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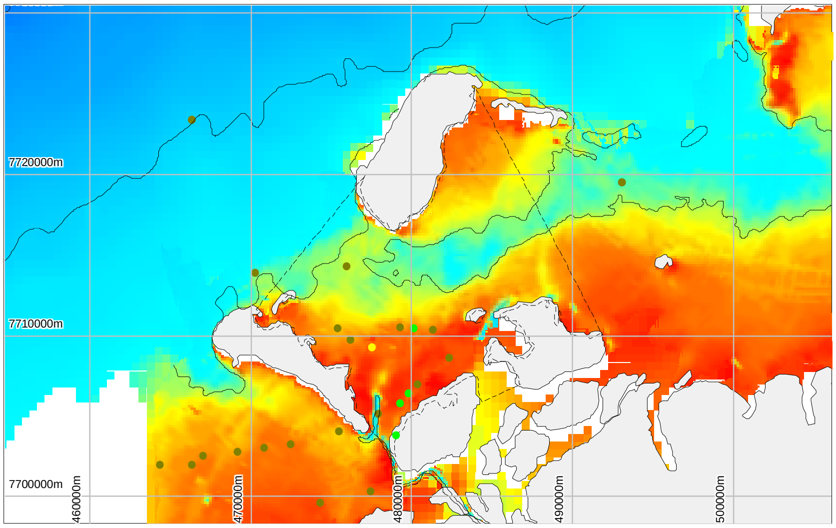
The Mineral Potential of the Proposed Mackenzie Delta Marine Protected Areas

S.M. Solomon



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EXECUTIVE SUMMARY

This study addresses the evaluation of mineral and aggregate resources in the 3 candidate Marine Protected Area (MPA) sites identified by the Department of Fisheries and Oceans (DFO) in the southern Canadian Beaufort Sea. In this report, they are referred to as Mackenzie Bay, Kendall Island and Kugmallit Bay MPAs. The MPA sites were defined based on the boundaries of the Zone 1a areas as established under the auspices of the Beaufort Sea Beluga Management Plan (BSBMP). At the present time, BSBMP guidelines exclude oil and gas exploration, production or related construction and mining activities in these areas. As part of the process of developing regulations that would govern the proposed MPA, non-renewable resource assessments are required.

Non-renewable resources within the Beaufort MPAs include two general types: industrial minerals and metallic minerals. Industrial minerals refer to sand and gravel (aggregates), silica sand, calcium carbonate and phosphorite. Metallic minerals, often referred to as placer minerals, are usually concentrations of heavy minerals with a specific gravity greater than quartz. In general, the proposed MPAs are in very shallow water locations, so that many of the usual surveys required for the assessment of marine minerals are not available. In particular, there are no useable high-resolution seismic or sidescan sonar surveys within the MPAs. This limits our understanding of subsurface and surficial conditions to only those specific locations where samples or boreholes have been collected. Extrapolation between samples and boreholes had to be undertaken by analogy with other locations and/or based on our understanding of sedimentary processes and depositional models in those environments.

Because of these limitations, assessments employ a likelihood of existence system, which can accommodate situations where sample data is lacking and other indirect evidence such as the presence of suitable source rock, appropriate depositional environments and known geological history is applied. It can also accommodate negative factors such as dilution by glacial depositional processes or burial by recent sedimentation. Thus, this report includes an extensive summary of the available data on sedimentary texture and mineralogy and interpretations of geological history and sedimentary processes. The mineral assessments are based on a combination of sediment texture and heavy minerals and local depositional models.

Sources of industrial minerals to the MPAs include the sediments transported by the Mackenzie River, materials eroded from the adjacent delta and older tundra deposits which fringe the MPAs. However, in general, the Mackenzie River supplies only very fine sand and silt, so it is a less important source than reworked coastal deposits. Coastal deposits form from erosion and reworking of sediments by waves which accompany wind storms occurring during the open water season. Waves attack coastal cliffs and rework sediments on beaches and in the nearshore resulting in removal of the fine materials (silt and clay) and the concentration of coarser sediments and associated heavy minerals. Wave energy is limited by the length of the ice-free period, extent of open water, the intensity and direction of storm winds and the shallow depths which characterize the nearshore zone.

Of the 215 surficial grab samples with textural information compiled from water depths of 5 m or less in the Beaufort-Mackenzie region, 5 samples were located in the Mackenzie Bay MPA (1165 km^2), 13 samples in the Kendall MPA (205 km^2), and 40 samples in the Kugmallit Bay MPA (379 km^2). Sampling density is obviously very low. Nine boreholes with textural data were located within the Kendall MPA; only one very shallow (< 1 m) borehole is located in the Kugmallit Bay and 7 boreholes are located in the Mackenzie Bay MPA. The fraction of sand in most of the samples within the MPAs is less than 75% and for many is less than 25%.

Aggregate resources in the form of sand and lesser amounts of gravel are known to occur on beaches and in the offshore regions of the Beaufort Shelf and there are potentially exploitable deposits of sand and gravel within the MPAs. In all cases, there was insufficient data to quantify either the extent or quality of the potential resource, therefore, they are classified either as known or speculative occurrences. Table 1 summarizes the estimated quantities of materials in the known occurrences for each MPA. Considerable additional work would be required to quantify those occurrences with some confidence. In most cases, we have quantified potential resources in waters adjacent to beaches. Exploitation of those types of deposits would cause rapid and potentially severe erosion of the adjoining subaerial deposits. In addition, we anticipate that any deposits in water depths of less than 1-1.2 m are likely to be ice-bonded within 1-2 m of the seabed.

Table 1: Aggregate potential in the proposed MPAs

MPA	**Known Occurrence**
Mackenzie Bay	8 x 10^6 m^3
Kendall Island	17 x 10^6 m^3
Kugmallit Bay	3 to 13 x 10^6 m^3 0.25 to 0.5 x 10^6 m^3 4.5 x 10^6 m^3
Total	33 to 43 x 10^6 m^3 (conservative estimate) 183 to 493 x 10^6 m^3 (speculative)

The scale of the individual estimated MPA resources are generally similar to the scale of some of known offshore resources (Macleod, 1993). For example, the Issigak deposit located offshore from the Kendall Island MPA has about 14 x 10^6 m^3 of quantified, probable and speculative amounts of sand and gravel. It is similar in magnitude to the occurrence in the Kendall area and may be an example of a drowned coastal deposit.

