this part of the well.

Shoreface

The uppermost interval in Roberval C-02 from 706 m to 550 m comprises sandstone with lesser siltstone, conglomerate, claystone, and limestone. Sandstones are white, medium- to coarse-grained, poorly sorted, and loosely consolidated to calcite cemented, with mostly subrounded to subangular grains and lesser rounded grains, as well as abundant quartz pebbles, rare chert grains, and rare siderite. Sandy conglomerates are localized, and claystone units bear indeterminate shell fragments, pyrite, mica, and siderite. Brown limestone is sandy, silty, and partly sideritized, with grey-brown sandy siltstone also present. A ragged to blocky gamma-ray log is noted, with coarse-grained strata found at the base of the interval (Fig. 24).

Sandstone units are reasonably blocky and 20–30 m thick, this combined with the grain size and fossil content is consistent with shoreface deposition. The slightly heterolithic character could also indicate some deltaic influence. The interpretation from the present study matches well with the inner shelf or shallow neritic settings of previous workers (Doeven and McIntyre, 1980; Miller and D'Eon, 1987). These sandy deposits form the Saglek Formation, which extends from 706 m to 535 m at the top of the electric logs (Table 42).

Lithostratigraphy

Based on the discussion around lithostratigraphic refinements to the framework of Moir (1989) in Roberval C-02, the lithostratigraphic picks from the present study are summarized in Table 42. There are no type or reference sections for this well.

Lithostratigraphic unit	Moir (1989)		The present study		Type or reference section
	Base (m)	Top (m)	Base (m)	Top (m)	
Saglek Fm	701	375	706	535	None
Mokami Fm	1690	701	1690	706	None
Kenamu Fm (Leif Mb)	1732	1690	1716	1690	None
Kenamu Fm	2196	1690	2196	1690	None
Gudrid Fm (upper)	2483	2196	2482	2196	None
Markland Fm	2803	2483	2803	2482	None
Unnamed Precambrian	2823	2803	2823	2803	None

Table 42: Lithostratigraphic assignment for Roberval C-02 from the present study and compared to that of Moir (1989). Fm=Formation; Mb=Member.

ROBERVAL K-92

Situated near Roberval C-02 in the Hopedale Basin is the Roberval K-92 well (Fig. 1). The well history report for Roberval K-92 by Cadenel et al. (1978) contains information on the cuttings and the report by Total Eastcan Exploration Ltd. (1979b) includes conventional core and sidewall core descriptions, all of which were used in the present study to develop the below interval descriptions. This is in addition to the Canadian Stratigraphic Service Ltd. Total Roberval K-92 log (log EC-132) that provides detailed information regarding the lithology, grain size, and grain rounding, with sample descriptions. Two conventional cores, one from the Bjarni Formation and one from the Markland Formation, were analyzed by Dafoe and Williams (2020a) in terms of both their age and paleoenvironment and form important contributions to the understanding of the adjacent strata. The well plot is shown in Figure 25 with the key well logs, lithology, grain size, rock colour, ages, and paleoenvironmental and lithostratigraphic information. Recent biostratigraphy study by Williams (2017b) is used to constrain the ages in the present study. Paleoenvironments are summarized below in Table 43 and compared below with those of previous studies by Miller and D'Eon (1987) and Ainsworth et al. (2014), with the latter study presumably using both microfossils and palynomorphs as the basis of their interpretations. As with Roberval C-02, Williams (2017b) provided some qualitative and quantitative paleoenvironmental results for this well, but they are quite similar to those of Ainsworth et al. (2014). The lithostratigraphic units are refined in the present study in relation to the original work of Moir (1989) and are shown in Figure 25 and listed in Table 44.

At the very base of the well, the unnamed Paleozoic interval remains unchanged from that of Moir (1989; 3874–3544 m; Table 44). Fenton and Pardon (2007) gave an early Ordovician age, but Bingham-Koslowski et al. (2019) suggested middle to late Ordovician. Lithostratigraphic refinements are made to the top of the Alexis Formation, which is defined here at 3187 m based on both the prominent log and lithological breaks at that depth, with the resistivity log best exemplifying the change from basalts into the overlying sandstones (Fig. 25; Table 44).

Base (m)	Top (m)	Paleoenvironment
3187	3085	DELTA FRONT AND PRODELTA
3085	3056	OUTER SHELF
3056	2679	SLOPE
2679	2356	SHOREFACE
2356	2131	OUTER SHELF
2131	1750	OUTER TO MIDDLE SHELF
1750	1250	MIDDLE SHELF
1250	737	INNER SHELF
737	690	DELTA FRONT

Table 43: Paleoenvironmental determinations for Roberval K-92 from the present study.

Delta front and prodelta

The lowermost Mesozoic-aged sedimentary unit in Roberval K-92 is present from 3187 m to 3085 m and is composed of interbedded sandstone, with lesser shale and siltstone. Sandstones are white to light brown, medium- to coarse-grained, moderately sorted, silty, and argillaceous, with calcite and kaolinite cements, scattered very coarse-grained sand grains, subangular to subrounded grains, feldspar clasts, and thin shale partings. Grey shale is silty, sandy (very fine-grained), and slightly fissile, and grey siltstone is argillaceous and sandy. The gamma-ray log shows relatively high API values for the sandstones, but an overall ragged character is prevalent (Fig. 25).

The heterolithic character of this interval, combined with a coarse grain size, shale partings, and lack of fossil material is taken to indicate delta front to prodeltaic deposition, with prodeltaic conditions likely dominating the finer-grained portions of the interval. This agrees well with the analyses of core 2 (3112.5–3095 m) by Dafoe and Williams (2020a), where they determined a river-influenced delta front setting. For the overall interval, Ainsworth et al. (2014) gave a similar nonmarine to transitional setting, and Miller and D'Eon (1987) postulated nonmarine to marginal marine conditions including a beach or fan delta setting, but indicated shelf conditions for the uppermost part of this interval. The present study's findings appear to agree relatively well with these previous results.

This interval marks the Bjarni Formation in the well as defined in the present study (Table 44). Several changes were made to this lithostratigraphic interval relative to the findings of Moir (1989), including a change to the base of the formation at 3187 m based on the pronounced log breaks described above, although the gamma-ray log is less conclusive since the Bjarni Formation is feldspar-rich giving an anomalously high gamma-ray log value (cf. Umpleby, 1979). The top of the Bjarni Formation is also modified to the top of this interval at 3085 m, thus separating the medium- to coarse-grained sandstones of the Bjarni Formation from the fine-grained, glauconitic sandstone at 3082–3081 m, which is described as part of the overlying Markland Formation (*see* below). Additionally, based on the sandstone-dominated lithology and nature of core 2 (Dafoe and Williams, 2020a), the entire interval is considered to comprise the Bjarni Formation without a Snorri Member as proposed by Moir (1989; Table 44). The age of this interval is Aptian according to Williams (2017b), which reasonably agrees with the early Albian or older age for core 2 (Dafoe and Williams, 2020a).

Outer shelf

A thin sandy and silty shale interval occurs between the depths of 3085 m and 3056 m. The silty dark grey shale is sandy (very fine-grained) at the base of the interval, micaceous, and fissile, with abundant glauconite and rare carbonaceous flakes. A brown thin, interbedded, glauconitic, argillaceous sandstone occurs near the base of the interval, and an argillaceous, glauconitic siderite interval forms the very base of the interval. A fining-upward trend is seen in the corresponding gamma-ray log (Fig. 25).

The decrease in sand content upward, combined with the abundance of glauconite and presence of siderite are typical of transgressive intervals and reducing conditions (Amorosi, 2003; Scholle and Ulmer-Scholle, 2003). Based on this and the fine-grained nature of the strata and lack of fossil content, a distal marine, likely outer shelf setting is interpreted here. Ainsworth et al. (2014) suggested a nonmarine-transitional setting for the very base of the interval, but upper-middle bathyal conditions for the remaining part. The interpretation of Miller and D'Eon (1987) is, however, in better agreement with the present study as they found shelf to outer shelf conditions. Log changes in the gamma-ray, sonic, and resistivity logs separate this interval from under- and overlying strata. This interval marks the base of the Markland Formation, which is picked here at 3085 m, as described above. Williams (2017b) and Nøhr-Hansen et al. (2016) gave Santonian to Campanian ages for this part of the well.

Slope

A thick interval of shale persists from 3056 m to 2679 m. The dark grey, fissile, micro-micaceous, hard shale contains siderite bands, rare limestone, rare pyrite, and extremely rare plant remains.

A homogeneous shale without sand, silt, or fossil content is suggestive of slope-equivalent water depths. This setting was confirmed by Dafoe and Williams (2020a) in their analysis of core 1 (3017–3014 m), which was interpreted to represent an open-ocean, slope-equivalent paleoenvironment. The bathyal water depths postulated by Ainsworth et al. (2014) agree well with the present study, as do the outer shelf to bathyal settings of Miller and D'Eon (1987). This interval forms the bulk of the Markland Formation in Roberval K-92, with the top at 2679 m (Table 44). This interval was assigned Campanian, early Campanian, early Maastrichtian, latest Maastrichtian, and early Danian (Early Paleocene) ages by Williams (2017b). As noted in their study, Dafoe and Williams (2020a) found a most likely early Campanian age for core 1. Within this slope-equivalent interval, parts of the late Campanian and late Maastrichtian may be missing, indicating possible condensed intervals considering the water depth and lack of log or lithological indications of missing section. However, similar unconformities were not noted in other studies (e.g. Nøhr-Hansen et al., 2016; Fig. 25).

Shoreface

Spanning the depths of 2679 m to 2356 m is a prominent sandstone succession. A thick, coarsening-upward sandstone is followed by a thin shale that separates it from the uppermost coarsening-upward sandstone unit, which is also observed in the gamma-ray log, in addition to a general blocky profile (Fig. 25). The sandstones are white to light brown and coarsen upward from medium-to coarse-grained and are moderately sorted, argillaceous, and locally silty. The sandstones contain subrounded grains, feldspar grains throughout, very coarse-grained sand grains and pebbles present throughout the interval, some glauconite at the base of the interval, and rare grey-green chert and kaolinite near the top of the interval.

The blocky gamma-ray character, dominance of sandstone, and rounding of grains supports a shoreface interpretation, but the lack of fossil material is unusual, but possibly related to high-energy upper shoreface conditions. Previous studies have, however, reported contrary paleoenvironments including outer shelf to bathyal or open ocean water depths (Miller and D'Eon, 1987; Ainsworth et al., 2014; Williams, 2017b). Dafoe, Dickie et al. (in press) confirmed the shallow-marine nature of the Gudrid Formation using various lines of evidence. In this well, the Gudrid Formation is characterized by two sandstone units with a shale break dividing the informal lower and upper Gudrid Formation. This interpretation differs from that of Moir (1989), where he suggested that only the upper Gudrid Formation was present (Table 44). Williams (2017b) gave a Thanetian (Late Paleocene) to Ypresian (Early Eocene) age, very similar to the results of Nøhr-Hansen et al. (2016). The sharp base and top of the sandstone interval, shingled seismic character (Dickie et al., 2011), and grain round suggests a forced regressive shoreface with extensive wave reworking.

Outer shelf

A silty claystone is present from 2356 m to 2131 m. Dark brown shale is silty, fissile, and micaceous, with dolomite stringers, siltstone stringers, fossil fragments scattered throughout (foraminifera), rare carbonaceous detritus, and rare very fine-grained sand grains. Brown limestone and dolostone interbeds are argillaceous and silty.

The silty and calcareous nature of the shale with foraminifera is consistent with an outer shelf setting. Miller and D'Eon (1987) and Ainsworth et al. (2014) both found bathyal to upper bathyal conditions, in relative agreement with the present study. Marking the base of the Kenamu Formation, this interval is Ypresian (Early Eocene) to Lutetian (Middle Eocene) in age according to Williams (2017b).

Outer to middle shelf

The interval from 2131 m to 1750 m includes dark brown to grey-brown shale with rare limestone and dolostone beds. Shales are fissile, silty, and locally slightly dolomitic, with limestone stringers, scattered sand grains (very fine-grained), scattered fossil fragments (foraminifera), and rare carbonaceous flakes. Dark brown, argillaceous, silty, and slightly sandy limestone and dolostone intervals are rare.

A slight increase in sand content relative to the underlying interval suggests a progressive shallowing from an outer to middle shelf setting. A fossil suite dominated by foraminifera further agrees with a relatively distal marine setting. However, previous studies only documented bathyal conditions, with turbidite fans possibly explaining the sand content (Miller and D'Eon, 1987; Ainsworth et al., 2014). The integration of sand within the strata, as opposed to discrete horizons is not consistent with turbidite fan accumulations. This part of the well spans the uppermost Kenamu Formation and into the basal Mokami Formation. There is a prominent log break separating the two formations at 1815 m (gamma-ray increase and sonic velocity and resistivity decreases), but there is no definitive lithological or sedimentological break (Fig. 25). Williams (2017b) gave a Lutetian through Bartonian (Middle Eocene) age for this part of the well.

Middle shelf

Within the interval from 1750 m to 1250 m is another succession of both very silty and very sandy claystone. Brown claystone is silty and micaceous, with very fine- to fine-grained sand grains abundant throughout, dolostone stringers, rare fossil fragments (foraminifera), rare medium-grained sand grains, and rare carbonaceous flakes. Very rare brown argillaceous, silty, sandy dolostone and argillaceous, sandy, dolomitic brown siltstone units are also present.

The continued increase in sand content relative to underlying intervals suggests shallowing, but the lack of a diverse fossil suite implies a setting that is no shallower than the middle shelf. This setting is in relative agreement with part of Ainsworth et al.'s (2014) inner–outer neritic assessment and Miller and D'Eon's (1987) middle shelf interpretation, but is slightly shallower than the outer shelf to upper bathyal settings postulated for the lower part of this interval. This part of the Mokami Formation was found to be Priabonian (Late Eocene) to Rupelian (Early Oligocene) based on the findings of Williams (2017b).

Inner shelf

A thick interval spanning 1250 m to 737 m is composed of brown claystone with increasing siltstone and sandstone at the top of the interval and rare limestone. Claystone is silty, micaceous, and slightly dolomitic, with abundant very fine- to medium-grained sand grains, localized shaly units, scattered coarse-grained sand grains, and rare carbonaceous flakes. Brown, dolomitic, argillaceous, sandy siltstones include rare indeterminate shell fragments. Rare brown dolostones and limestones are sandy and argillaceous. Finally, rare sandstones are light brown, coarse-grained, and poorly sorted, containing abundant quartz pebbles and rounded grains.

This interval differs from the underlying strata in the presence of coarse grains and shell fragments that imply continued shallowing into an inner shelf setting. This interpretation agrees well with the inner to middle or inner to outer shelf settings postulated by previous studies (Miller and D'Eon, 1987; Ainsworth et al., 2014). The Mokami Formation is capped by this interval as defined here, where the top is at 737 m at the base of sandstones and limestones forming the overlying Saglek Formation (*see* below), an interpretation that differs slightly from that of Moir (Table 44). Williams (2017b) provided an age of Rupelian (Early Oligocene) to Chattian (Late Oligocene) for these inner shelf strata.

Delta front

Based on the original Canadian Stratigraphic Service Ltd. log (but missing from in the digital version shown in Figure 25), the uppermost interval in Roberval K-92 includes heterolithic sandstone, siltstone, claystone and limestone from 737 m to 690 m. Sandstones are white, medium- to coarse-grained, and poorly sorted, with abundant quartz pebbles, calcite cement, and rounded grains. Siltstones are brown, calcareous, and argillaceous. Limestones are brown, argillaceous, silty, and sandy.

Claystones are brown and silty, with very fine- to medium-grained sand grains. In the gamma-ray log, a ragged character is seen, but with a coarse-grained lithology (Fig. 25).

The grain rounding and coarse-grained nature suggests significant wave reworking, but the prominent interbedding of lithologies is inconsistent with a shoreface setting. Rather, the ragged gamma-ray log character and lack of fossil material is better aligned with a delta front setting. A deltaic or lower shoreface paleoenvironment was interpreted by Miller and D'Eon (1987), and the inner neritic setting of Ainsworth et al. (2014) is also similar to the results from the present study. This interval marks the base of the Saglek Formation in the well and is Chattian (Late Oligocene) according to Williams (2017b). Differing from Moir's (1989) interpretation, the Saglek Formation is defined herein from 737–616 m, with the top marked by the end of the electric log signatures (Fig. 25; Table 44).

Lithostratigraphy

Based on the discussion around lithostratigraphic refinements to the framework of Moir (1989) in Roberval K-92, the lithostratigraphic picks from the present study are summarized in Table 44. There are no type or reference sections in this well.

Lithostratigraphic unit	Moir (1989)		The present study		Type or reference section
	Base (m)	Top (m)	Base (m)	Top (m)	
Saglek Fm	726	340	737	616	None
Mokami Fm	1815	726	1815	737	None
Kenamu Fm	2356	1815	2356	1815	None
Gudrid Fm*	2679	2356	2679	2356	None
Markland Fm	3080	2679	3085	2679	None
Bjarni Fm (Snorri Mb)	3197	3080	--	--	None
Bjarni Fm	3187	3080	3187	3085	None
Alexis Fm	3544	3197	3544	3187	None
Unnamed Paleozoic	3874	3544	3874	3544	None

Table 44: Lithostratigraphic assignment for Roberval K-92 from the present study and compared to that of Moir (1989). *Moir's (1989) Gudrid Formation was indicated as the informal upper member. Fm=Formation; Mb=Member.

RUT H-11

Located in both a landward proximal and northerly position in the southern part of the Saglek Basin is the Rut H-11 well (Fig. 1). The lithological information for this well is derived from a series of three well history reports. The well was initially drilled in 1981 and cuttings are described for the interval from 3528 m to 670 m in Duff (1981c). In 1982, a sidetrack was drilled and Steeves (1983c) reported on cuttings from 4093 m to 2377 m. Finally, in 1983, the well was completed with both sidewall core and cuttings descriptions for 4470–4090 m included in Steeves (1983d) and used in the present study as well. The Canadian Stratigraphic Service Ltd. Petro-Canada Rut H-11 log (log EC-179) further provides extensive information for the well including the lithology, grain size, and grain rounding, as well as sample descriptions. Figure 26 depicts the well plot with key well logs, lithology, grain size, rock colour, ages, and paleoenvironmental and lithostratigraphic information. The biostratigraphic constraints from Nøhr-Hansen et al. (2016) are used in the present study, which are closely based on Fensome (2015). The paleoenvironments from the present study are summarized in Table 45 and shown in Figure 26, and are compared in the text below with Miller and D'Eon (1987) and Bujak Davies Group (1989h), with the latter study based on microfossils. Moir (1989) developed an initial lithostratigraphic framework based on the data available at the time. In the present study, the lithostratigraphy is revised, with some substantial changes shown on the well plot (Fig. 26) and in Table 46.