Heavy mineral potential of the MPAs is considered to be low to very low based primarily on the lack of observed heavy mineral concentrations in either source material or marine sediments and the relative lack of marine energy available for sorting and concentrating minerals. However, the presence of precious metals and diamonds in the region and the relative paucity of directed sampling efforts indicate that the possibility cannot be ruled out.

More accurate and complete assessment of the non-hydrocarbon resources within the proposed MPAs and adjacent nearshore waters will require a significant investment in surveying and sampling. Shallow waters with acoustically “hard” bottoms associated with sand and permafrost are notoriously difficult environments for geophysical surveying. However, given the scarcity of surface samples and cores in the proposed MPAs, we would recommend that efforts be made to improve the sampling density both for aggregate and for geotechnical purposes.

1 INTRODUCTION

This study addresses the evaluation of mineral and aggregate resources in the 3 candidate Marine Protected Area (MPA) sites identified by the Department of Fisheries and Oceans (DFO) in the southern Canadian Beaufort Sea (Figure 1 – see Terms of Reference in Appendix 1)). For the purposes of this report they are referred to as Mackenzie Bay, Kendall Island and Kugmallit Bay MPAs. The sites are located entirely in shallow waters of the estuary of the Mackenzie River with their landward boundaries defined by the low tide line. The MPA sites were defined based on the boundaries of the Zone 1a areas as established under the auspices of the Beaufort Sea Beluga Management Plan (BSBMP). At the present time, BSBMP guidelines exclude oil and gas exploration, production or related construction and mining activities in these areas. As part of the process of developing regulations that would govern the proposed MPA, non-renewable resource assessments are required.

The report is based on published and gray literature and unpublished data that is currently held by the Canadian Government. The timeframe for delivery of the assessment precluded any new data collection or any detailed reinterpretation of existing data. Much of the information available for this report was collected for other scientific purposes, mostly to do with potential development of hydrocarbons; therefore, there is little specific literature on aggregate and mineral potential in these specific localities. This is despite the extensive aggregate explorations that were undertaken by oil industry in the region during the 1970s and 1980s (MacLeod 1993 and references therein). This report includes

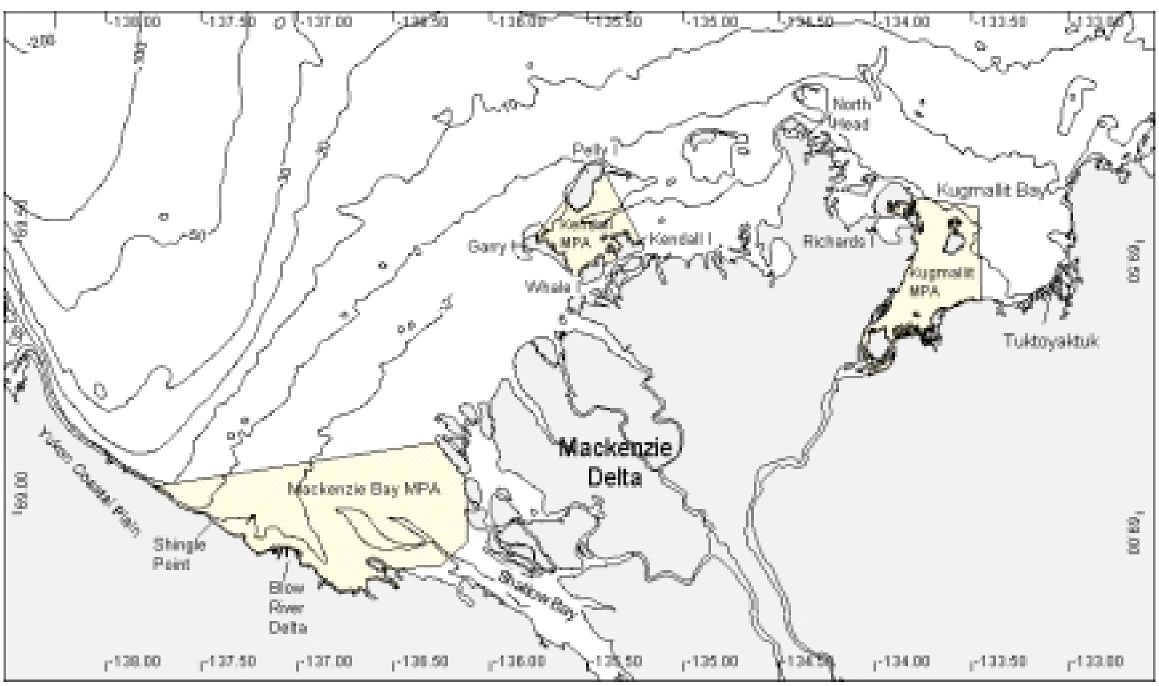


Figure 1: Study area location of the three proposed MPA sites (in yellow) and place names used in the text

a review (section 3) of the regional physiography, oceanography and geology and the associated processes that control the distribution of sediment in the region. The mineral assessment section (4) includes a description of the database of sediment texture and heavy minerals and the depositional models upon which the assessment is based.

2 MARINE MINERALS AND MINERAL ASSESSMENT PROCEDURES

2.1 Marine Minerals

Marine minerals on the continental shelf are classified into two general types: industrial minerals and metallic minerals. Industrial minerals include sand and gravel (aggregates), silica sand, calcium carbonate and phosphorite. Shelf metallic minerals, often referred to as placer minerals, are usually concentrations of heavy minerals with a specific gravity greater than quartz. Placer deposits can be divided into allochthonous and autochthonous types. Autochthonous placers are residual deposits formed close to their source and include gold and platinum. Allochthonous minerals form through processes of selective grain sorting and can occur at great distances from source. Examples include zircon, rutile, ilmenite, garnet and diamonds.

Metallic minerals can be sourced from terrigenous and sometimes marine rock types. Those considered to be of economic value are gold, platinum group metals, rutile, zircon, monazite, garnet, ilmenite and magnetite. Industrial minerals tend to occur in large deposits and have a low unit volume while metallic minerals command higher unit values and generally occur in localized deposits of low volume. Emory-Moore (1993) evaluated geological controls on the formation of placer deposits in a former glaciated environment for the Newfoundland region. In order to determine potential mineral areas, characteristics such as sediment cover, mineral occurrences, bedrock lithologies, ice flow directions, transport distances and drainage basin locations were evaluated. This approach identifies and ranks areas based on their suitability to contain placers.

2.2 Mineral Assessment Procedures

Scoates et al. (1986) developed a procedure for assessing mineral potential. Geological environment, knowledge of mineral occurrences, likelihood of accumulations and uncertainty are criteria established to rate the mineral potential of a region. The potential ranges from “not assessed”, through “low”, “moderate” and “high” ranges and is given numeric ratings ranging from 1 to 7 where 1 represents very high potential and 7 very low. Areas to be assessed in this proposed MPA mineral potential study are divided into regions and are delineated on the basis of bedrock geology and coastal geomorphology (physiography).

It is also important to clarify definitions regarding potential mineral resources as a framework for mineral assessment. A *resource* is a mineral concentration the existence of which we are confident based on fact. If it can be extracted economically, it is considered a *reserve*. Many so-called resource inventories are in fact geological assessments that determine only the likelihood of existence.

The Shelf Working Group (1980) prepared a framework for assessing the mineral potential of an area that incorporates the likelihood of existence and exploitability. This system uses 5 subdivisions of likelihood of existence which are:

1) Quantified deposit: direct evidence demonstrates the quality and quantity of a mineral
2) Known Occurrence: mineral concentrations are known by direct evidence , but quality and quantity are uncertain
3) Speculative occurrence: only indirect indications of minerals such as geological setting suggest a concentration
4) Unknown: direct or indirect evidence in not sufficient to indicate a mineral occurrence
5) Absent: direct evidence is sufficient to indicate no presence of a mineral occurrence

This classification is also useful for this study. The likelihood of existence system can accommodate situations where sample data is lacking and other indirect evidence such as the presence of suitable source rock, appropriate depositional environments and known geological history is applied. It can also accommodate negative factors such as dilution by glacial depositional processes or burial by recent sedimentation.

Industrial minerals (principally sand) are known and expected to occur within proposed MPAs based on knowledge of: bedrock geology, Quaternary geology, sediment texture and mineralogy, sea level history and geological history of the Beaufort coast and shelf. There is little evidence to suggest the presence of placer minerals in economic quantities, but the possibility cannot be ruled out without more directed sampling and analysis. These will be discussed in more detail in the following sections.

3 BACKGROUND INFORMATION

This section provides information on the regional physiography, physical processes, bedrock and surficial geology and Quaternary history of the study area. Information about onshore characteristics is important because the MPA borders are at the low tide line and the land is the primary source of coarse materials and heavy minerals. This information is used to infer mineral potential in areas where sampling is limited.

3.1 Study Area: Regional Physiography and Permafrost Regime

3.1.1 Onshore

The 3 MPA candidate areas are at the mouths of distributary channels of the Mackenzie River and lie almost entirely within the estuary in water depths of 5 m or less (Figure 1). The delta and valley are bounded on the west by the narrow Pleistocene uplands of the Yukon coastal plain, which are backed in turn by the Richardson Mountains. On the east, the delta is split by Richards Island, a large area of Pleistocene uplands consisting of gravel and sand hills, till plains, organic-rich drained lake basins and ice-thrust terrain with variable amounts of ground ice (Rampton, 1982, 1988; Dallimore et al, 1996; Murton et al. 1997). Maximum elevations on Richards Island are 60-70 m, however most coastal elevations are less than 30 m. On the west side of Richards Island, the delta has prograded over the Pleistocene terrain and left high-standing outliers of Pleistocene materials surrounded by the fine-grained modern delta sediments (Figure 2). To the east of Richards Island the East Channel of the Mackenzie River cuts through the Pleistocene materials of the Tuktoyaktuk lowlands to discharge into Kugmallit Bay. A delta has formed at the head of the Bay mostly within the confines of the Kugmallit Bay proposed MPA.

The low bluff coast of the Blow River delta lies west of the modern Mackenzie River delta. Still further west, 20-30 m high coastal cliffs composed of hummocky till-capped terrain and drained lakes beds extend past Shingle Point. The main part of the Mackenzie delta is composed of a subaerial delta plain, the distributary channel mouth region and the subaqueous delta (Hill et al, 2001). Relief on the modern delta plain is low and generally featureless; elevations at the coast are 1-1.5 m above mean sea level. The monotony is broken by an occasional pingo with heights of up to 15 m. Abandoned channels and lakes cover 30-50% of the upper delta (lake density of >3 km^{-2} – Hill et al, 2001). In the lower delta plain, lakes appear less numerous, but there are many small ponds in addition to a few large lakes. Channels are anastamosing with a predominance of bifurcation and they occupy 20% of the delta plain surface (Hill et al, 2001). Elevations of channel levees vary from 9 m above summer water levels at the head of the delta, to less than 1.5 m near the coast (Hill et al. 2001). At the channel mouths, primary channels (> 5m water depth) carry much of the river flow and can extend up to 15 km beyond the coastline forming submarine distributaries (Hill et al, 2001). Secondary channels which form as a result of bar accretion are shallower (1-2 m water depth).