Base (m)	Top (m)	Paleoenvironment
4473	4451	IGNEOUS SILL
4451	4432	ALTERED SEDIMENTARY ROCK
4432	4362	DELTA FRONT
4362	4316	PRODELTA
4316	4263	DELTA FRONT
4263	4080	PRODELTA
4080	4045	DISTAL DELTA FRONT
4045	3993	OUTER SHELF
3993	3667	MIDDLE SHELF
3667	3591	INNER SHELF
3591	3100	MIDDLE TO OUTER SHELF
3100	2550	MIDDLE SHELF
2550	2428	INNER SHELF
2428	2275	OUTER SHELF
2275	1975	MIDDLE SHELF TO PRODELTA
1975	1916	DELTA FRONT
1916	1657	PRODELTA
1657	1385	DISTAL DELTA FRONT
1385	1154	DELTA FRONT
1154	1049	DELTA FRONT
1049	670	DELTA FRONT

Table 45: Paleoenvironmental determinations for Rut H-11 from the present study.

Igneous sill

A thin interval at the base of Rut H-11 from 4473 m to 4451 m is described as light to medium green and grey-green and medium- to coarse-grained crystalline rock. Minerals within this interval include green, brown, and black (possible feldspar, olivine, mica, pyroxene, and quartz), with possible talc, chlorite, and serpentine. The interval possesses an overall high velocity and high resistivity that contrasts with the overlying rocks (Fig. 26).

This interval was described as unnamed by Moir (1989) and is here refined to an unnamed sill. Keen et al. (2018b) confirmed the presence of an extensive sill complex in the region of Rut H-11 based on seismic interpretation, and the mineralogical composition would agree with a diabase sill with talc, chlorite, and serpentine likely related to alteration of surrounding rocks during contact metamorphism. Miller and D'Eon (1987) suggested a dyke or flow, with the former in agreement with the interpretation from the present study. Steeves (1983d) indicated a possible basalt or dolerite (diabase) and gave a tentative Early Paleocene age.

Altered sedimentary rock

Overlying the sill from 4451 m to 4432 m is an interval composed of white to light grey, silty, soft tuffite, with calcite veining, black specs ((?)minerals) that often form a cross shape or two parallel lines, possible bentonite, and pyrite. The interval has moderate to low gamma-ray values that resemble the overlying sandstone-dominated interval (*see* below; Fig. 26).

Since there is a diabase sill below this interval, it is unlikely that there would be subaerial tuff or pyroclastic material at this depth in the well. Resistivity and porosity log values resemble the overlying sedimentary rock and further imply a non-igneous origin. The black mineral described in the well reports could be staurolite which twins at 60–90 degrees, indicating metamorphic alteration, but the development of this mineral is beyond the metamorphic grade normally encountered with contact metamorphism. The silty nature of the interval suggests sedimentary origin, so the interval is interpreted as an altered portion of sedimentary rock, likely a sandstone-dominated succession. Miller and D'Eon (1987) did not provide a definitive paleoenvironmental interpretation for this interval (Fig. 26).

The base of the Markland Formation and Freydis Member are demarcated by this interval (Table 46). While Moir (1989) did not pick a Freydis Member, the character of the sandstones in the lower part of Rut H-11 closely resemble the Freydis Member of the nearby Gilbert F-53 well (*see* above). Despite the relatively shaly nature of the interval, the shallow marine depositional settings (*see* below) fit well with that of the Freydis Member (*see* Dafoe, Dickie et al., in press). However, the age of this particular interval is unclear, possibly due to poor palynomorph preservation associated with alteration.

Delta front

Spanning the depths of 4432 m to 4362 m is a thickly bedded silty sandstone to silty and sandy shale, with lesser siltstone. Shales are grey, silty, and sandy, with siltstone partings, pyrite throughout, and scattered quartz grains. Grey, argillaceous, slightly siliceous siltstone contains pyrite throughout. Sandstones are light brown to mostly grey, very fine-grained, well sorted, silty, friable, and rarely calcareous, with subangular grains, pyrite throughout, and trace feldspar. The gamma-ray log shows sandstone units with generalized coarsening-upward patterns, but an overall heterolithic character (Fig. 26).

The log character, combined with a lack of fossil material is taken to indicate delta front progradation. The lack of plant detritus or coal is unusual, however. Miller and D'Eon (1987) gave a much deeper, possible shelf or bathyal setting with turbidites explaining the sandstone accumulation. However, turbidite deposits tend to be fining-upward as current strength wanes, which is opposite to the trends noted here. This interval falls within the Freydis Member of the Markland Formation based on the assessments in the present study and the sandstone-dominated nature of the strata. Recent biostratigraphic studies have been, however, unable to provide ages at this depth in the well (e.g., Nøhr-Hansen et al., 2016).

Prodelta

Interbedded shale and siltstone characterize the interval from 4362 m to 4316 m. Shales are grey, sandy, and silty, with siltstone stringers. Grey, argillaceous, micaceous siltstones include rare pyrite.

The Interbedded nature of the siltstone and shale, with sand grains present and a lack of fossil material is interpreted to reflect a prodeltaic setting. A possible shelf to bathyal setting was proposed by Miller and D'Eon (1987), but this does not agree with the interbedding seen here and locally sandy nature of the shale. This finer-grained interval sits between sandier intervals of the Freydis Member of the Markland Formation. There are no modern age assignments for this part of the well (e.g., Nøhr-Hansen et al., 2016).

Delta front

The interval covering 4316 m to 4263 m is composed of sandstone, shale, and lesser siltstone in an interbedded succession that is overall coarsening upward. Sandstone units are grey, very fine- to fine-grained, well sorted, argillaceous, silty, and friable, with feldspar throughout and subangular grains. Grey, sandy, silty shales contain sandstone stringers, pyrite, and rare ironstone. Grey siltstones are argillaceous, sandy, and micaceous. The gamma-ray profile shows a clear coarsening-upward trend, but also ragged character (Fig. 26).

The rough coarsening-upward trend, but heterolithic nature suggests delta front deposition. This is confirmed by a lack of fossils detritus, and the dominance of feldspar suggests an immature nature to the sandstone and relatively rapid sedimentation rates. Similar to the underlying intervals, Miller and D'Eon (1987) gave a much deeper, shelf to bathyal setting, with turbidites explaining the presence of sandstones. The coarsening-upward nature, however, again confirms progradation rather than turbidity current deposition, which wanes over time and results in a fining-upward succession. This interval caps the top of the Freydis Member of the Markland Formation as defined in the present study from 4451–4263 m (Fig. 26; Table 46). No recent ages were given for this delta front interval (e.g., Nøhr-Hansen et al., 2016).

Prodelta

Shale with siltstone units characterizes the interval from 4263 m to 4080 m, with one part of the interval containing thin sandstone and limestone units. Grey shales are silty, with rare siltstone stringers and rare glauconite. Siltstones are grey-brown, argillaceous, and locally sandy, with rare glauconite occurring in units located adjacent to the sandstone unit. Brown, argillaceous, silty, glauconitic sandstone is present, as well as brown, argillaceous, sandy, and silty limestone. Rare indeterminate shell material and foraminifera are found at the base of the interval.

The silty nature of the shale suggests possible shelfal conditions, but the lack of fossils and interbedding of siltstone and shale is more characteristic of a prodeltaic setting. The fossils at the base of the interval could indicate the onset of a minor marine flooding event. The proposed prodeltaic setting is in contrast to the possible shelfal to bathyal water depths postulated by Miller and D'Eon (1987); however, Bujak Davies Group (1989h) reported a similar inner to middle neritic setting that is comparable with the present study.

This interval forms part of the Markland Formation, with the uppermost part being assigned a Thanetian (Late Paleocene) age by Nøhr-Hansen et al. (2016). This age is, however, younger than expected for the Markland Formation according to McWhae et al. (1980), Dickie et al. (2011) and Dafoe, Dickie et al. (in press). The overall thickness of the Thanetian section and uncertain age at the base of the well questions the validity of the age assignment for the uppermost Markland Formation, especially considering that few palynoevents constrain the lower part of this age assignment (*see* Nøhr-Hansen et al., 2016).

Distal delta front

Between the depths of 4080 m and 4045 m is sandy shale and lesser sandstone interval. Grey shales are sandy and silty, with rare pyrite and fossil fragments at the top of the interval (bivalve and foraminifera). Sandstones are grey, very fine- to fine-grained, well sorted, argillaceous, and silty, with feldspar and subangular grains. A ragged gamma-ray log character confirms the heterolithic nature of the strata (Fig. 26).

The overall character of the succession resembles the underlying sandy shales and sandstones. The lack of fossil material suggests deltaic deposition, but within a distal delta front setting considering the dominance of shale over sandstone. The inner-middle neritic setting of Bujak Davies Group (1989h) is compatible with the interpretation of the present study, but Miller and D'Eon's (1987) bathyal interpretation doesn't appear to agree with the observations described above. Also within the Markland Formation, this sandy shale is Thanetian (Late Paleocene) based on the findings of Nøhr-Hansen et al. (2016), although the age is somewhat suspect as described for the underlying interval (*see* above).

Outer shelf

From 4045 m to 3993 m is a grey, partly silty shale, with fossil fragments throughout (bivalve) and rare pyrite. The logs are defined by a high gamma-ray signature and low resistivity (Fig. 26).

The fine-grained nature of the strata, but presence of fossil material suggests an outer shelf setting, which is consistent with the clean shale indicated by the logs. This interpretation agrees well with the inner to outer neritic settings of Bujak Davies Group (1989h), but is slightly shallower than the bathyal interpretation of Miller and D'Eon (1987). This interval caps the top of the Markland Formation as refined in the present study at 3993 m, which is considerably deeper in the well than that of Moir (1989; Fig. 26; Table 46). However, an increase in both the sonic velocity and resistivity logs at this depth is consistent with the Markland to Cartwright Formation boundary seen in other wells along the margin (Fig. 26). This part of the well is considered to be Thanetian (Late Paleocene) by Nøhr-Hansen et al. (2016). As with the immediately underlying intervals, a Thanetian age for the Markland Formation is younger than typically encountered for this formation. Accordingly, the Early Paleocene age of Bujak Davies Group (1989h) is preferred for this interval.

Middle shelf

Shale with common siltstone interbeds and rare thin sandstones persists from 3993 m to 3667 m. Grey shales are partly silty, with fossil fragments scatted to common (bivalve and foraminifera), rare pyrite, and rare sand grains. Brown-grey, argillaceous, locally sandy, rarely micaceous siltstones contain scattered fossil fragments (bivalve and foraminifera) and rare pyrite. Brown-grey, argillaceous, silty sandstones are rare.

The silty nature of the shale and common presence of bivalve and foraminiferal fossil material suggests a middle shelf setting, with a subtle overall shallowing upward trend. Bujak Davies Group (1989h) interpreted a similar middle to outer neritic setting, but Miller and D'Eon (1987) proposed bathyal water depths that are inconsistent with the observations described above. This interval marks the base of the Cartwright Formation as modified in the present study (Table 46). The decrease in gamma-ray values and higher resistivity compared to the underlying Markland Formation is taken to mark the lithostratigraphic boundary, similar to the boundary seen in Karlsefni A-13 (*see* above). Nøhr-Hansen et al. (2016) gave a Thanetian (Late Paleocene) age for this section of the well, but an older Early Paleocene age could also be possible (Bujak Davies Group, 1989h).

Inner shelf

Shale with siltstone and rare sandstone beds occurs between the depths of 3667 m and 3591 m. Grey shales are sandy and silty, and further contain fossils throughout (foraminifera and bivalve), glauconite locally throughout, rare coal fragments, rare pyrite, coal stringers near the top of the interval and rare trace fossils at the top of the interval. Sandstones are grey argillaceous, silty, and friable. Grey to brown, argillaceous, sandy siltstones include carbonaceous flakes, glauconite, and rare mica.

The increase in sand grains, evidence of bioturbation, and presence of carbonaceous and coal detritus suggests shallowing to an inner shelf paleoenvironment. While sandy, the succession is not proximal enough to be considered part of the Gudrid Formation sandstones, as noted in other nearby wells. Both Bujak Davies Group (1989h) and Miller and D'Eon (1987) gave outer neritic to bathyal water depths, that do not agree with the evidence presented above. Within the Cartwright Formation, this sandy shale is Thanetian (Late Paleocene) according to Nøhr-Hansen et al. (2016), but an Early Paleocene age could also be possible (Bujak Davies Group, 1989h).

Middle to outer shelf

The interval from 3591 m to 3100 m is composed of a succession of mostly shale with occasional siltstone, limestone, and very rare marlstone and sandstone beds. Grey locally silty shales include common fossil fragments throughout (foraminifera, bivalve, rare ostracod, rare gastropod, and rare brachiopod), siderite stringers, nodules locally common throughout the interval, locally common glauconite, rare carbonaceous and coal fragments (possibly reworked from the underlying interval), rare trace fossils, and pyrite common in the upper half of the interval. Siltstones are grey and argillaceous, with rare glauconite. Light brown, argillaceous, silty, calcareous sandstone is present, as well as brown, argillaceous limestones and brown marlstones, with rare foraminifera.

The fine-grained nature of the lithology, commonality and diversity of fossils, and prevalence of siderite and glauconite suggests a middle to outer shelf setting and relatively low sedimentation rates. This is slightly shallower than the bathyal to upper bathyal settings of Bujak Davies Group (1989h) and Miller and D'Eon (1987). This thick interval spans the upper Cartwright Formation and into the lower Kenamu Formation, with no definitive lithological break between the two units. However, the shale at the top of the interval (3166–3100 m) marks a thick unit with a paucity of siltstone that could demarcate outer shelf flooding at the base of the Kenamu Formation. Accordingly the top of the Cartwright Formation is placed at 3166 m where there is a change in the sonic velocity and resistivity log character, with the formation base at 3993 m (Table 46). Nøhr-Hansen et al. (2016) gave an age of Thanetian (Late Paleocene) for these middle to outer shelf strata, in good agreement with the regional understanding of the Cartwright Formation (Dafoe, Dickie et al., in press).

Middle shelf

Between the depths of 3100 m and 2550 m is a thick interval of shale with common siltstone interbeds and rare limestone. Shales are brown-grey and silty, and contain siltstone stringers, common fossil fragments throughout (foraminifera, bivalve, ostracod, and gastropod), locally common ironstone, localized pyrite, rare bioturbation, and rare carbonaceous flakes. Siltstone units are dark brown and argillaceous, with scattered fossil fragments (foraminifera and bivalve), rare pyrite, rare sand grains, and rare carbonaceous flakes. Brown, argillaceous limestones, with rare foraminifera and bivalve fragments are rare.

The increase in silt content relative to the underlying interval, the diversity and abundance of fossil material, and the presence of rare carbonaceous material suggest shallowing to a middle shelf paleoenvironment. Despite this interpretation and the evidence presented above, both Miller and D'Eon (1987) and Bujak Davies Group (1989h) suggested bathyal or upper bathyal settings. Such distal marine settings are atypical for the upper part of the Kenamu Formation (Balkwill and McMillan, 1990; Dafoe, Dickie et al., in press). This interval makes up much of the Kenamu Formation and is Thanetian (Late Paleocene) to Priabonian (Late Eocene) in age according to Nøhr-Hansen et al. (2016), although the top of the interval ending in the Middle Eocene (Bujak Davies Group, 1989h) is preferred in the present study.

Inner shelf

Sandy claystone with siltstone and sandstone interbeds characterizes the well from 2550 m to 2428 m. Brown claystone is sandy and silty, and includes common fossil fragments throughout (bivalve and belemnite-like fragments), scattered carbonaceous flakes throughout, and occasional sandstone stringers. Sandstone units are brown, very fine-grained, well sorted, argillaceous, and silty, with bivalve fragments, mica, carbonaceous flakes, and subangular grains. Brown siltstone units are sandy and argillaceous. The gamma-ray log shows a blocky unit with low resistivity (Fig. 26).

The increase in sand content relative the underlying strata, abundance of fossils, and presence of carbonaceous flakes implies inner shelf conditions. The gamma-ray log values are relatively high, but the low resistivity could indicate a tight, well-cemented sandy interval. Previous studies, however, reported bathyal or upper bathyal conditions (Miller and D'Eon, 1987; Bujak Davies Group, 1989h) that do not agree well with the evidence presented above. Several authors have confirmed the shallow marine nature of the Leif Member of the Kenamu Formation (Umpleby, 1979; McWhae et al., 1980; Dafoe, Dickie et al., in press), which agrees with the finding herein. In the present study, this interval is taken to indicate a distal expression of the Leif Member, thus increasing the thickness of the member slightly from that defined by Moir (1989) to range from 2550–2448 m (Table 46). A Lutetian–Bartonian (Middle Eocene) to Priabonian (Late Eocene) age was reported by Nøhr-Hansen et al. (2016), although the Middle Eocene age of Bujak Davies Group (1989h) is preferred here. With the modification to the Leif Member, the Kenamu Formation is now suggested to extend from 3166 m to 2428 m, with the overlying Kenamu Formation shales of Moir (1989) now retained within the Mokami Formation (Table 46; *see* below).

Outer shelf

From 2428 m to 2275 m is a shale to claystone succession with rare siltstone and limestone interbeds. Claystones are brown and locally silty, with rare pyrite, fossil fragments throughout (bivalve, indeterminate shell material, and foraminifera), and rare carbonaceous flakes. Dark brown, argillaceous, silty limestone includes rare pyrite, and brown, argillaceous siltstone, with mica and rare pyrite also present.

The fossil content and lithology are consistent with outer shelf deposition, especially the lack of sand grains, but the degree of bivalve and shell material is unusual for such a distal marine setting. This is slightly shallower than the upper bathyal to bathyal settings of Miller and D'Eon (1987) and Bujak Davies Group (1989h), but these authors indicated a shallowing to outer shelf or outer neritic conditions near the top of this interval.

This finer-grained interval marks the base of the Mokami Formation as defined in the present study. Moir (1989) placed an interval of Kenamu Formation rocks above the Leif Member. However, following the framework of Dickie et al. (2011) and Dafoe, Dickie et al. (2011), transgressive flooding occurs at the base of the Mokami Formation and suggests that this part of the well (2428–2331 m) should be included in that formation. There is a significant sonic velocity decrease at the top of Moir's (1989) Kenamu Formation (Fig. 26), but the overall change in log character at 2428 m is more suggestive of the lithostratigraphic break. This outer shelf interval was found to be Lutetian–Bartonian (Middle Eocene) to Priabonian (Late Eocene) by Nøhr-Hansen et al. (2016).

Middle shelf to prodelta

From 2275 m to 1975 m are strata composed of claystone with siltstone and lesser sandstone and limestone interbeds. Grey-brown, silty, sandy throughout claystones include locally common fossil fragments that decrease in abundance upwards (indeterminate shell material, foraminifera, bivalve, and scaphopod). Siltstones are brown, argillaceous, sandy, and micaceous, with rare fossil fragments (foraminifera). Marlstone and limestone units are dark brown, sandy, silty, and argillaceous. Brown sandstones are very fine-grained, argillaceous, silty, locally dolomitic, and well sorted, with subangular grains. The gamma ray-log shows an overall coarsening-upward trend, but with a very ragged (heterolithic) character (Fig. 26).

The increase in sand content relative to the underlying interval and fossil diversity and abundance suggests a middle shelf setting, but the reduction in fossil material upwards can be attributed to prodeltaic influence. A prodeltaic setting further agrees well with the ragged and progradational gamma-ray log profile. The interpretation from the present study conforms well with that of Miller and D'Eon (1987) where they interpreted outer shelf to inner–middle shelf (prodeltaic) conditions, and similar settings were proposed by Bujak Davies Group (1989h). As part of the Mokami Formation, this sandy and silty claystone interval is Lutetian–Bartonian (Middle Eocene) to Rupelian (Early Oligocene) in age based on the findings of Nøhr-Hansen et al. (2016).

Delta front

Spanning the section of Rut H-11 from 1975 m to 1916 m is a heterolithic sandstone, claystone and siltstone interval. Brown-grey, sandy, silty claystones include rare bivalve fragments. Sandstones are light brown, very fine- to coarse-grained (mostly coarse-grained), poorly sorted, argillaceous, dolomitic, silty, and friable, and further contain very coarse-grained sand grains scattered throughout, coal stringers, and subrounded grains. Brown-grey, argillaceous siltstone includes carbonaceous flakes. In the gamma-ray profile, three generally coarsening-upward intervals are observed (Fig. 26).

The coarsening-upward and heterolithic nature of the strata, lack of fossils, presence of coaly material, and coarse-grained lithology are interpreted to represent a delta front setting. Miller and D'Eon (1987) proposed a similar deltaic to interdeltaic settings and Bujak Davies Group (1989h) also found the setting to be transitional to middle neritic, in reasonable agreement with the present study. This sandier interval is part of the Mokami Formation, and a Rupelian (Early Oligocene) age was assigned by Nøhr-Hansen et al. (2016).

Prodelta

A claystone with interbedded siltstone persists from 1916 m to 1657 m. Grey silty claystones are characterized by localized carbonaceous flakes, a prominent coal interval, rare plant remains, and rare bivalve and indeterminate shell fragments. Siltstones are brown-grey, argillaceous, micaceous, and friable, with rare carbonaceous flakes. Dark brown, argillaceous, silty limestone units are very rare.

The overall lack of sand, but continued heterolithic character suggest a relatively distal marine setting, but the lack of fossils implies environmental stress likely related to prodeltaic deposition. This interpretation is consistent with the presence of coaly and plant detritus. Bujak Davies Group (1989h) gave a similar transitional to middle neritic setting, and Miller and D'Eon (1987) indicated possible nonmarine to inner shelf conditions including deltaic and restricted embayment or lacustrine facies. In general, these previous interpretations agree well with the present study. This part of the Mokami Formation was found to be Rupelian (Early Oligocene) in age by Nøhr-Hansen et al. (2016).

Distal delta front

The interval from 1657 m to 1385 m is composed of silty and sandy claystone with common siltstone interbeds and rare sandstone and limestone units. Claystones are grey, silty, and sandy throughout, with rare coal stringers and rare fossil fragments (bivalve). Grey, argillaceous, micaceous, partly sandy siltstones are common. Brown-grey sandstones are very fine-grained, well sorted, argillaceous, and silty and include subangular grains. Limestone is brown, sandy, silty, and argillaceous.

The heterolithic character, increase in sand content relative to the underlying interval, and lack of fossil abundance or diversity is taken to indicate distal delta front deposition. Bujak Davies Group (1989h) gave a transitional to middle neritic interpretation, and Miller and D'Eon (1987) postulated marginal marine to inner shelf paleoenvironments including deltaic, interdeltaic, and distributary bar settings. Accordingly, the results of previous studies appear to agree well with the present interpretation. This interval defines the top of the Mokami Formation as indicated in the present study (Table 46). Moir (1989) brought the Mokami Formation higher in the well to 1322 m, but the first major sandstone unit and significant decrease in gamma-ray values are taken to mark the base of the overlying Saglek Formation at 1385 m (Fig. 26). Nøhr-Hansen et al. (2016) gave a Rupelian (Early Oligocene) age for this distal delta front interval.

Delta front

The strata found between the depths of 1385 m and 1154 m include coarsening- and cleaning-upward sandstones with heterolithic claystone units (one part of the interval contains no data; Fig. 26). Sandstones are light grey, fine- to coarse-grained (mostly coarse-grained), poorly sorted, argillaceous, and silty. These rocks further contain quartz pebbles and very coarse-grained sand grains throughout, localized chert grains scattered to locally common, pyrite cement, subrounded grains, chert pebbles, fossil fragments common throughout (bivalve), rare feldspar, and rare coal and wood fragments. Grey claystones are sandy and silty, with siderite nodules, fossil fragments increasing in abundance upward (bivalve), sandstone stringers, coal stringers, wood fragments, and rare pyrite. Rare brown limestone is sandy. A roughly coarsening-upward gamma-ray profile is noted, but the overall character is ragged (Fig. 26).

The coarse grain size, low fossil diversity, presence of coal and wood, and heterolithic nature is indicative of a delta front setting. The gamma-ray profile implies heterogeneity and progradation, further supporting a delta front interpretation. A deltaic setting was also reported by Miller and D'Eon (1987) including distributary bars and channels, and the transitional to middle neritic interpretation of Bujak Davies Group (1989h) is also in general agreement with the findings of the present study. This succession forms the base of the Saglek Formation, and Nøhr-Hansen et al. (2016) provided a Rupelian (Early Oligocene) age.

Delta front

Spanning 1154 m to 1049 m is another coarsening-upward unit from claystone to dominantly sandstone with some interbedded claystone units. Light grey sandstones are medium- to coarse-grained, poorly sorted, and argillaceous, and further contain very coarse-grained sand grains and quartz pebbles throughout, common fossil fragments throughout (bivalve), common chert fragments, subrounded grains, and rare feldspar. Claystones are grey and sandy, with fossil fragments throughout (bivalve) and wood fragments also present. A coarsening-upward trend with a ragged character is seen in the gamma-ray log (Fig. 26).

The heterolithic nature, log character, and low fossil diversity indicates continued delta front deposition. A shalier break at the base of this interval implies a slight marine flooding of the underlying interval. Miller and D'Eon (1987) gave a similar deltaic interpretation, and the transitional to middle neritic settings of Bujak Davies Group (1989h) somewhat agrees with the present study's findings. The sandy nature of this interval again places it within the Saglek Formation, with a latest Rupelian (Early Oligocene) to Chattian (Late Oligocene) age according to Nøhr-Hansen et al. (2016).

Delta front

The uppermost interval in Rut H-11 from 1049 m to 670 m comprises an overall coarsening- and cleaning-upward sandstone with interbedded claystones. Light grey to white sandstones are mostly coarse-grained and argillaceous, with very coarse-grained sand grains and quartz pebbles throughout, common fossil fragments throughout (bivalve), rare chert, and rare feldspar. Grey sandy claystone includes coal stringers, sandstone stringers, fossil fragments throughout (bivalve and indeterminate shell material), rare carbonaceous flakes, and rare ironstone. Rare brown, sandy, bivalve-bearing limestone is present, as well as sandy conglomeratic beds at the very top of the interval that contain quartz, igneous, and limestone pebbles, with rare bivalve fragments. The gamma-ray log illustrates the ragged (heterolithic) character, but with some subtle coarsening-upward trends (Fig. 26).

The heterolithic lithology, indication of progradation, low fossil diversity, and coarse-grained nature is again interpreted as representing a delta front setting. The presence of relatively common fossil material may indicate that it is a wave-dominated delta where wave-action mitigated the environmental stresses associated with fluvial discharge (Bhattacharya, 2010). As with the underlying intervals, Miller and D'Eon (1987) proposed deltaic settings and Bujak Davies Group (1989h) gave a transitional to middle neritic paleoenvironment, both in reasonable agreement with the present study. This upper part of the Saglek Formation is Chattian (Late Oligocene) to Middle Miocene and late Neogene in age according to Nøhr-Hansen et al. (2016).

Lithostratigraphy

Based on the discussion around lithostratigraphic refinements to the framework of Moir (1989) in Rut H-11, the lithostratigraphic picks from the present study are summarized in Table 46. There are no type or reference sections in this well.

Lithostratigraphic unit	Moir (1989)		The present study		Type or reference section
	Base (m)	Top (m)	Base (m)	Top (m)	
Saglek Fm	1322	249	1385	648	None
Mokami Fm	2331	1322	2428	1385	None
Kenamu Fm (Leif Mb)	2544	2440	2550	2428	None
Kenamu Fm	3125	2331	3166	2428	None
Cartwright Fm	3620	3125	3993	3166	None
Markland Fm	4451	3620	4451	3993	None
Markland Fm (Freydis Mb)	--	--	4451	4263	None
Unnamed sill*	4473	4451	4473	4451	None

Table 46: Lithostratigraphic assignment for Rut H-11 from the present study and compared to that of Moir (1989). *The unnamed sill was indicated as an "Unnamed" unit by Moir (1989). Fm=Formation; Mb=Member.

SKOLP E-07

The Skolp E-07 well is found in a landward proximal setting at the southern end of the Saglek Basin (Fig. 1). Key lithological information was derived from the well history report by Prim et al. (1978) including cuttings, sidewall core, and conventional core descriptions. However, the Total Skolp E-07 log (log EC-129) from Canadian Stratigraphic Service Ltd. includes additional detailed information on the lithology, grain size, and grain rounding, with sample descriptions. The seven cores of the well were assessed by Dafoe and Williams (2020a) in terms of their age and paleoenvironments of deposition and provide vital information for interpreting adjacent section in the well. The well plot is shown in Figure 27 and includes key well logs, lithology, grain size, rock colour, ages, and paleoenvironmental and lithostratigraphic information. In the present study, the biostratigraphic framework of Dafoe and Williams (2020b) is used, and the paleoenvironments determined in the present study are shown here and summarized in Table 47. The paleoenvironmental results are also compared in the descriptions below with those of Miller and D'Eon (1987) and of Dafoe and Williams (2020b), with the latter study relying on palynomorphs. The lithostratigraphy of Skolp E-07 was developed as part of the regional framework of Moir (1989) and was subsequently revised by Dafoe and Williams (2020b). In the present study, we further modify this work as shown in the well plot and in Table 48.

The base of Skolp E-07 is defined by an unnamed Precambrian interval described as gneissic based on core 7 (2992–2988 m). The crystalline rock is well defined by a low API value, with an abrupt change in the gamma-ray log at 2967 m into the overlying sedimentary section; thus the basement rock interval extends from 2992–2967 m, as was defined by Moir (1989; Table 48).

Base (m)	Top (m)	Paleoenvironment
2967	2915	ALLUVIAL TO FLUVIAL
2915	2620	FLUVIAL CHANNELS, FLOOPLAINS, SWAMPS
2620	2473	LACUSTRINE
2473	2022	DELTA FRONT
2022	1707	OUTER SHELF
1707	1243	SHOREFACE TO OUTER SHELF
1243	990	MIDDLE TO OUTER SHELF
990	852	INNER SHELF
852	685	LAGOONAL
685	540	BAYHEAD DELTA

Table 47: Paleoenvironmental determinations for Skolp E-07 from the present study.

Alluvial to fluvial

At the base of the sedimentary succession in Skolp E-07 is an interval from 2967 m to 2915 m of sandstone, siltstone, conglomerate, and rare shale and coal. Sandstones are grey, medium- to coarse-grained, moderately sorted, micaceous, calcareous, and argillaceous, and contain abundant pebbles (chert), coal stringers, very coarse-grained sand grains, and rare kaolinite. Thick conglomerates are grey, calcareous, and argillaceous, with very coarse-grained sand grains, siliceous pebbles, and rare kaolinite. Siltstone beds are also relatively common and are grey, very sandy, micaceous, and argillaceous, with coal fragments. Rare green, silty shales are present, as well as thin coal units. Despite the coarse-grained nature described above, the gamma-ray log shows moderate API values, possibly as a result of elevated feldspar content as seen in other Labrador Shelf wells for the Bjarni Formation (cf. Umpleby, 1979). The resistivity is, however, similar to the sandstone succession lying above (*see* below; Fig. 27).

The coarse-clastic nature of this interval, combined with coal suggests a possible alluvial to fluvial interpretation. The presence of kaolinite could indicate surface weathering, and green shales are common when developed under reducing conditions in floodplain settings (Myrow, 2003). Furthermore, Dafoe and Williams (2020a) indicated that core 6 (2918.77–2915.5 m), located at the top of this interval, is representative of a fluvial setting with channel abandonment. The alluvial to fluvial interpretation from the present study agrees reasonably well with the nonmarine alluvial fan setting of Miller and D'Eon (1987) and Dafoe and Williams' (2020b) nonmarine interpretation. This coarse-grained, clastic interval is part of the Bjarni Formation, but lies below the shale-dominated Snorri Member according to Dafoe and Williams (2020b; Table 48). In their age assessment, these same authors gave an Aptian to early Albian age determination.

Fluvial channels, floodplains, and swamps

Spanning the depths between 2915 m and 2620 m is a succession of interbedded, heterolithic shale, sandstone, siltstone, and lesser coal. Grey shales are silty, with siltstone stringers, common carbonaceous fragments, localized coal stringers, and rare plant fragments. Sandstones are brown to grey, fine- to medium-grained, moderately to well sorted, calcareous, argillaceous, silty, and slightly dolomitic, and further include very coarse-grained sand grains throughout, subangular grains, common coal fragments, and common carbonaceous fragments. Siltstones are brown to cream, sandy, argillaceous, and locally calcareous, with common coal fragments or carbonaceous fragments, scattered plant fragments, and a rare micaceous character. Coals are scattered throughout, but are more common at the base of the interval. A ragged gamma-ray profile is observed for this interval, further confirming the heterolithic character (Fig. 27).

The heterolithic nature of this succession combined with dominance of coals suggests alternating nonmarine conditions likely related to fluvial channel development with floodplains and swamps predominating. Miller and D'Eon (1987) also gave a nonmarine interpretation (fluvial, swamp, and floodplain), and Dafoe and Williams (2020b) further confirmed a nonmarine paleoenvironment. This thick section is attributed to the Snorri Member of the Bjarni Formation, with an early Albian age based on the findings of Dafoe and Williams (2020b).

Lacustrine

The interval from 2620 m to 2473 m encompasses shales with localized sandstone interbeds. Brown-grey shales are soft, sandy, silty, and micro-micaceous, with plant remains and brown speckled material (possibly tuffaceous). Sandstones are white-grey to dark brown-grey, medium- to coarse-grained, moderately to well sorted, silty, calcareous, and argillaceous, and contain subangular grains, very coarse-grained sand grains and pebbles, and scattered carbonaceous flakes.

There are no marine indicators in this interval and multiple tuffaceous beds (at approximately 2610 m, 2580 m, 2530 m, and 2490 m) would be best preserved in a quiet, aquatic setting. Accordingly, the paleoenvironment is interpreted as lacustrine, with the sandstones possibly indicating fluvial influx or fan delta development. Miller and D'Eon (1987) also gave a lacustrine origin, and Dafoe and Williams (2020b) reported nonmarine conditions for much of the interval, except the uppermost part, which could reflect cavings from the overlying succession (*see* Fig. 27).

Based on their palynological assessment, Dafoe and Williams (2020b) found a break between the early Albian and Cenomanian at 2460 m. They specifically reported on the cuttings sample covering 2465–2460 m based on the last occurrence of *Parvocavatus radiatus* and presence of *Matonisporites "skolpii"* indicating the top of the early Albian. However, a major log break occurs at 2473 m, approximately where Moir (1989) placed his top of the Bjarni Formation. Shales below the log break have a moderate gamma-ray API value, but shales above have a much higher value, and higher resistivity as well. The log break and corresponding change in paleoenvironments recorded in the present study (*see* below) appear to indicate a convincing top for the Bjarni Formation at 2473 m. The palynomorphs from Dafoe and Williams (2020b) are rather definitive, but could also have been reworked into younger strata during the onset of marine conditions and transgression. The lithostratigraphic boundary is thus convincingly between 2473–2460 m, but is herein picked at 2473 m (Table 48); accordingly, this lacustrine interval is early Albian in age (Dafoe and Williams, 2020b).

Delta front

Heterolithic sandstones and shales, with lesser siltstones and minor limestones occur between 2473 m and 2022 m depth. Grey-brown to cream, fine- to coarse-grained (becoming coarser grained towards the top of the interval), moderately sorted, argillaceous, shaly, and calcareous sandstones include subangular to subrounded grains, scattered carbonaceous flakes, very coarse-grained sand grains and pebbles increasing in abundance towards the top of the interval, rare mica, rare plant fragments, and rare pyrite. Shale units are grey, silty, and partly sandy, with rare plant remains and rare siderite. Dark brown to grey siltstones are argillaceous, shaly, sandy, slightly calcareous, and micro-micaceous, and are further characterized by scattered carbonaceous flakes and rare fossil fragments. Common fossil fragments are present in white to cream limestones that are argillaceous and sandy. The gamma-ray profile shows three subtle, coarsening-upward intervals and a slightly ragged character (Fig. 27).

The coarsening-upward trends, upward thickening of sandstone beds, heterolithic nature, and presence of fossiliferous limestones suggests a delta front setting. In slight contrast, Miller and D'Eon (1987) indicated nonmarine to marginal marine conditions including turbidite fans, lacustrine, and alluvial fan delta settings, and Dafoe and Williams (2020b) reported marginal marine and inner neritic conditions, with possible outer neritic water depths. A delta front setting appears to be within range of these previous studies.