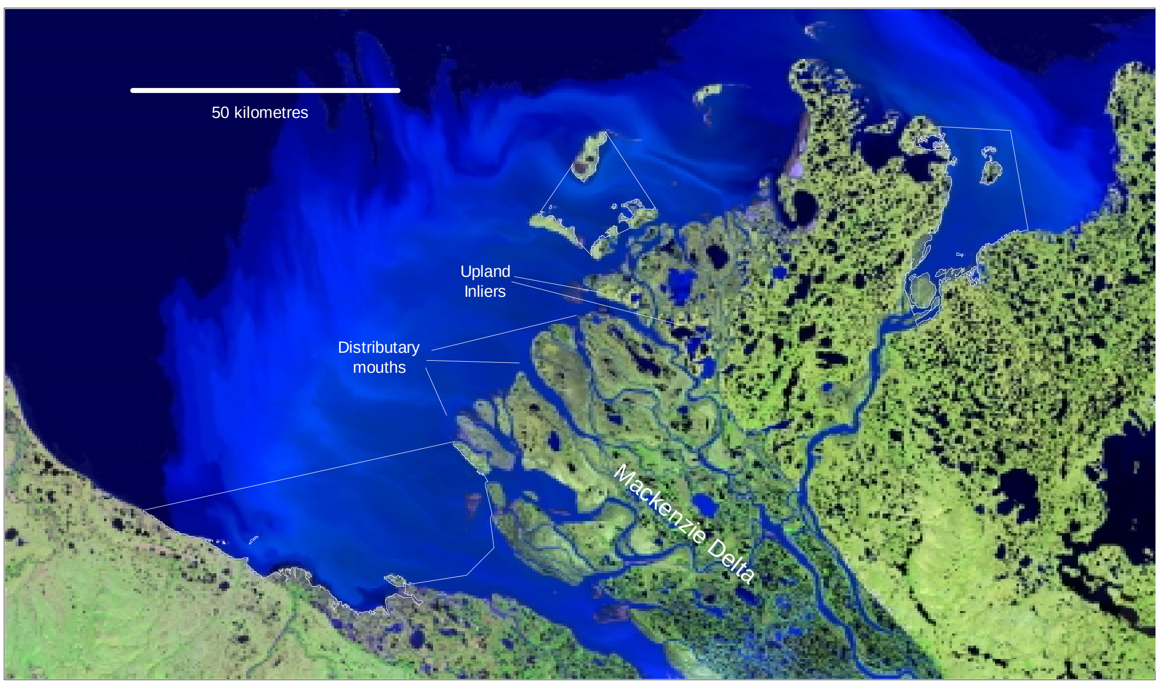


Figure 2: Landsat image of the lower and middle Mackenzie River Delta and the surrounding terrain. The brighter green areas east and west of the delta are Pleistocene uplands. There are inliers of upland terrain on the east side of the main delta where it has spilled out of its glacially cut trough. The bright blue water shows the location of the Mackenzie River freshwater and sediment plume. This image is a mosaic compiled by E. Malta of the Canadian Wildlife Service based on imagery from several years.

The shoreline of the main delta is characterized by lobe-shaped vegetated islands separated by funnel-shaped bays (Hill et al 2001). The islands are fronted by erosional coastal bluffs composed of peat, silt and fine sand which are eroding at mean rates of 2.5 m a^{-1} (Harper, 1990) and up to 10 m during single storm events. Flooding at the outer coast is common, based on the presence of recent silt and clay deposits and driftwood on the delta surface. Bar accretion occurs in the interior of large embayments where they may be emergent and at the mouths of distributary channels where they are lower. The erosional nature of the delta front, drowned morphology and other features indicate that the Mackenzie River delta is undergoing transgression resulting in limited water depths for sediment accumulation.

The modern delta is underlain by permafrost to depths of more than 60 m (Dallimore and Matthews, 1997) which formed as deposition raised the subaqueous delta above sea level during its development over the past 10,000 years. At the Unipkat well, 25 km from the delta front, permafrost conditions were established within the past 4500 years (Taylor et al, 1996). In the adjacent older upland areas, permafrost has formed over a much longer time period and can reach over 700 m in thickness on Richards Island (Judge, 1986). Taliks, in some cases extending entirely through the permafrost layer exist under lakes and river channels which are deeper than 1.5 m (Mackay, 1979 as cited in Hill et al, 1990). The active layer thickness varies depending on sediment and surface characteristics such as snow cover and vegetation types but is invariably less than 1.2 m and is usually less than 0.5 m.

3.1.2 Coastal areas

The coastal fringes of the proposed MPA and adjacent areas are characterized by narrow fringing beaches backed by moderate to low cliffs composed of silt and peat in the modern delta or sand and diamict in other locations (Figure 3). Less frequent, wide fringing beaches are found in areas of abundant sand supply. Extensive spits form at exposed headlands. In some locations barrier islands have formed where spits have become detached from their headland sources. The spits and barriers are characterized by storm berms which rise 1.5 –2 m above sea level and they are cut by frequent wave washover channels which are formed during storm surges. Most spits and barriers are migrating landwards at rates of >1 m a^{-1}. Beach and nearshore profiles in most of the areas backed by upland terrain are characterized by a relatively steep slope from the water line flattening out at about the 3-4 m depth. Detailed profiles are not available at the modern delta front, but beaches are virtually non-existent and water depths within 10 m of the bluff are close to 1 m. The nearshore water depths do not exceed 2 m until a distance of about 15 km from the waterline except in channels (see below). As discussed above, subaqueous and emergent bars are found at distributary channel mouths. Many of them exhibit some degree of erosion on the seaward-facing sides.

Figure 3: On the left, an oblique air photo of the low silt and peat bluff (< 2 m above mean sea level) with recent mud deposition on the delta top. The width of the deposit is 100-150 m. The photo on the right shows a typical sand and gravel beach in front of an actively eroding cliff approximately 10 m high.

Permafrost in the coastal regions is complex because the thermal environment changes so rapidly from the subaerial to the submarine conditions. The region includes the inter- and supratidal environments of the beaches and flats. Tides, waves and storm surges periodically inundate these environments, winnowing or depositing sediments, adding salts and affecting the thermal regime (Are, 1988). Thaw rates and active layer thickness in intertidal zones are controlled by sediment texture (i.e. permeability), sea water salinity and temperature, snow cover, erosion and deposition of sediments, and air temperatures. The mean annual ground temperature regime in the coastal zone is largely unaffected by vegetation, however snow cover and sediment dynamics do play a role (e.g. Dyke and Wolfe, 1993; Dyke, 1991). Sediment deposition raises the intertidal surface insulating and protecting permafrost beneath whereas erosion exposes permafrost to degradational influences (positive water and air temperatures, elevated salinity).

High ice content in the form of pore, wedge and massive ice is typical of some coastal localities. Where these ice bodies straddle the water line, rapid subsidence will take place when thaw fronts intersect them (e.g. Wolfe et al 1998). Thermokarst depressions resulting from thaw consolidation in nearshore and coastal environments are likely to be quite transient as sediments from adjacent areas are scavenged by normal coastal processes. However, the accommodation space created by intertidal thermokarst processes may play a role in forcing local erosion rates and nearshore thermokarst will have substantial impacts on coastal infrastructure (e.g. pipelines).

3.1.3 Nearshore and Offshore

With the exception of the extreme western portion of the study area, the nearshore is very shallow. Within most of the MPAs and adjacent areas in front of the modern delta, water depths are less than 2 m at distance in excess of 15 km from the shore, except where primary channels are present (Figure 4). Where channels do exist, they do not cross the inner shelf, but terminate by shoaling. The termination has the appearance of broad distributary mouth bar (Hill et al, 2001). Hydrographic surveys in the study area are difficult because of the shallow water depths. Where field sheets are available there appears to be subtle relief in the shallow water depths which reveal a system of slightly shallower bars or platforms on a scale of kilometres, which are separated by slightly deeper channels. Very limited side scan surveys in the region in water depths of less than 4 m suggest that transient shallow scours form due to moving ice, possibly during break up of the landfast and bottom fast ice cover in the spring (Zevenhuisen and Solomon 1994). In water depths of less than about 1.5 m, sea ice freezes to the seabed generally confining winter river discharge to the channels. However, adfreezing of sediments to the base of the ice suggests that it may be periodically lifted off the bed by tides and/or storm surges.