This interval forms the base of the Markland Formation in the well. Dafoe and Williams (2020b) further found these strata to be part of the lower Freydis Member (beginning at 2460 m depth), similar to the interval defined by Moir (1987d; Table 48). Since the Bjarni and Markland formation boundary is modified in the present study, the base of the lower Freydis Member of the Markland Formation is also taken at 2473 m. This modifies the reference section from previous studies (McWhae et al. 1980; Moir, 1989; Dafoe and Williams, 2020) to 2473–2022 m (Table 48). Dafoe and Williams (2020b) further gave an age of early Albian to Coniacian; however, the Albian age likely indicates reworked specimens from the underlying Bjarni Formation during transgressive flooding (*see* Fig. 27).

Outer shelf

Spanning the depths between 2022 m to 1707 m is shale with limestone beds and rare, thin sandstone units. Grey shale to claystone is silty, platy, locally sandy, and micro-micaceous, and includes limestone stringers, scattered siderite nodules, rare carbonaceous flakes, and rare mollusc shell fragments, with the sand content including very coarse-grained sand grains near the top of interval. Limestones are dark brown, argillaceous and silty, with rare indeterminate fossil fragments. Rare coarse-grained sandstone beds are brown, very argillaceous, and silty, with very coarse-grained sand grains.

The inclusion of fossiliferous limestones suggest marine deposition and the dominance of siderite may indicate some degree of reducing conditions in a more distal setting (Scholle and Ulmer-Scholle, 2003). The general lack of fossil material could indicate either brackish or distal marine conditions, but is taken here to indicate an outer shelf paleoenvironment. In contrast, Williams and Dafoe (2020b) suggested inner to middle neritic conditions, but Miller and D'Eon (1987) gave a possible shelf setting. This shale interval is typical of the Markland Formation and forms a break between the sandstone-dominated Freydis Members. A Coniacian to early Campanian age was assigned to this part of the well by Dafoe and Williams (2020b).

Shoreface to inner shelf and lesser middle to outer shelf

Brown-grey sandstones, siltstones, and shales representing four major coarsening-upward cycles with blocky sandstones and rare limestones (at the base of the interval) are found between 1707 m and 1243 m. Sandstones are brown-grey to white-cream, medium- to coarse-grained, moderately sorted, argillaceous, calcareous, and locally silty, with subangular grains, common mica, very coarse-grained sand grains present throughout, scattered pebbles (quartz), carbonaceous flakes abundant at the base of the interval, rare coal stringers, rare indeterminate fossil fragments, and very rare glauconite. Brown-grey claystones are silty and sandy, and include scattered carbonaceous flakes, scattered coal stringers in the basal coarsening-upward cycle, scattered sandstone stringers, rare very coarse-grained sand grains, and rare indeterminate fossil fragments. Siltstones are grey, sandy, and argillaceous, with scattered carbonaceous flakes. Cream limestones are argillaceous and sandy, with indeterminate fossil fragments. The sandstones are locally blocky on the gamma-ray log, and there is an overall coarsening-upward trend, in addition to the four coarsening-upward sub-units (Fig. 27).

Dafoe and Williams (2020a) reported on core intervals 1–5 from this part of the well and indicated shoreface to distal outer shelf conditions, with some deltaic or terrestrial influence. Accordingly, this interval of the well is interpreted to reflect primarily shoreface to inner shelf conditions, but shalier units likely reflect middle to outer shelf conditions as noted in the core intervals. This interpretation is supported by the coarse grain size and presence of coal and carbonaceous material. Dafoe and Williams (2020b) also indicated a dominance of inner neritic deposition, and similarly, Miller and D'Eon (1987) suggested marginal marine to middle shelf conditions, including alluvial fan delta deposition. This thick interval in Skolp E-07 was assigned to the early Campanian to early late Maastrichtian by Dafoe and Williams (2020b), and their upper Freydis Member reference section is retained (Table 48).

Middle to outer shelf

In the interval from 1243 m to 990 m are grey-brown shales with limestone interbeds (abundant at the base of the interval) and sandstone interbeds (abundant towards the top of the interval). Claystones are grey, silty, and locally sandy, with mica, rare siderite, and rare sandstone stringers. Sandstones are dark brown, medium- to coarse-grained, moderately sorted, calcareous, argillaceous, and silty, and are further characterized by very coarse-grained sand grains and pebbles (quartz) and subangular grains. Brown, very argillaceous, and sandy limestone contains common fossil fragments (foraminifera and mollusc). The sandstone units are generally poorly represented in the gamma-ray log due to their low API values (Fig. 27).

The interbedding of fossil-bearing limestones containing foraminifera suggests a distal marine, outer shelf setting. Upwards, however, the interspersion of sandstones within the claystone and limestone appear to indicate turbidite-like deposition, or possibly storm or distal deltaic influence. From the palynology, Dafoe and Williams (2020b), found inner neritic conditions to prevail. Miller and D'Eon (1987), however, postulated marginal marine (delta) to possible outer shelf conditions, in reasonable agreement with the present study. This interval characterizes the uppermost part of the Markland Formation, which in totality extends from 2473 m to 990 m (Table 48). An early late Maastrichtian to early Danian (Early Paleocene) age was ascertained by Dafoe and Williams (2020b) for this middle to outer shelf succession.

Inner shelf

A return to sandstone-dominated sedimentation is recorded in the strata from 990 m to 852 m, with shale and rare limestone units. Medium- to coarse-grained, moderately to-well sorted, argillaceous, locally silty, calcareous sandstones contain subrounded to subangular grains, very coarse-grained sand grains common throughout, common fossil fragments (indeterminate mollusc material and bivalve), rare pebbles (quartz), rare coal stringers, and rare carbonaceous flakes. Claystones are brown-grey, sandy, silty, and locally calcareous, with rare pyrite, rare fossil fragments, and rare very coarse-grained sand grains. Less common limestone is dark brown, very sandy, and very argillaceous, with abundant mollusc fragments. Overall, the interval is fining-upward on the gamma-ray log (Fig. 27).

The alternation between sandstone, claystone and limestone suggests varying depositional conditions. The fining-upward character, combined with the commonality of fossil material indicates more normal marine conditions consistent with the inner shelf, possibly during transgression. The heterolithic character could imply storm influence and alternation between fair-weather and storm deposits. Dafoe and Williams (2020b) gave a similar marginal marine to inner shelf paleoenvironment and Miller and D'Eon (1987) reported nonmarine to inner shelf conditions, in relative agreement with the present study.

This heterolithic unit spans the Kenamu Formation and basal Mokami Formation as defined by Dafoe and Williams (2020b). This lithostratigraphic designation is partly based on the age, wherein the Ypresian (Early Eocene) and Bartonian (Middle Eocene) units identified by Dafoe and Williams (2020b) conform to the Kenamu Formation, and the missing Priabonian (Late Eocene) section would suggest a break between the lithostratigraphic intervals. Lithologically, there is a better break in section at the top of this inner shelf interval at 852 m, so the formation boundary is likely between this depth and 870 m at the top Bartonian. Furthermore, the Gudrid Formation and Leif Member of Moir (1989) were discounted by Dafoe and Williams (2020b) due to the age and lack of obvious lithostratigraphic boundaries (Fig. 27; Table 48).

Lagoonal

From 852 m to 685 m is a succession of claystones and rare sandstones. Brown-grey claystones are silty, very sandy, and locally calcareous, with rare very coarse-grained sand grains, scattered fossil fragments (mollusc and indeterminate shell material), and rare plant remains. Rare sandstones are brown, fine- to coarse-grained, moderately sorted, argillaceous, locally silty, and slightly calcareous, with subrounded grains and rare very coarse-grained sand grains.

The dominance of claystone, but sandy character with indeterminate shell fragments suggests a lagoonal setting as opposed to a more distal marine setting where there would be enhanced fossil diversity. Miller and D'Eon (1987), however, interpreted inner to middle shelf conditions, but Dafoe and Williams (2020b) agreed with a marginal marine paleoenvironment. This interval encompasses much of the Mokami Formation defined by Dafoe and Williams (2020b), where there is a decrease in gamma-ray log character above, likely corresponding to development of Saglek Formation sandstones (Fig. 27; Table 48). The age of this interval is Rupelian (Early Oligocene) according to Dafoe and Williams (2020b).

Bayhead delta

The uppermost interval of Skolp E-07 from 685 m to 540 m is composed of heterolithic sandstones and shales based on the original Canadian Stratigraphic Ltd. log (but excluded in the digital compilation shown in Figure 27). Sandstones are light brown to brown, medium- to coarse-grained, moderately sorted, and argillaceous, and further contain subrounded grains, abundant carbonaceous flakes, very coarse-grained sand grains and pebbles increasing in abundance towards the top of the interval, and common fossil fragments at the top of the interval (mollusc and indeterminate shell material). Brown-grey claystones are silty, sandy, and locally calcareous, and include rare fossil fragments and common plant fragments. The gamma-ray log provides further evidence of a heterolithic character through the ragged profile, but both coarsening- and fining-upward units are evident (Fig. 27).

The ragged nature of the gamma-ray log, abundance of plant and carbonaceous detritus, and coarse-grained nature indicates a deltaic setting. Considering the lagoonal nature of the underlying strata, this succession may reflect bayhead delta progradation. This part of Skolp E-07 comprises the Saglek Formation as defined by Dafoe and Williams (2020b), and the same authors gave an age of Rupelian (Early Oligocene), possible Chattian (Late Oligocene), Aquitanian–Burdigalian (Early Miocene) and Serravallian (Middle Miocene).

Lithostratigraphy

Based on the discussion around lithostratigraphic refinements to the framework of Moir (1989) and Dafoe and Williams (2020b) in Skolp E-07, the lithostratigraphic picks from the present study are summarized in Table 48. Modifications were made to the Freydis Member reference sections of the Markland Formation.

Lithostratigraphic unit	Moir (1989)		Dafoe and Williams (2020b)		The present study		Type or reference section
	Base (m)	Top (m)	Base (m)	Top (m)	Base (m)	Top (m)	
Saglek Fm	685	350	685	505	685	505	None
Mokami Fm	855	685	870	685	870	685	None
Kenamu Fm	974	855	990	870	990	870	None
Kenamu Fm (Leif Mb)	974	937	--	--	--	--	None
Gudrid Fm (upper)	986	974	--	--	--	--	None
Markland Fm	2472	986	2460	990	2473	990	None
Markland Fm (Freydis Mb, upper)*	2472	1355	1707	1243	1707	1243	Reference section from 1707–1243 m of Dafoe and Williams (2020b) is retained (Moir (1987d) indicated a “tongue 1” as 1707–1355 m).
Markland Fm (Freydis Mb, lower)*			2460	2022	2473	2022	Reference section from 2427–1355 m of McWhae et al. (1980), 2472–2008 m (“tongue 2”) of Moir (1987d), and 2472–1355 m of Moir (1989), and 2460–2022 m of Dafoe and Williams (2020b) is modified to 2473–2022 m
Bjarni Fm (Snorri Mb)	2924	2472	2915	2460	2915	2473	None
Bjarni Fm	2967	2472	2967	2460	2967	2473	None
Unnamed Precambrian	2992	2967	2992	2967	2992	2967	None

Table 48: Lithostratigraphic assignment for Skolp E-07 from the present study and compared to that of Moir (1989) and Dafoe and Williams (2020b). *Moir (1989) reported a lithostratigraphic assignment for the Freydis Member without reference to the lower and upper informal units. Fm=Formation; Mb=Member.

SNORRI J-90
In the northern part of the Hopedale Basin, near the Okak Arch is the Snorri J-90 well (Fig. 1). Detailed lithological information for this well comes from the well history report by McWhae et al. (1975) where they described conventional core, sidewall core, and cuttings samples. Additional sidewall core descriptions are recorded in Umpleby (1975c). The Canadian Stratigraphic Service Ltd. Eastcan Snorri J-90 log (log EC-110) also provides a complete record of the lithology, grain size, and grain rounding, as well as sample descriptions. Conventional core 1 from the Gudrid Formation was described by Dafoe and Williams (2020a), including an assessment of the age and paleoenvironment of deposition. Figure 28 details key well logs, lithology, grain size, rock colour, ages, and paleoenvironmental and lithostratigraphic information. The age assignments of Nøhr-Hansen et al. (2016) are used in the present study, with consideration of other studies in the uppermost section of the well. Paleoenvironments from the present study are summarized in Table 49 below and are compared below with the results of Miller and D'Eon (1987) and Williams (2007c), the latter being based on palynomorphs. Lithostratigraphic refinements from the present study build upon the original work of Moir (1989) and are summarized in Table 50.

The extent of the unnamed Precambrian basement rock at the base of the well is refined from that of Moir (1989) from 3210–3149.2 m based on the prominent gamma-ray and resistivity log breaks at the base of the overlying Bjarni Formation (Fig. 28; Table 50).

Base (m)	Top (m)	Paleoenvironment
3149.2	3045.9	NONMARINE FLUVIAL FLOODPLAIN, MARSH, AND CHANNEL
3045.9	3023.7	NONMARINE FLOODPLAIN AND MARSH
3023.7	3011.8	(?)SHELF
3011.8	2715.8	SLOPE
2715.8	2551.2	OUTER SHELF
2551.2	2515.5	PRODELTA
2515.5	2491.8	DELTA FRONT (STORM-DOMINATED)
2491.8	2225.1	UPPER SLOPE
2225.1	1956.8	OUTER TO MIDDLE SHELF
1956.8	1884.9	INNER SHELF TO PRODELTA
1884.9	1813.6	DISTAL DELTA FRONT
1813.6	1714.8	PRODELTA
1714.8	1636.8	OUTER SHELF
1636.8	1493.5	MIDDLE SHELF
1493.5	996.7	INNER SHELF
996.7	839.7	LOWER SHOREFACE
839.7	706.2	SHOREFACE
706.2	534.6	INNER SHELF
534.6	384.1	DELTA FRONT

Table 49: Paleoenvironmental determinations for Snorri J-90 from the present study.

Nonmarine fluvial floodplain, marsh, and channel

Lying above the unnamed Precambrian basement rock in Snorri J-90 is an interval of heterolithic shale or claystone, sandstone, and coal from 3149.2 m to 3045.9 m (10332–9993 ft.). Grey shale to brown claystone units are sandy, silty, and micaceous, with coal stringers, locally abundant sideritized pellets, and plant remains. Light brown sandstones are medium- to coarse-grained, poorly sorted, silty, calcareous, and slightly shaly, with siliceous cement, angular grains, quartz granules, and scattered very coarse-grained sand grains. Coal and lignite are common at the base and top of the unit, and rare igneous fragments are found at the base (resulting in the green colouration there).

The green colouration at the base of the interval is possibly related to weathering of pyroxene to chlorite, with pyroxene sourced from the underlying granitic interval when basement rock was exposed. The claystone itself also contains minerals possibly derived from the weathering of feldspar and thus are suggestive of subaerial conditions. The predominance of coal and plant remains further implies a nonmarine setting. Accordingly, a fluvial floodplain, marsh, and channel setting would explain the heterolithic nature of the strata. Miller and D'Eon (1987) gave a similar nonmarine, meandering fluvial and floodplain interpretation, but with subaerial volcanic deposition. There appears to be no evidence of the latter, as the greenish colouration is interpreted here to reflect weathered basement rock. Williams (2007c) gave a nonmarine to marginal marine setting, in general accord with the present findings. This interval is considered to form part of the Snorri Member of the Bjarni Formation, and Nøhr-Hansen et al. (2016) indicated an Aptian age for this part of the well.

Nonmarine floodplain and marsh

The interval spanning 3045.9 m to 3023.7 m (9993–9920 ft.) comprises a succession of homogeneous shale that is dark brown to grey, carbonaceous, laminated, silty, micaceous, bituminous, and non-calcareous, with plant remains throughout.

The carbonaceous to bituminous nature suggests continued floodplain to marsh conditions, but without significant fluvial channel development. Miller and D'Eon (1987) gave the same interpretation for this interval, and Williams (2007c) reported a similar nonmarine to coastal-marginal marine setting. This interval comprises the upper part of the Snorri Member of the Bjarni Formation and is mostly Aptian in age according to Nøhr-Hansen et al. (2016). There is a slight discrepancy where Nøhr-Hansen et al. (2016) picked the top of the Aptian at 3025.45 m, but the top of the Snorri Member as proposed here (3023.7 m) shows better agreement with a prominent log shift from the high API values of this unit to the low values within the overlying strata, as well as decreases in both the sonic velocity and resistivity logs. Accordingly, the Snorri Member is modified from that of Moir (1989), as well as the original type section defined by Umpleby (1979) and McWhae et al. (1980) to 3149.2–3023.7 m (Table 50).

(?)Shelf

The interval from 3023.7 m to 3011.8 m (9920–9881 ft.) is thin and poorly described in existing reports (the Canadian Stratigraphic Service log noted poor recovery), but appears to consist of brown to grey, slightly silty shale, with rare muscovite and pyrite. Uncharacteristically, there are low gamma-ray, as well as density and resistivity log values for this shale (Fig. 28).

A possible shelf setting is most likely, but there is little lithological information to make a definitive interpretation. Miller and D'Eon (1987) also gave a possible outer to inner shelf setting, and Williams (2007c) found inner shelf conditions in the adjacent overlying strata. With relatively pronounced log breaks at the top and base of this interval, it appears to reflect a slightly different setting compared to the overlying strata, but forms the base of the Markland Formation (Table 50). Nøhr-Hansen et al. (2016) gave an age of Danian (Early Paleocene) for this interval. Ainsworth et al. (2014) suggested caved Maastrichtian sedimentary rocks at 3033 m in the underlying interval, which could have been caved from this part of the well (*see* Fig. 28).

Slope

A thick interval of dark grey shale with intercalated limestone and marlstone beds persists from 3011.8 m to 2715.8 m (9881–8910 ft.). The shale is micro-micaceous and locally calcareous, with limestone stringers, rare siderite nodules, and rare foraminifera. Limestones and marlstones are light grey to dark brown, argillaceous, and dense.

The lack of silt and sand grains suggests a distal marine setting, and there is a general lack of fossil material aside from rare foraminifera, which suggests slope-equivalent conditions. This is, however, more distal than the outer-inner shelf/neritic settings of previous authors (Miller and D'Eon, 1987; Williams, 2007c).

This succession forms a typical Markland Formation shale interval, but also extends into the lower half of the Cartwright Formation, with a Danian (Early Paleocene) to Thanetian (Late Paleocene) age postulated by Nøhr-Hansen et al. (2016). The boundary between the two formations is based on the increase in gamma-ray and resistivity logs, a typical expression of the junction between the two shale-prone lithostratigraphic units (Balkwill and McMillan, 1990; Dafoe, Dickie et al., in press). Thus the extent of the Markland Formation in the present study differs from that of Moir (1989), who placed the top of the formation at 2816 m (Table 50). Termination of the Markland Formation within the Selandian (Middle Paleocene) as shown in Figure 28 is in good agreement with the regional framework described in Dafoe, Dickie et al. (in press).

Outer shelf

From 2715.8 m to 2551.2 m (8910–8370 ft.) is a silty shale with rare limestone and siderite units. Grey shale is slightly silty, micro-micaceous, and slightly calcareous, with occasional limestone stringers, rare siderite nodules, and rare foraminifera. Brown, argillaceous, dense, possibly glauconitic limestone is also present.

The increase in silt compared to the underlying interval suggests a gradual shallowing from the underlying slope-equivalent setting, consistent with outer shelf conditions. This interpretation is further supported by the presence of calcareous intervals and rare foraminifera. Miller and D'Eon (1987) gave an equivalent, although tentative, outer shelf interpretation, but Williams (2007c) suggested inner to outer shelf conditions. Forming part of the Cartwright Formation, this shale interval was reported as Thanetian (Late Paleocene) in age by Nøhr-Hansen et al. (2016).

Prodelta

Shale with both siltstone and sandstone interbeds increasing in abundance upward occurs in the interval from 2551.2 m to 2515.5 m (8370–8253 ft.). Brown shale is very silty with trace limestone stringers. Sandstones are light brown, very fine-grained, well sorted, silty, argillaceous, and calcareous, and also contain subangular grains and rare glauconite. Rare light brown dolostone is also glauconitic, and siltstone is brown, very argillaceous, sandy, and dolomitic. Buff to white, chalky limestone is very rare.

The interbedded nature with increased sand and silt content upwards is suggestive of a prograding prodeltaic setting, which agrees with the delta front interpretation from core 1 in the overlying interval (*see* below). The lack of fossil material is also consistent with a prodeltaic setting. Miller and D'Eon (1987) postulated inner shelf bar or possible deltaic sedimentation for much of this interval, and Williams (2007c) gave an inner to outer neritic interpretation, both in relative agreement with the present study. This prodeltaic interval is part of the uppermost Cartwright Formation. The extent of this formation is modified from that of Moir (1989), to include the section of the well from 2935 m to 2515.5 m (Table 50). The age of this prodeltaic interval is Thanetian (Late Paleocene) to basal Ypresian (Early Eocene) based on the findings of Nøhr-Hansen et al. (2016), and in good agreement with the framework established for the Cartwright Formation as outlined by Dafoe, Dickie et al. (in press).

Delta front (storm-dominated)

A thin interval of sandstone with lesser shale and limestone is found between the depths of 2515.5 m and 2491.8 m (8253–8175 ft.). Light brown to white, very fine- to fine-grained, well sorted, silty, argillaceous, and friable sandstone contains subangular grains, pyrite, limestone stringers, rare glauconite, and rare carbonaceous plant remains. Intercalated limestone is brown, sandy, argillaceous, and silty, and includes pyrite and occasional indeterminate fossil fragments. Shale is brown and silty. A clear coarsening-upward succession is seen in the gamma-ray log (Fig. 28).

The overall coarsening-upward trend implies progradation, with the heterolithic character indicating deltaic conditions. Dafoe and Williams (2020a) analyzed core 1 from this interval and interpreted a storm-dominated delta front setting. Accordingly, a delta front setting is proposed for the entire interval, which is similar to the inner shelf interpretation of Miller and D'Eon (1987) where they indicated possible deltaic conditions. However, Williams (2007c) gave a much deeper, outer neritic setting for part of this interval, perhaps related to cavings from the overlying succession (*see* Fig. 28). This interval forms the upper Gudrid Formation, which is slightly modified here relative to that of Moir (1989; 2515.5–2491.8 m; Table 50), and a basal Ypresian (Early Eocene) age was given by Nøhr-Hansen et al. (2016), with a late Thanetian (Late Paleocene)–earliest Ypresian (Early Eocene) age for core 1 assigned by Dafoe and Williams (2020a).

Upper slope

Shale with occasional limestone units dominates the section from 2491.8 m to 2225.1 m (8175–7300 ft.). Medium to dark brown shale is partly fissile, rarely silty, and micro-micaceous, with siderite nodules, limestone stringers, rare to locally common foraminifera, rare gastropods, and rare pyrite. Limestones are medium to dark brown and argillaceous.

Similar to the underlying Markland Formation, the lack of sand and silt suggests deep-water conditions, but perhaps within upper slope-equivalent water depths due to the enhanced fossil content, especially foraminifera. A similar outer neritic to open ocean setting was postulated by Williams (2007c), and the bathyal conditions of Miller and D'Eon (1987) also agree well with the present study. This interval demarcates the base of the Kenamu Formation, and is of basal Ypresian (Early Eocene) through to Lutetian (Middle Eocene) in age according to Nøhr-Hansen et al. (2016).

Outer to middle shelf

Between the depths of 2225.1 m and 1956.8 m (7300–6420 ft.) is a succession of silty claystone or shale with limestone units. Brown shale to claystone units are slightly silty to very silty upwards in the section and are also micaceous, with scattered foraminifera and indeterminate shell fragments and intercalated dark brown limestone stringers. Medium to dark brown limestone is argillaceous and silty.

The increasingly silty nature of the claystone upwards indicates shallowing over time within a shelfal setting. This combined with the fossil assemblage is characteristic of an outer to middle shelf paleoenvironment. This interpretation reasonably agrees with the inner to outer neritic and open ocean interpretations of Williams (2007c), but is slightly shallower than the bathyal setting of Miller and D'Eon (1987). This interval forms part of the Kenamu Formation and is Lutetian to Bartonian (Middle Eocene) based on the findings of Nøhr-Hansen et al. (2016).

Prodelta

An interval predominated by claystone with an increasing abundance of sand grains upward is present between 1956.8 m and 1884.9 m (6420–6184 ft.). Brown claystone is silty, sandy, and micaceous, and further includes rare limestone stringers, fossil fragments (indeterminate shell and foraminifera), and rare lignite. Siltstones are brown, argillaceous, sandy, micaceous, and friable, with rare limestone stringers. Rare limestone interbeds are brown, silty, sandy, and argillaceous.

The silty and sandy nature of the claystone suggests a more shoreline proximal setting compared to the underlying strata, with the presence of lignite and general lack of fossils suggesting a possible nearby fluvial source. Accordingly, a prodeltaic interpretation is most consistent with the evidence presented above. Miller and D'Eon (1987) inferred a much more distal bathyal setting, but the presence of lignite is inconsistent with their interpretation. Williams (2007c) proposed inner to outer neritic conditions in relative agreement with the present study. This interval comprises part of the upper Kenamu Formation and is Bartonian (Middle Eocene) in age according to Nøhr-Hansen et al. (2016).

Distal delta front

From 1884.9 m to 1813.6 m (6184–5950 ft.) there is a change to heterolithic claystone, siltstone, and sandstone. Brown claystone units are silty, sandy, and micaceous, with rare lignite. Siltstones are brown, argillaceous, sandy, micaceous, and friable. Brown very fine- to fine-grained sandstones are well sorted, silty, argillaceous, and friable, with subrounded grains, and rare lignite fragments. The gamma-ray log records only moderate API values, but shows a ragged character with subtle coarsening-upward units (Fig. 28).

The presence of lignite and lack of fossils suggests a possible nearby fluvial source and deltaic conditions, as does the heterolithic nature and log character. However, a distal delta front setting is most plausible considering the degree of fine-grained sediment. This is slightly shallower than the inner to outer neritic interpretation of Williams (2007c), but significantly shallower than the outer shelf to bathyal interpretation of Miller and D'Eon (1987), where they explained the presence of sandstones as turbidite fan accumulations. There is no evidence to support such a distal marine setting and no fining-upward units typical of turbidity current deposition. This sandier succession can be denoted as the Leif Member of the Kenamu Formation, which is modified in the present study from the work of Moir (1989) to 1884.9–1813.6 m (Table 50). Nøhr-Hansen et al. (2016) gave a Bartonian (Middle Eocene) to Priabonian (Late Eocene) age for this part of the well.

Prodelta

A claystone-dominated interval with lesser siltstone, sandstone and limestone is found between 1813.6 m and 1714.8 m (5950–5626 ft.). Brown claystone units are silty, sandy, and micaceous, and further include rare limestones stringers and rare indeterminate shell fragments. Siltstones are brown, argillaceous, sandy, micaceous, and friable. White to brown very fine- to medium-grained sandstones are well sorted, very silty, argillaceous, and friable, with subangular grains. Rare limestone interbeds are brown, silty, sandy, and argillaceous.

The limited fossil diversity within a fine-grained interval suggests continued environmental stress and a return to prodeltaic conditions. This setting agrees well with the inner-outer neritic interpretation of Williams (2007c), but is slightly shallower than the middle to outer shelf conditions assigned by Miller and D'Eon (1987) for much of this interval. This prodeltaic interval caps the top of the Kenamu Formation, adjusted slightly from that of Moir (1989) to match the log changes typical for the top of the Kenamu Formation, particularly the decrease in sonic velocity (*see* Dafoe, Dickie et al., in press). The Kenamu Formation as a whole, thus ranges from 2491.8 m to 1714.8 m in Snorri J-90 (Table 50).

Outer shelf

Spanning the depths of 1714.8 m to 1636.8 m (5626–5370 ft.) is a succession of brown, silty claystone that is micro-micaceous and contains rare brown limestone stringers and very rare very fine-grained sand grains.

The lack of sand-sized material implies outer shelf conditions, but the complete lack of fossils is atypical for such a setting. However, similar inner to outer shelf or neritic settings were previously proposed for this interval (Miller and D'Eon, 1987; Williams, 2007c). This part of the well characterizes the base of the Mokami Formation, which is known to reflect transgressive flooding and a slight deepening above the Kenamu Formation (Dickie et al., 2011; Dafoe, Dickie et al., in press). A Priabonian (Late Eocene) age was assigned by Nøhr-Hansen et al. (2016) for this part of the well.

Middle shelf

Claystone that becomes increasingly sandier upward from 1636.8 m to 1493.5 m (5370–4900 ft.) is medium to light brown, silty, micro-micaceous, with very fine-grained sand grains, rare siltstone stringers, rare indeterminate shell fragments, and rare pyrite.

The increase in sand content upwards indicates progressive shallowing, and the amount of silt and sand is typical of a middle shelf setting. The lack of fossil diversity and abundance is, however, atypical and could indicate some brackish influence. This interpretation is in range of the previous middle to outer shelf interpretation (Miller and D'Eon, 1987), but the marginal marine to inner shelf settings of Williams (2007c) are slightly shallower than the present study. This interval forms part of the Mokami Formation and is Priabonian (Late Eocene) to Early Oligocene based on the findings of Nøhr-Hansen et al. (2016).

Inner shelf

The claystone-dominated succession between 1493.5 m and 996.7 m (4900–3270 ft.) includes increasingly prevalent sand and silt upward, with prominent interbedding of lithologies. Brown claystone units are sandy, silty, grading to siltstone locally, and soft, and further characterized by common fossil fragments throughout (indeterminate shell material, gastropod, and bivalve). Brown, argillaceous, sandy siltstone is commonly interbedded, but decreases in abundance upward in the interval. Light brown sandstone is fine- to medium-grained, silty, argillaceous, and moderately sorted, with subrounded grains. Sandstone units increase in abundance upward, with some ragged and weak coarsening-upward trends. Rare chalky, white limestone is also present. The gamma-ray log shows a heterolithic character with relatively discrete sandstone beds and subtle coarsening-upward trends are also observed (Fig. 28).

The overall heterolithic character, fossil suite, and increase in sand content upward implies progradation within an inner shelf paleoenvironment. The clear alternation of sandstone and claystone could indicated storm-dominance in which storm and fair-weather beds alternate, respectively. The predominantly inner shelf settings of previous workers (Miller and D'Eon, 1987; Williams, 2007c) agree well with the present results. This interval marks the top of the Mokami Formation, defined in the present study from 1714.8–996.7 m, and thus modifying the type section of McWhae et al. (1980; Table 50). Nøhr-Hansen et al. (2016) gave the interval an Early Oligocene to earliest Pliocene age, but the Rupelian (Early Oligocene)–Chattian (Late Oligocene) age of Ainsworth et al. (2014) are preferred in the present study.

Lower shoreface

A sandstone-dominated interval with lesser claystone, conglomerate, and limestone extends from 996.7 m to 839.7 m (3270–2755 ft.). White to light brown, medium- to coarse-grained, argillaceous, loosely consolidated, moderately sorted, rarely silty sandstone contains common fossil fragments throughout (indeterminate shell material), calcareous cement, very coarse-grained sand grains, pebbles (quartz) throughout, subrounded to locally rounded grains, lignite or carbonaceous detritus, rare chert, rare glauconite, and rare pyrite. Localized conglomerate units are white to light brown, sandy, argillaceous, and unconsolidated, with indeterminate shell fragments present. Claystones are light grey, sandy, silty, and soft, with common indeterminate shell fragments and rare pyrite. Rare brown, sandy, argillaceous limestone is interspersed within the interval. The gamma-ray log illustrates the relatively blocky sandstones, with four, generally coarsening-upward units from shale to sandstone or conglomerate (Fig. 28).

The overall heterolithic nature of this interval, abundance of shell detritus, and general coarse grain size indicates a shoreface setting, but likely within the lower shoreface due to the prevalence of claystone. Miller and D'Eon (1987) presumed an inner shelf to lower shoreface setting, and Williams (2007c) also gave a marginal marine to inner neritic interpretation, both in good agreement with the present study. This interval characterizes the base of the Saglek Formation, with a Pliocene age according to Nøhr-Hansen et al. (2016), but older ages were reported by Fenton and Pardon (2007).

Shoreface

A consistently blocky, sandstone-dominated succession is found between 839.7 m and 706.2 m (2755–2317 ft.). White and light grey sandstone is medium- to coarse-grained, moderately sorted to locally poorly sorted, unconsolidated, argillaceous, and locally grades to conglomerate. Within the sandstone, grains are subrounded becoming well rounded, fossil fragments are common throughout (indeterminate shell material), and quartz pebbles, calcite cement, rare pyrite, rare glauconite, rare pyritized lignite, rare dark chert, and rare igneous pebbles are also present. A coarsening-upward and blocky profile is seen in the corresponding gamma-ray log (Fig. 28).

The well rounded nature of grains, common presence of fossil fragments, and blocky gamma-ray signature implies shoreface deposition. This agrees with the inner shelf (stacked bars) interpretation of Miller and D'Eon (1987) and the coastal-marginal marine setting indicated by Williams (2007c). This interval forms part of the Saglek Formation and was found to be Pliocene–Pleistocene by Nøhr-Hansen et al. (2016), but an older Middle–Late Miocene age was reported by Fenton and Pardon (2007) and is preferred here.

Inner shelf

Heterolithic strata between 706.2 m and 534.6 m (2317–1754 ft.) include sandstone and siltstone, with minor claystone. Sandstone units are light brown to white, very fine- to fine-grained, moderately to well sorted, silty, and argillaceous, and also include indeterminate fossil fragments throughout, quartz granules at the base of the interval, subrounded grains, and rare lignite. Light grey, argillaceous, sandy, friable siltstone contains fossil fragments throughout (bivalve) and rare lignite. Claystones are light grey, silty, and sandy with common indeterminate shell fragments and rare pyrite. The gamma-ray log exhibits moderate API values compared to the over- and underlying units with both subtle coarsening- and fining-upward trends (Fig. 28).

The increase in silt and clay content relative to the underlying unit, but presence of fossil fragments throughout suggest a return to an inner shelf paleoenvironment. The granules at the base of the interval could indicate reworking during a minor marine flooding of the underlying shoreface strata. Miller and D'Eon (1987) proposed a similar inner shelf setting, and Williams (2007c) interpreted a slightly shallower coastal to marginal marine paleoenvironment. This Pliocene–Pleistocene interval (Nøhr-Hansen et al., 2016) is also part of the Saglek Formation, but an Early Pliocene age is more likely (Fenton and Pardon, 2007).

Delta front

At the top of Snorri J-90 from 534.6 m to 384.1 m (1754–1260 ft.) is a mix of conglomerate, sandstone, and claystone. Sandstone to conglomerate intervals are white to grey, argillaceous, fine- to coarse-grained, and moderately sorted, with rare pyrite, common fossil fragments (indeterminate shell material and gastropod), igneous and quartz pebbles, mostly subrounded grains (subangular near top of the interval), and rare coal fragments. Claystones are light grey, sandy, silty, and soft, with common indeterminate shell fragments. The overall log character shows three, roughly coarsening-upward units with a slightly ragged gamma-ray profile (Fig. 28).

The grain size and fossil content are consistent with a return to a shoreface paleoenvironment, but the heterolithic nature and corresponding gamma-ray profile suggests likely delta front conditions. A wave- or storm-dominated delta front could account for the abundance of fossil material as wave activity mitigates harsh environmental stresses induced by fluvial influx (Bhattacharya, 2010). This upper part of the Saglek Formation is Pliocene–Pleistocene in age according to Nøhr-Hansen et al. (2016), but could be restricted to the Late Pliocene (Fenton and Pardon, 2007). Here, the Saglek Formation is modified to extend from 996.7 m to 374.3 m at the top of the gamma-ray log profile, which modifies the type section established by McWhae et al. (1980; Table 50).

Lithostratigraphy

Based on the discussion around lithostratigraphic refinements to the framework of Moir (1989) in Snorri J-90, the lithostratigraphic picks from the present study are summarized in Table 50. The present study modifies type sections for the Snorri Member of the Bjarni Formation, the Mokami Formation and Saglek Formation.

Lithostratigraphic unit	Moir (1989)		The present study		Type or reference section
	Base (m)	Top (m)	Base (m)	Top (m)	
Saglek Fm	997	267	996.7	374.3	Type section from 997–(?)267 m of McWhae et al. (1980) is modified to 996.7–374.3 m
Mokami Fm	1715	997	1714.8	996.7	Type section from 1715–997 m of McWhae et al. (1980) is modified to 1714.8–996.7 m
Kenamu Fm (Leif Mb)	1886	1815	1884.9	1813.6	None
Kenamu Fm	2491	1715	2491.8	1714.8	None
Gudrid Fm (upper)	2515	2491	2515.5	2491.8	None
Cartwright Fm	2816	2515	2935	2515.5	None
Markland Fm	3027	2816	3023.7	2935	None
Bjarni Fm (Snorri Mb)	3148	3027	3149.2	3023.7	Type section from 3061–3027 m of Umpleby (1979) and 3150–3024 m of McWhae et al. (1980) is modified to 3149.2–3023.7 m
Unnamed Precambrian	3210	3148	3210	3149.2	None

Table 50: Lithostratigraphic assignment for Snorri J-90 from the present study and compared to that of Moir (1989). Fm=Formation; Mb=Member.