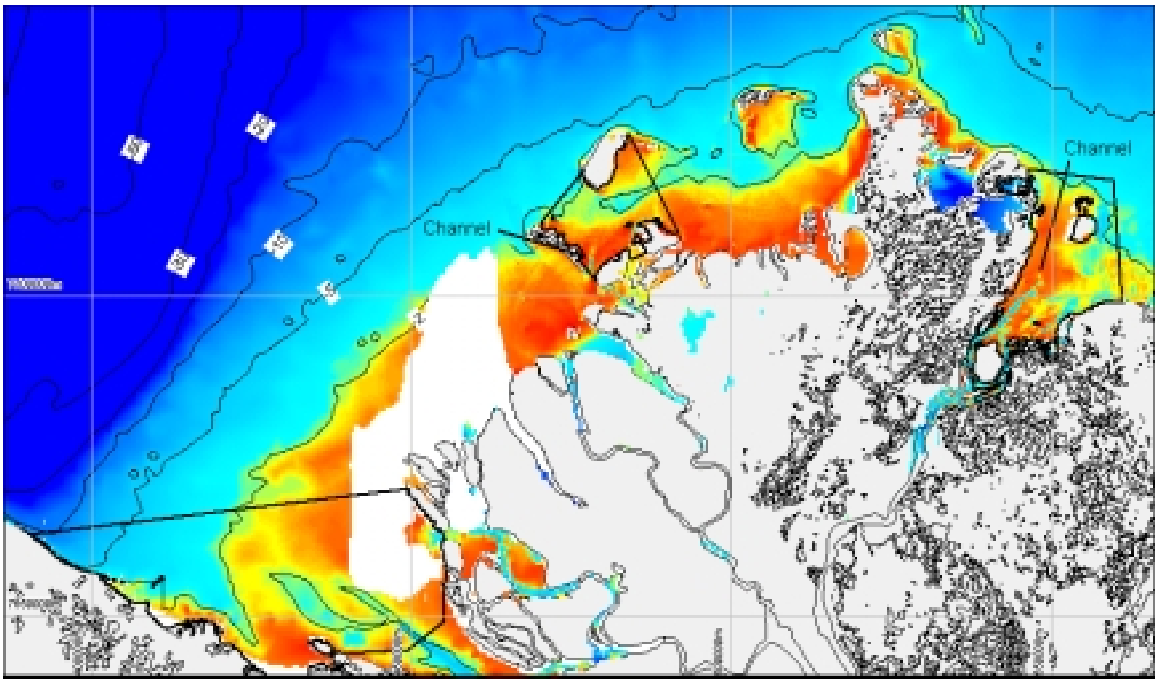


Figure 4: Most of the MPAs are within the 2 m isobath; all are within the 10 m isobath. Distributary channels can be identified crossing the foreshore and extending part of the way across the inner shelf where they terminate by shoaling. (Grid is UTM, zone 8 northings and eastings, NAD83).

In some parts of the study area the morphology of the seabed suggests that it was influenced by the initial land surface morphology. Field studies in embayed coastal settings reveal that inundation of areas with lakes with bottoms that are below sea level, result in complex systems of shoals and deeper basins (Hill and Solomon 1999). The deeper parts of the Kendall Island MPA may represent relict lake basins that have not yet been infilled. Surrounding shoals would thus represent the surrounding upland areas. Nearshore shoals are present in the lee of most of the outer islands

At the extreme west end of the study area, west of Shingle Point, the nearshore region is quite narrow; the 5 m contour is within 1 km of the shoreline. Beach and nearshore profiles at King Point (Hill et al., 1990), 10 km west of the MPA boundary, are much steeper and more concave than those at the delta front or on Richards Island (Figure 5).

Profiles on the seaward edge of the outer islands in front of the Delta (Ruz et al, 1992) at North Head and along the southern parts of the Kugmallit Bay coast are similar in that they flatten out at depths of several metres. Barred coasts tend to form where supplies of sand are high due to erosion of updrift sources (e.g. the west side of North Head – Figure 1), but they are less common than unbarred coasts. In sheltered locations where sand supply is large, shore-attached oblique or transverse bars form (e.g. Kittigaaryuit – Figure 6, Solomon, 2002).

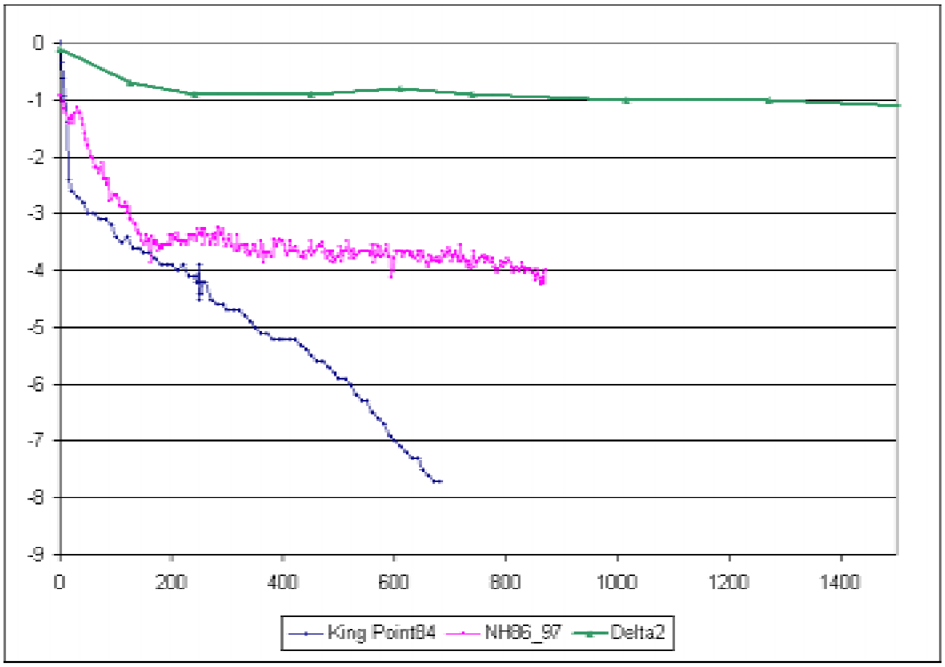


Figure 5: Typical seabed profiles from the Mackenzie Delta front (top curve), the North end of Richards Island (middle curve) and the Yukon coast at King Point (bottom curve) reveal significant differences due to wave exposure, sediment supply and stratigraphy. The y-axis is elevation below mean sea level in metres and the x-axis is distance from the shoreline in metres. The bottom 2 profiles are based on surveyed data; the top profile was generated from a grid interpolated from hydrographic field sheets and charts.