SOUTH HOPEDALE L-39

Located in a landward proximal position in the central part of the Hopedale Basin is the South Hopedale L-39 well (Fig. 1). The final well report by Canterra Energy Ltd. (1983) includes lithological descriptions of the well cuttings. The Canadian Stratigraphic Service Ltd. Canterra South Hopedale L-39 log (log EC-246) further includes information on the lithology, grain size, and grain rounding, with sample descriptions, which were also used in compiling the below interval descriptions. Figure 29 shows the well plot and details key well logs, lithology, grain size, rock colour, ages, and paleoenvironmental and lithostratigraphic information. The biostratigraphy of Ainsworth et al. (2016) provides the most recent study of the well, but other ages are also considered. Paleoenvironmental interpretations from the present study are summarized below in Table 51 and compared with those of Miller and D'Eon (1987) and Bujak Davies Group (1989i) in the interval descriptions, the latter being presumably based on microfossils. The lithostratigraphy of Moir (1989) is refined in the present study, with revised assignments shown in Figure 29 and in Table 52.

The base of the well is characterized by an unnamed Precambrian granitic unit (2365–2220 m), followed by Early Ordovician (Fenton and Pardon, 2007) carbonate rocks, but the age of these strata was later revised to Late Ordovician (Bingham-Koslowski et al., 2019). In total, the Ordovician rocks extend from 2220 m to 2007 m, with the top of the succession modified slightly from that of Moir (1989) based on an increase in gamma-ray and reduced sonic velocity and resistivity log values (Fig. 29). Within these strata is an igneous unit consistent with an unnamed intrusion from 2081–2057 m, which is in accord with the whole rock K-Ar age date of 112 +/-4 Ma (Krueger Enterprises, Inc., 1987).

Base (m)	Top (m)	Paleoenvironment
1920	2007	PRODELTA TO DISTAL DELTA FRONT
1890	1920	(?)OUTER SHELF
1746	1890	MIDDLE SHELF
1670	1746	OUTER SHELF
1551	1670	SLOPE
1474	1551	INNER SHELF OR PRODELTA
1462	1474	SHOREFACE OR DELTA FRONT
1444	1462	INNER SHELF
1141	1444	MIDDLE SHELF
955	1141	INNER SHELF

Table 51: Paleoenvironmental determinations for South Hopedale L-39 from the present study.

Prodelta to distal delta front

Lying above basement rock, the interval from 2007 m to 1920 m comprises two, weakly coarsening-upward units as noted in the gamma-ray log (Fig. 29), but with some ragged character. These strata are dominated by shale with siltstone, sandstone, and minor limestone. Shale units are grey, silty, locally glauconitic, micaceous, and fissile, with common pyrite throughout the interval and rare plant remains. Grey siltstones are argillaceous, sandy, and pyritic, with localized glauconite and scattered plant remains. Grey very fine-grained, well sorted, argillaceous, silty sandstones, also include plant remains and glauconite, with subangular grains. Also present is light brown sandy, silty, argillaceous limestone.

The generally coarsening-upward nature of the two units, lack of fossils, commonality of plant fragments, and influx of sand suggests prodeltaic to distal delta front deposition. Miller and D'Eon (1987) derived a similar marginal marine interpretation, but within a lagoon or embayment. However, Bujak Davies Group (1989i) suggested upper to lower bathyal conditions that don't appear to agree with the observations above.

This part of the well was defined as the Bjarni Formation by Moir (1989), but in the present study is considered to be part of the shale-dominated Snorri Member of the same formation, with a slightly adjusted base at 2007 m and a top at 1920 m (Table 52). The age was found to be middle–late Albian to early–middle Turonian by Ainsworth et al. (2016). An age extending above the Albian for the Bjarni Formation is inconsistent with the regional framework of Dafoe, Dickie et al. (in press), as these authors refuted Cenomanian and Turonian ages for the Bjarni Formation. Furthermore, the log break (increase in gamma-ray and decrease in sonic velocity) at the base of Bujak Davies Group's (1989i) Santonian unit is the most reasonable pick for the top of the Snorri Member. Accordingly, a middle to possibly late Albian age is preferred for this interval, but possibly extending into the early Albian (Bujak Davies Group, 1989i). Unconformities proposed by Fenton and Pardon (2007) and Ainsworth et al. (2016) reside within this deltaic interval and do not appear to correspond to major stratal changes.

(?)Outer shelf

A thin shale interval from 1920 m to 1890 m is grey, silty, and glauconitic, with common siderite fragments and/or nodules, fossil fragments throughout (foraminifera), and common pyrite. The interval is capped by a pink limestone that is argillaceous, silty, glauconitic, and dolomitic. Traces of red-brown shale and sandstone near top of the unit may indicate prevalent sideritization.

The fossil content and silty nature of the shale are interpreted to reflect shelfal water depths, perhaps within the outer shelf. The abundance of siderite and glauconite indicates slow sedimentation rates and reducing conditions that would agree with a transgressive phase relative to the underlying strata (Amorosi, 2003; Scholle and Ulmer-Scholle, 2003). An outer shelf setting is within range of previous interpretations: marginal marine to bathyal (Miller and D'Eon, 1987; Bujak Davies Group, 1989i). The prevalence of foraminifera is atypical of shallow marine settings (although the genera are not known), and the silty nature of the shale suggests deposition on the shelf some distance from the shoreline.

This interval demarcates the base of the Markland Formation. The age of the succession is, however, less clear and ranges from early–middle Turonian (Ainsworth et al., 2016), Cenomanian (approximately; Oliver and Awai-Thorne, 1984) to Santonian or early Santonian–Campanian (Bujak Davies Group, 1989i; Fenton and Pardon, 2007). Based on the discussion above, it is unclear how convincing the Turonian age is, and Ainsworth et al. (2016) do not indicate if they see diagnostic palynomorphs or microfossils in their Turonian section. Accordingly, a general Santonian age would appear to be the most consistent age designation for this part of the well.

Middle shelf

Spanning the interval from 1890 m to 1746 m is a grey shale with siltstone beds. The grey, silty, slightly sandy shale contains plant remains throughout, common fossil fragments throughout (foraminifera and scaphopod), pyrite throughout, rare glauconite, and rare ironstone fragments (siderite). Siltstone units are grey, argillaceous, sandy, and micaceous, and further include plant remains throughout and scattered glauconite. In the gamma-ray log, coarsening- and fining-upward trends are both seen (Fig. 29).

The silty and sandy nature of the shale and commonality of fossil material suggests a middle shelf paleoenvironment. Plant remains further attest to a relative shoreline proximity. This interpretation is in significant contrast to the lower bathyal and bathyal settings of Bujak Davies Group (1989i) and Miller and D'Eon (1987), respectively. The abundance of fossil material and log character, with plant remains would appear to indicate a shelfal rather than deep-water setting. This part of the

Markland Formation is Santonian through early Maastrichtian in age according to Ainsworth et al. (2016).

Outer shelf

A shale-dominated interval with rare siltstone and limestone units occurs between 1746 m and 1670 m. Grey shale includes siderite nodules or bands throughout the interval, common pyrite throughout, rare glauconite, rare plant remains, and rare foraminifera. Siltstone interbeds are rare and are grey, argillaceous, and micaceous, with pyrite and glauconite. Brown, silty, argillaceous limestone is also rare.

The overall grain size and lack of fossils, with limited terrestrial influx suggests a deepening to outer shelf conditions. This agrees with the degree of pyrite and siderite development, implying fluctuating oxygenation with some reducing conditions (Scholle and Ulmer-Scholle, 2003; Wilkin, 2003). This interpretation is slightly shallower than the lower bathyal to bathyal settings of previous authors (Miller and D'Eon, 1987; Bujak Davies Group, 1989i). This interval forms part of the Markland Formation and is early Maastrichtian (Ainsworth et al., 2016) to possibly late Maastrichtian (Fenton and Pardon, 2007) in age.

Slope

A brown-grey shale that is fissile, rarely silty, and micro-micaceous, with pyrite throughout is present from 1670 m to 1551 m.

The lack of silt, sand, and fossil material implies a deep-water setting consistent with slope-equivalent water depths. This agrees well with the lower bathyal to bathyal interpretations of Miller and D'Eon (1987) and Bujak Davies Group (1989i). This interval caps the top of the Markland Formation, which is modified in the present study from that of Moir (1989) to extend from 1920 m to 1551 m (Table 52). The top of the Markland Formation corresponds to a decrease in gamma-ray and increase in sonic velocity and resistivity logs (Fig. 29). This slope interval is Selandian (Middle Paleocene) according to Ainsworth et al. (2016).

Inner shelf or prodelta

In contrast to the underlying interval, sandy and silty claystone with minor siltstone and sandstone units characterizes the well from 1551 m to 1474 m. Claystones are brown, sandy, silty, soft, and glauconitic throughout, and also include fossil fragments throughout (foraminifera, bivalve, and worm tubes) and rare pyrite. Brown, argillaceous, sandy, micaceous, glauconitic siltstone is rare, as well as light brown sandstone units that are fine-grained, well sorted, calcareous, silty, glauconitic, and argillaceous.

The sandy and silty nature of the claystone along with the abundant and relatively diverse fossil content is indicative of a proximal setting corresponding to the inner shelf. Considering the nature of the overlying interval (*see* below), it is likely that this interval reflects prodeltaic deposition. Miller and D'Eon (1987) postulated that the sand content within this interval was related to turbidites in a bathyal setting, and Bujak Davies Group (1989i) agreed with a bathyal interpretation. The evidence presented above, however, does not agree well with these previous authors' interpretations as the sand content is intermixed within the claystone rather than developed as discrete turbidity current deposits. This interval forms the Cartwright Formation in South Hopedale L-39 as defined in the present study from 1551–1474 m, modified marginally from that of Moir (1989; Table 52). The top is taken at the major lithological boundary with the overlying sandstone, and corresponding increase in sonic velocity and resistivity logs (Fig. 29). Ainsworth et al. (2016) gave a Thanetian (Late Paleocene) age; however, Fenton and Pardon (2007) suggested several unconformities at about this depth in the well, none of which seen to be evident in the lithological or log data.

Shoreface or delta front

Between 1474 m and 1462 m is a very thin sandstone interval. This light brown to white sandstone is fine- to coarse-grained, poorly to moderately sorted, slightly calcareous, and friable, with dolomite cement, abundant glauconite, very coarse-grained sand grains, and subrounded clasts. Brown, argillaceous, sandy, silty, glauconitic limestone is also present.

The glauconitic nature of this unit suggests low sedimentation rates, but in a high-energy setting where coarse clastic detritus accumulated. A shoreface or delta front setting would be the most plausible, with the lack of fossil material indicating deltaic conditions, but grain rounding more typical of a shoreface setting. On the contrary, previous authors have indicated bathyal water depths, with turbidites possibly explaining the sandstone accumulation (Miller and D'Eon, 1987; Bujak Davies Group, 1989i). The presence of glauconite indicates low sedimentation rates, which is in contrast to the nature of turbidite fan accumulations that are rapidly deposited. As suggested for other wells, possible cavings from overlying intervals could explain the deeper-water signatures determined in previous studies, as Dafoe, Dickie et al. (in press) have used multiple lines of evidence to confirm the shallow marine origin of the Gudrid Formation. This interval forms the entire Gudrid Formation as defined in the present study, placing it lower in the well than Moir (1989) at 1474–1462 m (Fig. 29; Table 52). The Thanetian (Late Paleocene) or Ypresian (Early Eocene) age determinations of Fenton and Pardon (2007) and Ainsworth et al. (2016) confirms that the upper Gudrid Formation is present.

Inner shelf

Glauconitic, sandy, silty brown claystone that contains ironstone fragments, rare foraminifera, rare bivalve fragments, and rare pyrite is found between 1462 m and 1444 m.

The sandy and silty nature is interpreted to represent a return to inner shelf deposition. There is an odd mix of fossil fragments and a low diversity typical for such a setting, but the interval is thin and likely poorly represented in cuttings samples. As with underlying intervals, this is much shallower than the bathyal settings of previous studies (Miller and D'Eon, 1987; Bujak Davies Group, 1989i), but the silt, sand, and fossil content indicates a shelfal rather than deep-water paleoenvironment. This interval marks the base of the Kenamu Formation as indicated in the present study. The Thanetian (Late Paleocene) age of Ainsworth et al. (2016) is slightly older than expected for the Kenamu Formation according to the stratigraphic framework of Dafoe, Dickie et al. (in press), but the Ypresian (Early Eocene) age of Fenton and Pardon (2007) is preferred here.

Middle shelf

Spanning the depths between 1444 m and 1141 m is a brown claystone with minor siltstone and limestone. Brown, silty, soft, locally sandy claystones contain scattered glauconite, especially in lower portion of the interval, as well as siderite at the base of the interval. The claystones also include common fossil fragments throughout (foraminifera, bivalve, scaphopod, worm tube, and gastropod), rare pyrite, and rare very coarse-grained sand grains at the top of the interval. Brown, argillaceous, micaceous siltstone has rare pyrite, and dark brown limestone is argillaceous and silty, with rare pyrite.

The claystone-dominated nature, with silt content and a rich fossil assemblage suggests a middle shelf setting. This interpretation partially agrees with the inner to outer shelf interpretations of Miller and D'Eon (1987) and Bujak Davies Group (1989i) for the upper part of the interval, but not with these same authors' bathyal interpretations for the base of the interval. The consistent lithology and fossil content for this interval does not appear to reflect the diverse settings previously interpreted. This claystone comprises much of the Kenamu Formation, and is likely Ypresian (Early Eocene) to Bartonian (Middle Eocene) based on the findings of Ainsworth et al. (2016).

Inner shelf

The uppermost part of South Hopedale L-39 between 1141 m and 955 m is characterized by a silty and sandy claystone. This brown claystone, is silty, sandy (increasing in abundance upward), and soft, with common fossil fragments throughout (foraminifera, bivalve, indeterminate shell material, scaphopod, and gastropod), rare very coarse-grained sand grains, and rare pyrite.

The fossil-rich and sandy nature of the claystone is consistent with an inner shelf paleoenvironment. It is unclear if the setting differs greatly in the overlying Mokami Formation as is typically encountered, since this boundary is very near the top of this inner shelf interval (Fig. 29). Miller and D'Eon (1987) and Bujak Davies Group (1989i) both provided similar interpretations of the setting for this part of the well.

This interval includes the uppermost part of the Kenamu Formation and very base of the overlying Mokami Formation, with the boundary modified here to 970 m at the top of the sandier portion of the overall claystone interval where there is a corresponding decrease in the sonic velocity (Fig. 29). There is no rationale for picking a Saglek Formation in this well, as in Moir (1989), as the lithological and log information does not extend above 960 m; accordingly, the Mokami Formation is restricted here to 970–946 m (Table 52). Further, the ages presented by Bujak Davies Group (1989i), Fenton and Pardon (2007) and Ainsworth et al. (2016) appear to indicate an overwhelmingly Middle Eocene age, which is more consistent with the top of the Kenamu Formation and basal Mokami Formation, with the boundary thought to be in the late Bartonian (Middle Eocene; Dickie et al., 2011; Dafoe, Dickie et al., in press).

Lithostratigraphy

Based on the discussion around lithostratigraphic refinements to the framework of Moir (1989) in South Hopedale L-39, the lithostratigraphic picks from the present study are summarized in Table 52. There are no type or reference sections in this well.

Lithostratigraphic unit	Moir (1989)		The present study		Type or reference section
	Base (m)	Top (m)	Base (m)	Top (m)	
Saglek Fm	812	630	--	--	None
Mokami Fm	1062	812	970	946	None
Kenamu Fm	1461	1062	1462	970	None
Gudrid Fm (upper)	1466	1461	1474	1462	None
Cartwright Fm	1549	1466	1551	1474	None
Markland Fm	1920	1549	1920	1551	None
Bjarni Fm (Snorri Mb)	2008	1920	2007	1920	None
Unnamed Paleozoic	2220	2008	2057	2007	None
Unnamed intrusion*	--	2030	2081	2057	None
Unnamed Paleozoic	2365	2220	2220	2081	None
Unnamed Precambrian	--	--	2365	2220	None

Table 52: Lithostratigraphic assignment for South Hopedale L-39 from the present study and compared to that of Moir (1989). *Unnamed intrusion was called "Unnamed" by Moir (1989). Fm=Formation; Mb=Member.

SOUTH LABRADOR N-79

The South Labrador N-79 well is located within the central part of the Hopedale Basin, forming an important record of the stratigraphy north of the Bjarni wells (Fig. 1). The cuttings and sidewall core are both described in the final well history report (Chevron Standard Ltd., 1980) and provide a basis for the descriptions below. This is in addition to the Chevron South Labrador N-79 log (log EC-151) from Canadian Stratigraphic Service Ltd., which includes comprehensive information regarding the lithology, grain size, and grain rounding, with detailed sample descriptions. The well plot is shown in Figure 30 and includes key well logs, lithology, grain size, rock colour, ages, and paleoenvironmental and lithostratigraphic information. The work of Nøhr-Hansen et al. (2016) gives an updated biostratigraphic framework, and is similar to that of Williams (2007b). Table 53 presents a summary of the paleoenvironmental interpretations from the present study, which are compared below with those of Miller and D'Eon (1987) and Williams (2007b), the latter being based on palynology. Lithostratigraphic assignments from present study are compared with those of Moir (1989) in both Figure 30 and Table 54.

At the base of the well, the top of the unnamed Precambrian granitic basement rock is modified here to 3544 m based on the lithology from Canadian Stratigraphic Service Ltd., which ties with the breaks in the gamma-ray and sonic velocity logs at that depth (Fig. 30).

Base (m)	Top (m)	Paleoenvironment
3544	3494	SHELFAL
3494	3460	MIDDLE SHELF
3460	3360	OUTER SHELF
3360	3150	SLOPE TO SHELF EDGE
3150	2952	OUTER SHELF
2952	2717	MIDDLE SHELF
2717	2635	OUTER SHELF
2635	2432	MIDDLE SHELF
2432	2307	UPPER SLOPE
2307	2020	OUTER SHELF
2020	1820	MIDDLE SHELF
1820	1643	OUTER SHELF
1643	1370	MIDDLE SHELF
1370	1175	OUTER SHELF
1175	850	MIDDLE SHELF
850	772	INNER SHELF TO PRODELTA
772	720	SHOREFACE OR DELTA FRONT

Table 53: Paleoenvironmental determinations for South Labrador N-79 from the present study.

Shelfal

Lying above the basement rock is an interval from 3544 m to 3494 m of green-grey shale with marlstone, limestone, and siltstone. The green-grey shale is dolomitic, silty, and waxy, with rare pyrite, rare foraminifera (some benthonic), and rare indeterminate fossil fragments. Marlstone is also abundant and is grey, silty, dolomitic, and shaly. Grey, argillaceous, silty, slightly dolomitic limestone contains possible coral fragments, and light grey, dolomitic, argillaceous siltstone is also present.

The calcareous nature of the strata, combined with the presence of foraminifera is interpreted to represent a shelfal setting, and a green colouration to the shales could indicate reducing conditions

(Myrow, 2003). However, a more precise setting is difficult to derive from the given data. Miller and D'Eon (1987) also gave a shelf interpretation, but they also proposed nonmarine conditions for part of the interval. Williams (2007b) proposed a much shallower, marginal marine setting, which would be consistent with the general understanding of the Snorri Member (*see* Dafoe, Dickie et al., in press).

This interval demarcates the Snorri Member of the Bjarni Formation, which is the fine-grained member of the generally sandstone-dominated lithostratigraphic unit. In this well, the lithology is atypically calcareous and the extent of the Bjarni Formation (and Snorri Member) are modified from that of Moir (1989) to match this interval and the corresponding log breaks (3544–3494 m; Table 54). Williams (2007b) indicated a Barremian to early Aptian age for this interval, but Nøhr-Hansen et al. (2016) only interpreted Aptian strata, but also gave a Coniacian age for the upper part of the interval. The presence of a major mid-Cretaceous unconformity is not substantiated by the lithology in this interval. However, an unconformity likely occurs at the top of this interval at 3494 m where there is an abrupt log break (increase in gamma-ray and decrease in sonic velocity and resistivity logs). Accordingly, the Bjarni Formation is likely only Early Cretaceous in age and cavings or limitations related to sampling intervals may have resulted in the Coniacian ages found below 3494 m.

Middle shelf

The interval from 3494 m to 3460 m is composed of dark grey shale that is fissile, micaceous, silty, and slightly calcareous, with siltstone laminae, common fossil fragments throughout (Inoceramus prisms and indeterminate shell material), and siderite nodules. Rare brown siltstone is argillaceous, very fine-grained sandy, and micaceous.

The silty nature of the shale combined with the fossil content implies a likely middle shelf setting. This is in relative agreement with the inner neritic interpretation of Williams (2007b) and the possible shelf setting suggested by Miller and D'Eon (1987). This interval forms the base of the Markland Formation, which was found to be Coniacian by Williams (2007b) and Nøhr-Hansen et al. (2016).

Outer shelf

Shale with limited silt content encompasses the interval from 3460 m to 3360 m. The dark grey shale is fissile, micaceous, and slightly silty and further contains scattered fossil fragments (foraminifera, gastropod, and bivalve), rare siltstone beds, rare siderite nodules, and rare carbonaceous plant remains.

The fine-grained lithology, but relative fossil diversity is taken to represent continued shelf deposition, but perhaps deepening to the outer shelf based on a prevalence of foraminifera and reduction in silt content compared to the underlying interval. This interpretation falls within range of previous studies that reported inner neritic to open ocean or shelf to bathyal water depths (Miller and D'Eon, 1987; Williams, 2007b). This part of the Markland Formation is Coniacian to early Maastrichtian according to Nøhr-Hansen et al. (2016), but there is no apparent unconformity that could be correlated to missing Santonian section, although it could be condensed. Fenton and Pardon (2007) and Bujak Davies Group (1989i) both reported some Santonian section, albeit from deeper within the well.

Slope to shelf edge

Between the depths of 3360 m and 3150 m is a shale interval without measurable silt content. This grey to dark grey shale contains scattered siderite nodules and bands throughout, scattered fossil fragments (bryozoa, foraminifera, and gastropod, with some fragments replaced by pyrite), very rare silt, and a single coal fragment was noted.

The fine-grained lithology and lack of silt suggests a distal marine setting, with pyritized fossils indicating reducing conditions (Wilkin, 2003). However, the fossil diversity implies some proximity to the shelf and a slope to shelf edge setting is interpreted here, which agrees well with the open ocean or bathyal to outer neritic interpretations of previous authors (Miller and D'Eon, 1987; Williams, 2007b).

This shale makes up part of the Markland Formation, which Nøhr-Hansen et al. (2016) gave an early Maastrichtian to Danian (Early Paleocene) age in good agreement with the findings of Williams (2007b) and Bujak Davies Group (1989i).

Outer shelf

Slightly silty shale is present between 3150 m and 2952 m. Grey to dark grey shale is fissile, micaceous, and slightly silty, and also characterized by siltstone laminae, scattered fossil fragments throughout (foraminifera and rare gastropod), rare pyrite, and siderite bands or nodules.

The slight increase in silt content compared to the underlying interval indicates a minor shallowing to an outer shelf paleoenvironment, and the dominance of foraminifera agrees well with this interpretation. Williams (2007b) also found a generally outer neritic setting for this interval, but Miller and D'Eon (1987) proposed continued bathyal water depths. This interval caps the Markland Formation in South Labrador N-79, which extends from 3494–2952 m. The top of the formation is adjusted here to match the log change (reduced gamma-ray and sonic velocity, but increased resistivity log values), and with the overlying Cartwright Formation showing a more ragged log character (Fig. 30; Table 54). Nøhr-Hansen et al. (2016) gave a Danian (Early Paleocene) to Selandian (Middle Paleocene) age for these outer shelf strata, in agreement with the findings of Williams (2007b). A mid-Selandian top for the Markland Formation closely agrees with the regional framework outlined in Dafoe, Dickie et al. (in press).

Middle shelf

Spanning the depths of 2952 m to 2717 m is a succession of consistently silty and slightly sandy shale to claystone. The dark grey shales and claystones are silty throughout and micaceous, with common fossil fragments throughout (foraminifera, bivalve, and gastropod), localized siltstone beds, localized carbonaceous plant remains, scattered pyrite, rare coal fragments, rare sandstone beds, rare siderite bands, and very rare medium- to very coarse-grained sand grains. Rare brown siltstone is argillaceous, shaly, and sandy, with siderite, and very rare sandstone is light brown, very silty, and micaceous, with siderite.

The increase in silt, sand, and terrestrial influx (plant fragments) relative to the underlying strata implies shallowing to a middle shelf setting. This agrees with the fossil diversity, abundance, and taxa present. However, previous studies suggested more distal marine conditions including: outer neritic to open ocean (Williams, 2007b) and bathyal with turbidites or prodeltaic conditions (Miller and D'Eon, 1987). The above evidence is in better agreement with a more proximal shelf interpretation. This interval demarcates the base of the Cartwright Formation, and a Selandian (Middle Paleocene) to Thanetian (Late Paleocene) age was indicated by Nøhr-Hansen et al. (2016).

Outer shelf

A thin interval from 2717 m to 2635 m is further characterized by shale, but with limited silt content. The dark grey shale is only partly silty and micaceous, with siderite bands, common fossil fragments throughout (foraminifera, ostracod, and gastropod), and rare pyrite. There is a slight gamma-ray log change to higher API values for this interval as compared to the under- and overlying strata (Fig. 30).

The reduced silt and sand contents suggests a slight deepening to outer shelf conditions compared to underlying strata. However, the fossil diversity is relatively high and could be related to ample terrigenous influx associated with the contiguous Gudrid Formation (Umpleby, 1979; Dafoe, Dickie et al., in press). The present interpretation agrees somewhat with the outer neritic to open ocean settings of Williams (2007b), but is shallower than the bathyal interpretation of Miller and D'Eon (1987).

This shale makes up part of the Cartwright Formation, and a Thanetian (Late Paleocene) age assignment was given by Nøhr-Hansen et al. (2016).

Middle shelf

The interval covering 2635 m to 2432 m comprises dark grey shale with localized siltstone and sandstone units. Fissile, silty shale contains scattered fossil fragments throughout (foraminifera, gastropod, bivalve, and ostracod), localized sand grains, localized carbonaceous plant remains, rare coal, rare calcareous intervals, and rare siderite bands. Brown, argillaceous, micaceous siltstone is present, as well as light brown, very fine-grained, calcareous, very argillaceous sandstone, with siderite, subangular grains, and well to moderate sorting. Rare dark brown, argillaceous, hard limestone is also present.

The influx of terrestrial detritus and sand suggests a slight shallowing to a middle shelf paleoenvironment relative to the underlying strata. The fossil diversity and relative abundance further supports this interpretation. Previous studies, however, indicated a more distal outer neritic to open ocean or bathyal interpretations (Miller and D'Eon, 1987; Williams, 2007b). This section of the well forms the uppermost part of the Cartwright Formation defined in the present study. While Moir (1989) picked a slight log shift in sonic and resistivity logs at 2423 m, the sudden change in paleoenvironment to a more distal-marine setting at 2432 m (*see* below) is a better indicator of the overlying Kenamu Formation transgression (Fig. 30; Table 54). This depth also corresponds to major decreases in the sonic velocity and resistivity logs for the well. Accordingly, the Cartwright Formation extends from 2952–2432 m. The age is then Thanetian (Late Paleocene) to basal Ypresian (Early Eocene) according to Nøhr-Hansen et al. (2016).

Upper slope

Unlike the underlying interval, 2432 m to 2307 m is a homogeneous shale succession. Dark grey fissile, locally calcareous, micaceous shale includes pyrite throughout, scattered fossil fragments throughout (foraminifera and bivalve), rare siderite bands, rare brown limestone, rare carbonaceous plant remains, and very rare silt. The gamma-ray log shows a ragged, low API character that is likely related to the presence of calcareous units, a distinctive character for this interval.

Rare silt and a fossil suite dominated by foraminifera are interpreted to indicate an upper slope paleoenvironment, which is like that of the bathyal to open ocean interpretations of Miler and D'Eon (1987) and Williams (2007b), respectively. This unit marks the base of the Kenamu Formation as refined in the present study, with an early Ypresian (Early Eocene) age (Nøhr-Hansen et al., 2016).

Outer shelf

In the interval from 2307 m to 2020 m is a shale with siltstone, sandstone, and limestone horizons. Shales are dark grey, fissile, and silty throughout, with pyrite, siderite bands, scattered fossil fragments (foraminifera and bivalve), and localized carbonaceous plant remains. Siltstone units are grey, argillaceous, and shaly, with pyrite. Rare limestones and marlstones are dark brown, argillaceous, and slightly dolomitic, with pyrite. Very rare sandstone is grey to salt and pepper, very fine- to fine-grained, well sorted, calcareous, and friable, and further includes pyrite, subangular grains, and rare kaolinite.

The fine-grained, but silty nature of the shale with scattered fossil material is interpreted to represent outer shelf conditions. Open ocean to bathyal water depths were, however, indicated by previous studies (Miller and D'Eon, 1987; Williams, 2007b). This silty shale makes up part of the Kenamu Formation, with an early Ypresian to Ypresian (Early Eocene) age based on the findings of Nøhr-Hansen et al. (2016).

Middle shelf

Brown claystone with rare siltstone beds occurs from 2020 m to 1820 m. Grey to dark brown claystone is blocky, micaceous, soft, and silty throughout, and also includes localized fine- to medium-grained sand grains, very coarse-grained sand grains at the top of the interval, rare limestone interbeds, rare siderite bands, rare pyrite, rare fossil fragments (bivalve), rare carbonaceous plant remains, and rare quartz pebbles. Rare siltstones are brown to grey-brown, argillaceous, sandy, micaceous, and shaly, with pyrite present.

The influx of sand and coarser-grained material indicates a relative shoreline proximity and shallowing to a middle shelf paleoenvironment as compared to underlying strata. The reduction in fossil content is unusual, but could be indicative of distal prodeltaic influence. This setting is shallower than indicated by existing studies which interpreted bathyal to open ocean conditions (Miller and D'Eon, 1987; Williams, 2007b), and it is difficult to explain the consistent incorporation of silt and sand as turbiditic in nature. Within the Kenamu Formation, this interval was assigned a Ypresian (Early Eocene) to early Lutetian (Middle Eocene) age by Nøhr-Hansen et al. (2016).

Outer shelf

Claystone-dominated strata are present between 1820 m to 1643 m, but with less silt and sand content compared to the underlying interval. The brown to grey claystone is soft, micaceous, locally silty, and rarely locally sandy, with brown siltstone stringers or beds, rare fossil fragments (bivalve), rare medium- to coarse-grained sand grains, rare coal, and rare siderite.

The overall lithology and lack of sand suggests a deepening to an outer shelf paleoenvironment. The lack of fossil fragments is in contrast to underlying units, but could be a function of the shelf dynamics during Kenamu Formation time or distal deltaic influence. Open ocean to bathyal conditions were reported by previous authors (Miller and D'Eon, 1987; Williams, 2007b), indicating more distal marine conditions. Also in the Kenamu Formation, this part of South Labrador N-79 was given an early Lutetian to Bartonian (Middle Eocene) age, with the late Lutetian apparently missing (Nøhr-Hansen et al., 2016). This could be due to a condensed section, but Williams (2007b) ascertained a similar thin Lutetian section without a potential unconformity.

Middle Shelf

Sandy claystone occurs between 1643 m and 1370 m. The brown to dark brown claystone is soft, micaceous, silty, sandy, and slightly calcareous, with fine- to very coarse-grained sand grains throughout, localized carbonaceous flakes, rare sandstone lenses, rare fossil fragments (bivalve), and rare siderite.

The silty and generally sandy nature of this claystone interval indicates a more shoreline proximal setting compared to the underlying interval, as does the influx of carbonaceous flakes. A middle shelf setting is interpreted, but is shallower than recorded by previous studies which interpreted outer shelf to bathyal or outer neritic to open ocean conditions (Miller and D'Eon, 1987; Williams, 2007b). Such distal settings are atypical of the upper part of the Kenamu Formation (Balkwill and McMillan, 1990; Dafoe, Dickie et al., in press).

This interval characterizes the uppermost part of the Kenamu Formation as defined here (Table 54). Moir (1989) chose a formation break at 1447 m where it corresponds to a log break near a major scale change in the logs. The log character of the Kenamu Formation is less clear in this well as compared to other Hopedale Basin wells, partly as a result of the lack of Leif Member sandstones. However, the lithological and corresponding paleoenvironmental change at 1370 m is significant, whereby there is a distinct decrease in silt and sand within the overlying interval indicating a deepening that is typical for the base of the Mokami Formation (*see* Dafoe, Dickie et al., in press). Accordingly, the Kenamu Formation extends from 2132–1370 m. This middle shelf interval was found to be Bartonian

(Middle Eocene) to Priabonian (Late Eocene) by Nøhr-Hansen et al. (2016), slightly younger than indicated for the Kenamu Formation in Dafoe, Dickie et al. (in press).

Outer Shelf

From 1370 m to 1175 m is a succession of claystone with little silt and sand content. Brown to dark brown, very soft, micaceous, locally silty, locally sandy claystone includes siderite, localized very coarse-grained sand grains, rare sandstone lenses, and rare fossil fragments (scaphopod, gastropod, and rare indeterminate shell material). Rare very fine- to fine-grained, argillaceous, silty, friable, moderately sorted sandstone beds contain subangular to subrounded grains, siderite, and very rare very coarse-grained sand.

The silty nature of the claystone, fossil content and limited sand content are consistent with an outer shelf setting, with possible storm or turbidity currents forming the discrete sandstone beds. This interpretation falls within range of previous studies that found inner to outer shelf (Miller and D'Eon, 1987) and outer neritic to open ocean (Williams, 2007b) conditions. Forming the base of the Mokami Formation, this claystone is Priabonian (Late Eocene) as indicated by Nøhr-Hansen et al. (2016).

Middle Shelf

A thick interval of intermittently silty and sandy claystone occurs between 1175 m and 850 m. The dark brown, micaceous, soft, locally silty, locally sandy claystone is characterized by siderite, rare carbonaceous plant remains, rare carbonaceous flakes, rare very coarse-grained sand grains, and rare fossil fragments (foraminifera). Rare brown sandstone is very fine- to fine-grained, argillaceous, shaly, and calcareous.

The influx of terrestrially sourced material (sand grains, plant remains, and carbonaceous flakes) suggests a slight shallowing from the underlying strata to middle shelf conditions. This interpretation agrees closely with the inner to outer neritic settings of previous studies (Miller and D'Eon, 1987; Williams, 2007b). Derived from within the Mokami Formation, this claystone was found to be Rupelian (Early Oligocene) to Early Miocene in age according to Nøhr-Hansen et al. (2016).

Inner shelf to prodelta

A sandy claystone characterizes the section from 850 m to 772 m. This grey claystone is silty, sandy, micaceous, and soft, with fine- to very coarse-grained sand grains throughout, carbonaceous plant remains and flakes throughout, and rare chert pebbles. Light brown sandstone interbeds are argillaceous, shaly, and calcareous, and rare brown, argillaceous, silty limestone is also present.

The sand content and influx of terrigenous material is interpreted to reflect a proximal setting such as the inner shelf, but the lack of fossils may indicate prodeltaic and related brackish-water conditions. Miller and D'Eon (1987) also determined an inner-middle shelf setting, and Williams (2007b) further proposed inner neritic to possible outer neritic conditions, both in relative agreement with the present study. This interval caps the top of the Mokami Formation, such that the lithostratigraphic unit is defined from 1370–772 m, with the upper boundary indicated by the lithological and log shifts at the base of the overlying coarse-grained strata (Fig. 30). This interval is Early–Middle Miocene and possibly Plio-Pleistocene according to Nøhr-Hansen et al. (2016), but Williams (2007b) only recorded Miocene ages in his results.

Shoreface or delta front

At the top of South Labrador N-79 is a conglomerate and sandstone interval from 772 m to 720 m, with thin claystone and limestone beds. Conglomerate is white to salt and pepper and unconsolidated, with pyrite, chert pebbles, and a clay matrix. White to light brown, fine- to coarse-grained, poorly sorted, and unconsolidated sandstone has a clay matrix, with pyrite, chert, feldspar, very coarse-grained sand grains throughout, and rounded clasts. Grey, soft, silty claystone is micaceous and calcareous, and brown argillaceous, hard limestone is also present.