Permafrost may be either aggrading or degrading within the bottomfast ice zone depending on mean annual bottom temperatures which depend in turn on water depth and open water season sea water temperature. Brine rejection during freezing of the seawater and surficial seabed sediments can create localized high salinity conditions in the sediments which infiltrate the seabed. Once the sea ice is coupled to the seabed, a seaward-thinning seasonal active layer develops (e.g. Osterkamp et al. 1989; Dyke, 1991; Wolfe et al. 1998; see also citations and figures in Vigdorchik, 1980 – pg 32, 33). This zone is also characterised by very high horizontal temperature gradients and seasonally reversing vertical subbottom temperature gradients affecting seabed sediments to depths in excess of 10 m (Hunter, 1988). In the 2-10m water depth range, mean annual seabed temperatures are above 0° C because of the influence of the warm Mackenzie River plume. Therefore permafrost degrades from the top. The depth to the top permafrost in this zone increases to 10s of metres in many locations (O'Connor and Associates, 1982; Hunter et al, 1976).

Figure 6: Shore-attached oblique bars are forming in the intertidal zone at the base of the beach at Kittigaaryuit National Historic Site (within the proposed Kugmallit Bay MPA).

3.2 Sea Ice and Oceanography

The coastal areas of the Beaufort Sea are ice-covered for 8 to 9 months of the year. Freeze-up begins typically in October and break-up in June. The ice is often frozen to the seabed in water depths less than 2 m. Floating landfast ice extends offshore to a shear zone at the edge of the mobile polar pack. Pressure ridges, which develop in the shear zone, cause widespread scouring of the seabed in water depths greater than 8 m. The landfast ice zone is most extensive in the Mackenzie Delta region. The sea ice forms a protective cover preventing wave attack at the coasts during this time period.

During the open water season, ice-free fetches of more than 100 km are common. Strong winds, which become increasingly frequent in late August and September, blow predominantly out of the west and northwest, with a secondary mode from the east. Winds blowing over open coastal waters generate significant wave heights of 4 m or more with peak periods up to 10 s (Pinchin et al., 1985). The range of astronomical spring tides is no more than 0.5 m, but winds can generate positive and negative storm surges (Henry, 1975). The maximum storm surge limit in the Tuktoyaktuk area is about 2.5 m above mean water level (Forbes and Frobel, 1985; Harper et al., 1988). Water level changes during surges occur over a few hours and can generate significant currents (>0.5 m/s) within restricted embayments (Solomon and Forbes, 1993). Higher water levels during storms also allow larger waves to reach the shore and increase the limit of wave run-up. These northwest storms with attendant waves are responsible for suspending and transporting sediments in water depths of less than 10 m. Sediment transport from west to east is responsible for the development of large sand and gravel spits and barriers associated with exposed headlands.

3.3 Mackenzie River regime and sediments

The Mackenzie River is an obvious source of sediments to the coastal, nearshore and marine environments. The mean annual suspended sediment load (> 90% silt and clay) delivered to the delta is estimated to be 128 Mt with about 4 Mt of sandy bed material (Carson et al, 1998). Approximately half of that material ($65_{\pm}15$Mt) is estimated to be deposited in the delta itself (MacDonald et al, 1998) leaving about 63 Mt to be deposited in the marine environment. Since virtually all of that material is finer than sand sized, it is likely that it is only deposited in the nearshore where it is sufficiently sheltered so that it is not resuspended and advected offshore during storms. These sheltered environments are not conducive to the development of coarse aggregate or mineral placer deposits, therefore the modern Mackenzie River input is not considered to be an important source of materials for this assessment. It does play a role in the burial of potential deposits.

3.4 Late Quaternary History

The Quaternary period in the region was characterized by periodic glaciations accompanied by significant fluctuations in sea level of more than 140 m below present sea level during full glaciations (Hill et al, 1985). The timing and extent of glaciations during the last 40,000 years is somewhat contentious and the maximum glacial extent over the continental shelves remains a topic of active debate (Rampton, 1988; Hill et al, 1985; Dallimore et al, 1997). Without examining the details of the debate, there is evidence for a maximum extent of glaciation in the Early Wisconsinan which extended out onto the continental shelf. This was followed by deposition of sand and gravel outwash deposits. Aeolian deposits (Kittigazuit Formation) of Mid-Wisconsinan age (37,000 y BP) are overlain by diamict indicating a partial readvance sometime after 33,700 y BP which covered the Tuktoyaktuk Peninsula, Richards Island and parts of the Beaufort Shelf (Dallimore et al, 1997). The region was thought to have been ice-free by 20,000 y BP.

In the offshore, on the Eastern Beaufort Shelf, the earliest date from Wisconsinan sediments is from a fibrous peat in a sequence of sandy interbeds (Unit E) 135 m below sea level (Blasco et al, 1990). The date of 27,380 yBP indicates that the upper 100 m of sediment is younger than Late Wisconsinan and sea level has risen from a low stand of –140 m or more since that time. Lower (unit E) and upper (Unit C) sandy deposits are interpreted to be glaciofluvial outwash deposits. Unit C may have been deposited by a prograding deltaic and outwash system from a Late Wisconsinan ice advance (possibly close to the continental glacial maximum at 18000 yBP). The intervening fine grained Unit D is associated with a radiocarbon date on peaty mud of 21,260 y BP and is interpreted as an inner shelf, marine depositional environment. Deep valleys and lake basins are incised into the upper surface of Unit C indicating a period of subaerial exposure with sea levels at 70 m below present during the Late Wisconsinan. Holocene sea level rise has reworked the upper surface of Unit C and eroded pre-existing surficial sediments. Unit B represents the reworked Unit C sediments, along with the products of terrestrial erosion and fluvial inputs from the Mackenzie River in a high energy depositional setting. The uppermost Unit A is fine grained and consists of soft marine silts and clays deposited in relatively deep water beyond 10 m. Correlation between offshore and onshore is problematic, since offshore sediments which have been examined are younger than the units found onshore.

The offshore Mackenzie trough is thought to have been excavated to its maximum depth by ice in the Early Wisconsinan (Blasco et al, 1990) with a possible readvance during the mid- to late-Wisconsinan (15,000 y BP), coincident with a Tutsieta Lake advance as proposed by Hughes (1987). Transgression following the retreat of the ice is associated with the development of Glacial Lake Mackenzie 300 km up-valley from the modern delta during the period from 11760 to 10290 y BP (Smith, 1992). Following the drainage of the lake, the Mackenzie Delta prograded down the lower Mackenzie Valley and into the trough. The delta had reached Inuvik by 6900 y BP (Johnston and Brown, 1965) and a point several tens of km beyond the current subaerial delta position by 2000-3000 y BP (Hill, 1996). Since that time the delta front has been retreating (present rates of 2.1 m a^{-1} (Harper, 1990).

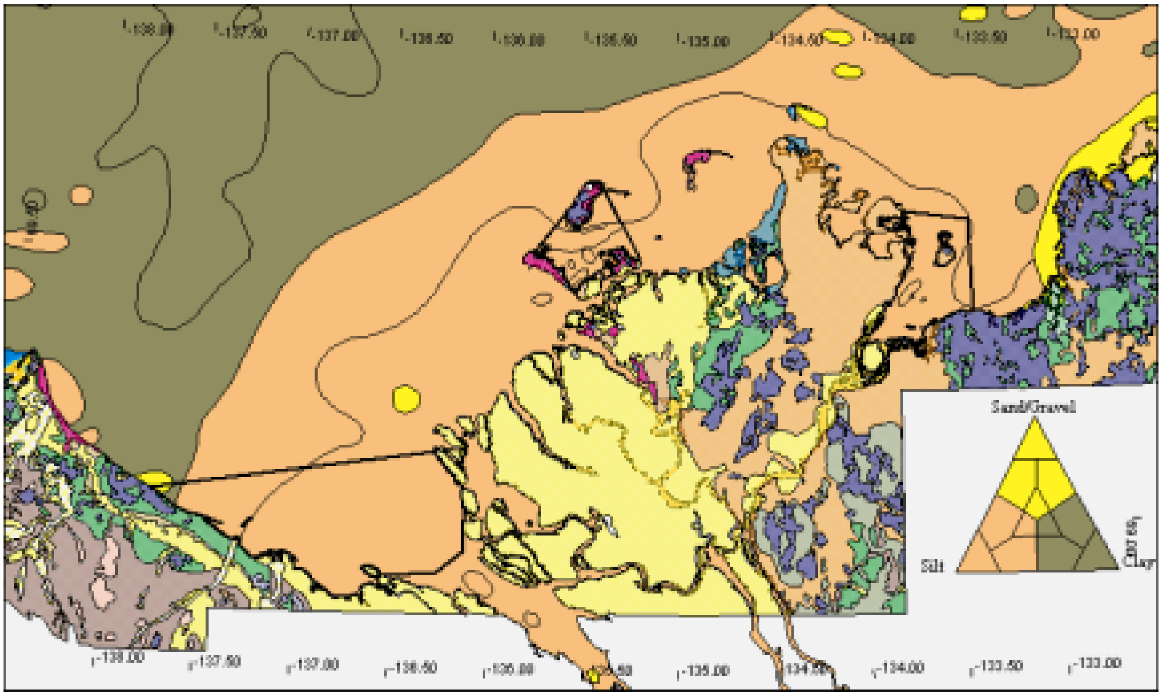
3.5 Recent Sea Level History

Sea level history in the region is important for assessing aggregate and heavy mineral resources because the zones of energy which control sediment movement from offshore to onshore migrate back and forth across the continental shelf as sea levels rise and fall. These variations in energy are responsible for separation of coarse and fine sediments (e.g. sand and gravel from silt and clay) and of heavy and light minerals (e.g. gold from quartz). Relative sea level has been rising at about 1-2 mm a^{-1} for the last 3000 years (Hill et al, 1993; Campeau, 2000). This is close to the eustatic rate. Recent tide gauge records suggest a rate of 2.5-3.5 mm a^{-1}. The rise in sea level is reflected by the transgressional nature of most to the Beaufort Sea coast which is characterized by erosional cliff or bluff shorelines.

3.6 Regional Stratigraphy and Surficial Geology – Sources and Sinks of Aggregate and Minerals

3.6.1 Onshore

The onshore surficial materials are the primary sources of coarse-grained sediments and placer materials supplied to the nearshore and coast regions of the MPA through erosion. Their properties and distribution are therefore very important for the assessment of the mineral potential of the MPAs. The surficial geology in the onshore region adjacent to the proposed MPAs was mapped by Rampton (1988) as a mixture of modern alluvial and lacustrine deposits and older Pleistocene and early Holocene, uplands, hills and ridges. The upland regions are composed of aeolian and/or glaciofluvial deposits of the Kittigazuit Formation (Rampton, 1988; Dallimore et al, 1997). The deposits consist mainly of sand of which 79-81% is in the fine to very fine range with a mean grain size of approximately 3ø (about 0.125 mm). In most locations the Kittigazuit Formation is overlain by a gravel lag or thin clay diamicton (Toker Point Till) and underlain by the less well-sorted sand of the Kidluit Formation. Occasional bouldery beds must be present in one of these formations since boulders are known to be scattered over intertidal and shallow subtidal flats close to Tuktoyaktuk (Mackay, 1963) and in the vicinity of Kittigazuit Island at the mouth of East Channel (Solomon, 2002).



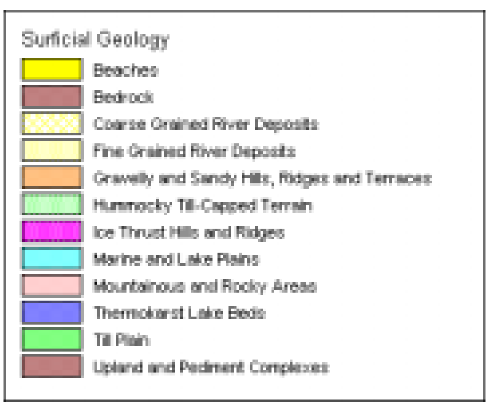


Figure 7: The surficial geology of the onshore and offshore are shown in this figure. Most of the Mackenzie River Delta is composed of fine-grained river deposits. The western end of the Mackenzie MPA is backed by till and till-capped terrain and thermokarst lake beds. The Kendall MPA is backed by lake beds, alluvium and ice thrust terrain. The Kugmallit MPA is backed by alluvium and gravely/sandy hills and ridges. (The surficial mapping is from Rampton in Pelletier, 1984). Nearshore surface texture is dominated by silt.