The coarse-grained nature and grain rounding suggests a shoreface setting, but the interbedded claystone and lack of fossils could indicate delta front conditions. The Saglek Formation is defined by this interval, with its base modified slightly from that of Moir (1989) and the top picked at 703 m at the top of the gamma-ray log. Nøhr-Hansen et al. (2016) suggested a Pliocene–Pleistocene age, but Bujak Davies Group (1989i) indicated that an older age could also be possible.

Lithostratigraphy

Based on the discussion around lithostratigraphic refinements to the framework of Moir (1989) in South Labrador N-79, the lithostratigraphic picks from the present study are summarized in Table 54. There are no type or reference sections for this well.

Lithostratigraphic unit	Moir (1989)		The present study		Type or reference section
	Base (m)	Top (m)	Base (m)	Top (m)	
Saglek Fm	773	546	772	703	None
Mokami Fm	1447	773	1370	772	None
Kenamu Fm	2423	1447	2432	1370	None
Cartwright Fm	2925	2423	2952	2432	None
Markland Fm	3496	2925	3494	2952	None
Bjarni Fm (Snorri Mb)	3548	3496	3544	3494	None
Unnamed Precambrian	3571	3548	3571	3544	None

Table 54: Lithostratigraphic assignment for South Labrador N-79 from the present study and compared to that of Moir (1989). Fm=Formation; Mb=Member.

TYRK P-100

Along the basin margin in the central part of the Hopedale Basin is the Tyrk P-100 well (Fig. 1). Information regarding the lithology of this well is found in the Total Eastcan Exploration Ltd. (1979c) final well report which includes cuttings and core descriptions. Additional core and sidewall core descriptions (Compagnie Française des Pétroles (CFP), 1979) were also used in the present study. Further detailed lithology, grain size, and grain rounding information, with sample descriptions were obtained from the Canadian Stratigraphic Service Ltd. Total Tyrk P-100 log (log EC-131). The age and paleoenvironmental interpretations of Dafoe and Williams (2020a) provide information on core 1 from within the uppermost Bjarni Formation. Figure 31 shows the well plot, including key well logs, lithology, grain size, rock colour, ages, and paleoenvironmental and lithostratigraphic information. Biostratigraphic results are best constrained by Fenton and Pardon (2007), except for the upper part of the well where previous studies show a younger age (Fig. 31). Paleoenvironmental interpretations from the present study are summarized in Table 55, and also compared in the descriptions below with the results of Miller and D'Eon (1987) and that of Caro et al. (1980), that latter of which are based on micropaleontology. Lithostratigraphic comparisons between the present study and that of Moir (1989) are indicated in Figure 31 and Table 56.

The unnamed Precambrian basement top of Moir (1989) is retained from 1739–1706 m and the presence of unnamed Paleozoic strata was recently confirmed by Bingham-Koslowski et al. (2019) with a Middle to Late Ordovician age (1706–1702 m; Table 56). Despite the lithology shown in Figure 31, these rocks are dolostones (Bingham-Koslowski et al., 2019).

Base (m)	Top (m)	Paleoenvironment
1702	1523	SUBAERIAL VOLCANIC ROCKS
1523	1182	RESTRICTED MARINE BAY
1182	1087	INNER SHELF OR PRODELTA
1087	1000	MIDDLE SHELF
776	720	MIDDLE SHELF
679	649	INNER SHELF
649	395	SHOREFACE
395	380	INNER SHELF

Table 55: Paleoenvironmental determinations for Tyrk P-100 from the present study.

Subaerial volcanic rocks

Overlying the Precambrian and Paleozoic basement is an interval of volcanic rocks from 1702 m to 1523 m. These rocks are grey-green to brown basalt and volcanic tuff that is weathered, with amygdales occasionally observed in the basalt, as well as a porphyritic texture, interbedded green shale, and soft to hard consolidation.

The mix of basalt and tuff suggests subaerial volcanic flows and air-fall accumulations, with amygdales indicating gases trapped within the lavas. Green shales may be altered or indicate reducing conditions (Myrow, 2003). Miller and D'Eon (1987) determined nonmarine conditions, with possible fluvial or alluvial settings or subaqueous accumulations. This interval comprises the Alexis Formation, and is unchanged from the designation of Moir (1989; Table 56). Fenton and Pardon (2007) assumed a Barremian–Aptian age, but without evidence of in situ palynomorphs or microfossils. Bujak Davies Group (1989j) suggested a possible late Aptian age with a low degree of confidence, but further explained that Aptian–Albian palynomorphs could be caved or derived from intercalated shales within the basalts.

Restricted marine bay

A thick interval from 1523 m to 1182 m is characterized by silty and sandy claystone. The brown-grey claystone to shale is very silty and increasingly sandy upwards, micaceous, and locally fissile, with scattered fine- to coarse-grained sand grains, rare siderite bands, rare pyrite, and rare limestone stringers. An overall coarsening-upward trend is further noted in the gamma-ray log (Fig. 31).

The claystone is sandy and silty, suggesting shoreline proximity, but lacks any fossil material. The shales from core 1 (1190–1185 m) were interpreted to reflect a restricted marine bay or lagoonal setting (Dafoe and Williams, 2020a). This, combined with the lack of fossils indicates an extended period of restricted marine bay deposition for the entire interval. Miller and D'Eon (1987) interpreted a number of different settings for this interval, despite its homogeneous nature, from lacustrine to marginal marine (brackish lagoon or lacustrine) to bathyal. Between the core and general homogeneous nature, a consistent restricted marine bay setting is most likely.

This claystone comprises the Snorri Member of the Bjarni Formation, which is adjusted here to extend from 1523–1182 m (Table 56). The top corresponds to an increase in sonic velocity and decrease in resistivity log values, but is also identified as a break between the late Albian below and Ypresian (Early Eocene) above (Fenton and Pardon, 2007). Fenton and Pardon (2007) proposed an Aptian to late Albian age for the interval, with a possible unconformity within the Albian. This unconformity corresponds to an increase in sand content and decrease in the gamma-ray log and not necessarily any related missing section. Dafoe and Williams (2020a) found core 1 to be middle to late Albian to late Albian, in general agreement with the findings of Fenton and Pardon (2007), but further suggesting that middle Albian section may be present.

Inner shelf or prodelta

The interval from 1182 m to 1087 m is characterized by a sandstone-dominated succession according to sidewall core results (Compagnie Française des Pétroles (CFP), 1979), but the Canstrat log and cuttings indicate a more claystone-dominated interval. Claystone is brown, very silty and sandy, with siderite bands, chert fragments, and scattered medium- to coarse-grained sand. Sandstones are grey to light brown or white, medium- to coarse-grained, moderately sorted, poorly cemented, and calcareous and further include a silty matrix, scattered very coarse-grained sand grains, orange feldspar, chert grains throughout, angular to subrounded grains, lithic quartz grains, rare carbonaceous flakes, rare pyrite, and rare glauconite. In the gamma-ray profile, two subtle coarsening-upward units can be observed (Fig. 31).

The coarse-grained nature of the strata and subtle progradational trends seen in the gamma-ray log suggest a proximal setting. There is a conspicuous lack of fossils and an indication of relatively immature sediment interpreted here to reflect inner shelf or possibly prodeltaic conditions. Caro et al. (1980) found a similar inner to middle shelf setting, but Miller and D'Eon (1987) gave a much deeper outer shelf to bathyal paleoenvironment with turbidites explaining the presence of sand. This deep-water interpretation is inconsistent with the palynomorph assemblages noted by Fenton and Pardon (2007).

This part of the well was suggested to comprise much of the upper Gudrid Formation by Moir (1989; 1195–1084 m). However, in the present study, the interval is considered to be part of the basal Kenamu Formation based on the Ypresian (Early Eocene) age from Fenton and Pardon (2007), the claystone lithology, and the proximal location of the well where Gudrid Formation sandstones were not likely preserved during the associated regression. Fenton and Pardon (2007) also showed overwhelming numbers of Eocene palynomorphs (no microfossils) attesting to a Ypresian age, including *Apectodinium* *homomorphum*, and confirming that the Kenamu Formation sits atop the Bjarni Formation as described here.

Middle shelf

From 1087 m to 1000 m is an interval of brown silty, very fissile, micaceous shale, with thin siderite bands, scattered very fine- to medium-grained sand grains, and rare pyrite.

The reduced silt and sand content compared to the underlying interval is suggestive of a deepening event, but the lack of fossils is unusual for a middle shelf setting, indicating that there may have been continued deltaic or brackish influence. Deeper-water, outer shelf to bathyal depths were interpreted previously (Miller and D'Eon, 1987; Caro et al., 1980), but the dispersed sand within the claystone would appear to contradict this interpretation.

There is a major break in the lithology as shown in Figure 31, which is poorly defined in the cuttings report as claystone with limited characteristics. A log shift at 975 m further complicates any interpretation of the overlying strata. However, the top of the Kenamu Formation can be picked within the lithological gap at 795 m where there is a change to higher resistivity, lower sonic velocity and a slight increase in gamma-ray values. This change in log character is consistent with a shift to finer-grained strata typical at the Kenamu to Mokami Formation transition (Dickie et al., 2011; Dafoe, Dickie et al., in press). Accordingly, the Kenamu Formation in Tyrk P-100 extends from 1182–795 m (Table 56). The middle shelf claystone interval is Ypresian (Early Eocene), with the remaining Kenamu Formation of Middle Eocene age (Fenton and Pardon, 2007) to possibly Late Eocene (Bujak Davies Group, 1989j).

Middle shelf

The interval spanning 776 m to 720 m is composed of a brown claystone that is silty, sandy, and calcareous, with scattered very fine- to medium-grained sand grains. Lesser marlstone is dark brown, silty and slightly shaly.

The silty and sandy nature of the sediment is like that of the underlying middle shelf strata. The lack of fossil content is again atypical and could also indicate some distal deltaic influence. A middle shelf paleoenvironment mostly agrees with the middle to outer shelf and possible middle shelf interpretations of Miller and D'Eon (1987) where they suggested turbidites generated from storms or a deltaic slope, and Caro et al. (1980) also gave a similar middle to outer shelf interpretation. This interval is from within the Mokami Formation and is likely Late Eocene in age based on Bujak Davies Group (1989j), Caro et al. (1980), and Oliver and Thorne (1979). Fenton and Pardon (2007) instead proposed a Middle Eocene age that extends up into the overlying Saglek Formation, which is older than expected according to the regional framework described by Dafoe, Dickie et al. (in press).

Inner shelf

Another gap in the Canadian Stratigraphic Ltd. log (Fig. 31) is overlain by a very silty and very sandy claystone extending from 679 m to 649 m. The brown claystone is silty, with fine- to coarse-grained sand, siderite, and common fossil fragments (indeterminate shell material, bivalve, and gastropod).

The increase in sand compared to underlying strata and fossil abundance and diversity is suggestive of an inner shelf setting. This is a shallower setting than previously proposed: middle to outer shelf (Caro et al., 1980; Miller and D'Eon, 1987), but is reasonably supported by the data. This interval marks the top of the Mokami Formation in Tyrk P-100, and is likely Early Oligocene in age (Bujak Davies Group, 1989j). Accordingly, the Mokami Formation is interpreted here to extend from 795–649 m (Table 56).

Shoreface

A thick sandstone and lesser conglomerate succession is present between 649 m and 395 m. The fine- to coarse-grained sandstone is blocky and found in 30–200 m thick units. This sandstone and conglomerates are light brown to yellow or white, poorly to moderately sorted, locally coarsening upward, with subrounded and lesser subangular clasts, common fossil fragments (gastropod, indeterminate shell material, worm tubes, and bivalve), common pebbles (quartz, iron, igneous, and feldspar), localized black chert grains, rare lignite, rare brown claystone, rare silt, and rare siderite. The gamma-ray log confirms an overall relatively blocky interval with a lesser ragged character (Fig. 31).

The blocky nature of the sandstone, fossil diversity and abundance, and coarse-grained nature is suggestive of shoreface deposition, with the abundance of fossil material at the base consistent with erosive conditions. Caro et al. (1980) gave a deeper, middle to outer shelf setting, but the inner shelf to lower shoreface interpretation of Miller and D'Eon (1987) agrees well with the present study. This interval forms the basal Saglek Formation and is Early Oligocene to Early Miocene (or older; Bujak Davies Group, 1989j).

Inner shelf

The final interval in Tyrk P-100 is from 395 m to 380 m and is composed of grey silty, sandy claystone with medium- to coarse-grained sand, rare quartz pebbles, and rare indeterminate shell fragments.

Based on the gamma-ray log, this interval appears to be a thicker claystone within an overall coarse-grained succession. The sandy nature of the strata and presence of shell material is interpreted to reflect inner shelf deposition, a setting that matches that of Miller and D'Eon (1987). This part of the Saglek Formation appears to be followed by a return to a sandstone or conglomeratic facies based on the gamma-ray log, such that the formation extends to 345 m at the top of the log, rather than the 372 m indicated by Moir (1989; Table 56). An Early Miocene age is plausible (Bujak Davies Group, 1989j).

Lithostratigraphy

Based on the discussion around lithostratigraphic refinements to the framework of Moir (1989) in Tyrk P-100, the lithostratigraphic picks from the present study are summarized in Table 56. There are no type or reference sections in this well.

Lithostratigraphic unit	Moir (1989)		The present study		Type or reference section
	Base (m)	Top (m)	Base (m)	Top (m)	
Saglek Fm	649	372	649	345	None
Mokami Fm	762	649	795	649	None
Kenamu Fm	1084	762	1182	795	None
Gudrid Fm (upper)	1195	1084	--	--	None
Bjarni Fm (Snorri Mb)	1523	1195	1523	1182	None
Alexis Fm	1702	1523	1702	1523	None
Unnamed Paleozoic	1706	1702	1706	1702	None
Unnamed Precambrian	1739	1706	1739	1706	None

Table 56: Lithostratigraphic assignment for Tyrk P-100 from the present study and compared to that of Moir (1989). Fm=Formation; Mb=Member.

SUMMARY

A variety of datasets were combined to develop best-fit paleoenvironmental interpretations for the 28 Mesozoic–Cenozoic wells of the Labrador margin. Where possible, analyses of well logs, lithology, fossil content, and core studies were considered. The results provide a refined, consistent, and regional paleoenvironmental assessment for the wells, which can be integrated with the stratigraphic framework described in Dafoe, DesRoches et al. (in press) and Dafoe, Dickie et al. (in press).

Changes in paleoenvironments reflect regressions and transgressions, and in some cases pronounced unconformities. Accordingly, these changes were also helpful in refining some lithostratigraphic boundaries. Formation tops within the wells were modified where lithological changes, log breaks, biostratigraphic breaks, and/or paleoenvironmental changes indicated a major depositional boundary. As a result of these modifications, most type and reference sections for the Labrador margin are also modified in the present study. The results from the present study provide a basis for future studies of the paleogeography and broader stratigraphic variations of the Labrador margin over time.

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APPENDIX A
Legend for all well plots

Header	Type and reference sections	Lithology		
CCore – Conventional core	1 – McWhae et al. (1980)	Conglomerate	Dolomite	Coal
CP – Casing point	2 – Dafoe and Williams (2020b)	Sandstone	Anhydrite	Volcanic
D – deep	3 – This study	Siltstone	Gypsum	Igneous
M – medium		Shale	Salt	Metamorphic
RSec. – Reference Section		Marlstone	Siderite	Other
TSec. – Type Section		Limestone	Siliceous	

Biostratigraphy

AL – Albian	CO – Coniacian	MI – Miocene	PP – Plio-Pleistocene
AP – Aptian	CR – Cretaceous	NA – no age assignment	PR – Priabonian
AQ – Aquitanian	CV – caved	NEO – Neocomian	PZ – Paleozoic
BA – Barremian	DA – Danian	NG – Neogene	RU – Rupelian
BAR – Barren	E – early	OD – or older	SA – Santonian
BMT – Basement	EO – Eocene	OL – Oligocene	SE – Selandian
BR – Bartonian	IND – indeterminate	OR – Ordovician	SEN – Senonian
BS – basal	INT – intrusives	PA – Paleocene	SR – Serravallian
BU – Burdigalian	L – late	PC – Precambrian	TH – Thanetian
CA – Campanian	LT – latest	PEN – Pennsylvanian	TO - Tortonian
CAR – Caradocian	LU – Lutetian	PI - Piacenzian	TU – Turonian
CE – Cenomanian	M – middle	PLE – Pleistocene	UC – unconformity
CH – Chattian	MA – Maastrichtian	PLI – Pliocene	YP – Ypresian

Paleoenvironment

AL – alluvial	DY – dyke	MD – middle	SI – sill
ASR – altered sedimentary rock	EM – embayment	MM – marginal marine	SL – slope
BA – bathyal	ES – estuary	MR – marsh	SQ – subaqueous
BD – braided	FL – fluvial	MS – middle shelf	SU – sublittoral
BE – beach	FP – floodplain	NE – neritic	SW – swamp
BK – brackish	FW – flow	NM – nonmarine	TD – tidal
BMT – basement	IG – igneous	OF – offshore	TF – tuff (subaerial)
BR – bar	IN – inner	OO – open ocean	TR – transitional
BS – basalts	IS – inner shelf	OS – outer shelf	TU – turbidite
CA – carbonate	IR - intrusive	OU – outer	UP – upper
CH – channel	LA – lacustrine	PD – prodelta	VC – volcaniclastic rock
DF – delta front	LG – lagoon	RE – regressive	WB – weathered basement
DI – distal	LI – littoral	RF – reef	
DL – deltaic	LW – lower	SA – shallow	*Note that some paleoenvironments required simplification to fit on the figure. Please refer to original references for more detail.*
DS – distributary	LSHF – lower shoreface	SB – subaerial	
DP – delta plain	MA – marine	SF – shoreface	
	ME – meandering	SH – shelf	

Lithostratigraphy

AF – Alexis Formation	FR – Freydis Member	LM – Leif Member	PZ – Paleozoic
ALT – altered	GF – Gudrid Formation	LW – lower	SF – Saglek Formation
BA – Basalt	GT – Gudrid Tongue	MB – Member	SI – sill
BF – Bjarni Formation	IN – intrusion	MF – Markland Formation	SM – Snorri Member
CF – Cartwright Formation	KF – Kenamu Formation	MOF – Mokami Formation	UN – unnamed
FM – Formation	LC – Late Cretaceous	PC – Precambrian	UP – upper