The surficial geology of the proposed Mackenzie Bay MPA is dominated by modern alluvial sediments of the Mackenzie and Blow River deltas. These are the fine-grained materials (silt, fine sand and silty clay) with abundant organic debris assigned by Rampton (1988) to the Aklavik Formation. West of the Blow River Delta, the older Yukon coastal plain sediments abut the coastline. These consist of a combination of morainal and lacustrine deposits. The morainal sediments form a series of cliffs 5-20 m in elevation and extending from the Blow River to the west of Shingle Point. They are fronted by sand and gravel fringing beaches, and 2 large spit complexes at the mouth of the Running River and at Shingle Point. The morphology of the spits indicates sediment transport from west to east and they consist of coarse sand and gravel. The beaches tend to be wider to the west of Shingle Point than they are to the east. The morainal deposits typically contain 5 to 20% of material which is coarser than 2 mm (sand sized) although the proportion is higher in areas where they are underlain by gravel deposits (Rampton, 1982). The westernmost portion of the proposed Mackenzie Bay MPA is abutted by lacustrine deposits likely of a thermokarst origin (Rampton, 1982). These deposits are mostly fine grained and organic rich.

The proposed Kendall Island MPA is bounded by surficial morainal deposits found on the islands. The morainal material is considered by Rampton (1988) to be a veneer overlying undifferentiated glacial sediments. The east side of Garry Island and part of Whale Island are composed of glaciofluvial deposits consisting of sand and gravel. Ice thrust features have been noted on Garry and Kendall Islands indicating the presence of an ice sheet, probably during the Early Wisconsinan Toker Point stade (Rampton, 1988).

The proposed Kugmallit Bay MPA is bounded by surficial deposits of modern alluvium (Aklavik Formation) to the south, by aeolian sands to the west and, to the east, by a mixture of glaciofluvial outwash and themokarst lake deposits with inliers of relatively thick (4-12 m) morainal materials. The alluvial materials consist of silt and fine sand deposited in the delta of East Channel. The modern aeolian sands are derived from and overlie the Kittigazuit and Kidluit sands. Glaciofluvial outwash deposits are 3-30 m thick and probably related to the Toker Point till deposits. The lacustrine materials are composed of silt, clay and fine sand with abundant organic material (4-5% - Solomon et al, 2000). According to Rampton (1988), the base of the lakes and their shore may be characterized by sand and gravel, if surrounding units or parent materials contain those constituents. The morainal materials are composed of stony clay diamicton with typical proportions as follows: 3-25% clasts> 2mm; 10-30% sand; 25-45% silt and 30-50% clay.

3.6.2 Offshore

The surficial materials on the seafloor of the Beaufort Shelf were mapped by Pelletier (1984) based on the texture of the materials (Figure 7). As mapped, silt and mixtures of silt with sand or clay dominate the regions within the proposed MPAs; no sand-dominated deposits were identified. In water depths of less than 5 m, onshore-offshore drilling programs at the north end of Richards Island depict sand and gravel-dominated beach and surf-zone units which grade rapidly offshore to laminated marine silts (Dallimore et al, 1988). Unpublished data from vibrocores acquired in the nearshore region at the N and NE sides of Richards Island (Solomon et al, 1992) are dominated by silts with little sand in water depths 3.5 m and greater. These coarser sand and interbedded mud deposits are essentially equivalent to the Unit B transgressive materials found beneath the Unit A muds in the offshore. Along the Tuktoyaktuk Peninsula coast, north of Tuktoyaktuk, the influence of the Mackenzie River Plume decreases and coastal sediments in water depths of 3.5-4 m are dominated by sand and gravel (Héquette and Hill, 1989). Sand and gravel sediments in water depths of >5 m along the Tuktoyaktuk Peninsula coast are covered by marine mud.

3.7 Bedrock Geology and Mineral Occurrences

The location and types of bedrock in the region are important because they are the source of metallic minerals which are transported and concentrated in placer deposits in rivers, coastal and marine settings. All three of the proposed MPAs are immediately backed by unlithified, but frozen coastal plain sediments deposited during the Pleistocene glacial and recent post-glacial period. As such, there is no known bedrock in their immediate vicinity. However, the MPAs are fed by rivers which drain a range of bedrock terrain. To the west of the Mackenzie Delta, the Yukon Coastal Plain is backed by the mountains of the northern Cordillera, which consist of structurally complex folded and faulted Mesozoic rocks. At the present time, gravel in the river beds of the Yukon North Slope consists primarily of resistant quartzitic sandstone with some exceptions (MacDonald and Lewis, 1973). To the east, the Mackenzie Delta and unlithified coastal plain is underlain and backed by largely undeformed rocks of the northern Interior Platform. These are Proterozoic and lower Palaeozoic clastics and carbonates which are in turn overlain by Cretaceous clastic sediments.

Norris and Hughes (1997) have compiled a list of mineral occurrences in the region based on the tectonic (or large-scale structural) elements which host them. The primary tectonic elements which either back or drain into the MPAs are: the Barn Uplift, the Rapid Depression, and the Aklavik Arch Complex (Figure 8). The Romanzof Uplift and Old Crow-Babbage Depression primarily drain into the Beaufort Sea to the west of the MPAs. The Aklavik Arch Complex appears to be the dominant source of minerals to the MPA regions, however, the local and subregional glacial and river patterns during the Pleistocene period will have had an affect on the distribution of minerals from all of the potential mineral sources. Mineral occurrences in the area are summarized in Table 1 (Norris and Hughes, 1997).

In all cases these are occurrences without sufficient information to allow them to be classified as to their abundance or economic significance. The Aklavik Arch Complex occupies and affects the Northern Interior Platform, and the mineral occurrences reflect that source being largely confined to those sedimentary hosted deposits. To the west of the MPAs, placer gold was mined from the Firth River in the late 1800s to the early 1900s.

Table 1: Commodities associated with the tectonic elements in the Mackenzie/Beaufort Drainage Region (after Norris and Hughes, 1997). Numbers in parentheses refer to the tectonic elements shown in Figure 8.

Tectonic Element	**Commodity**
Romanzof Uplift (1)	Au, W, Cu, Mo, Coal
Old Crow-Babbage Depression (2)	W, Pb, Zn, Cu, U, Mo
Barn Uplift (3)	U, W, Mo
Rapid Depression (4)	Sr, P, U, Cu, Fe, Coal
Aklavik Arch Complex (5)	gypsum, Fe, Zn, F, U, P, Ls, Dol, Coal

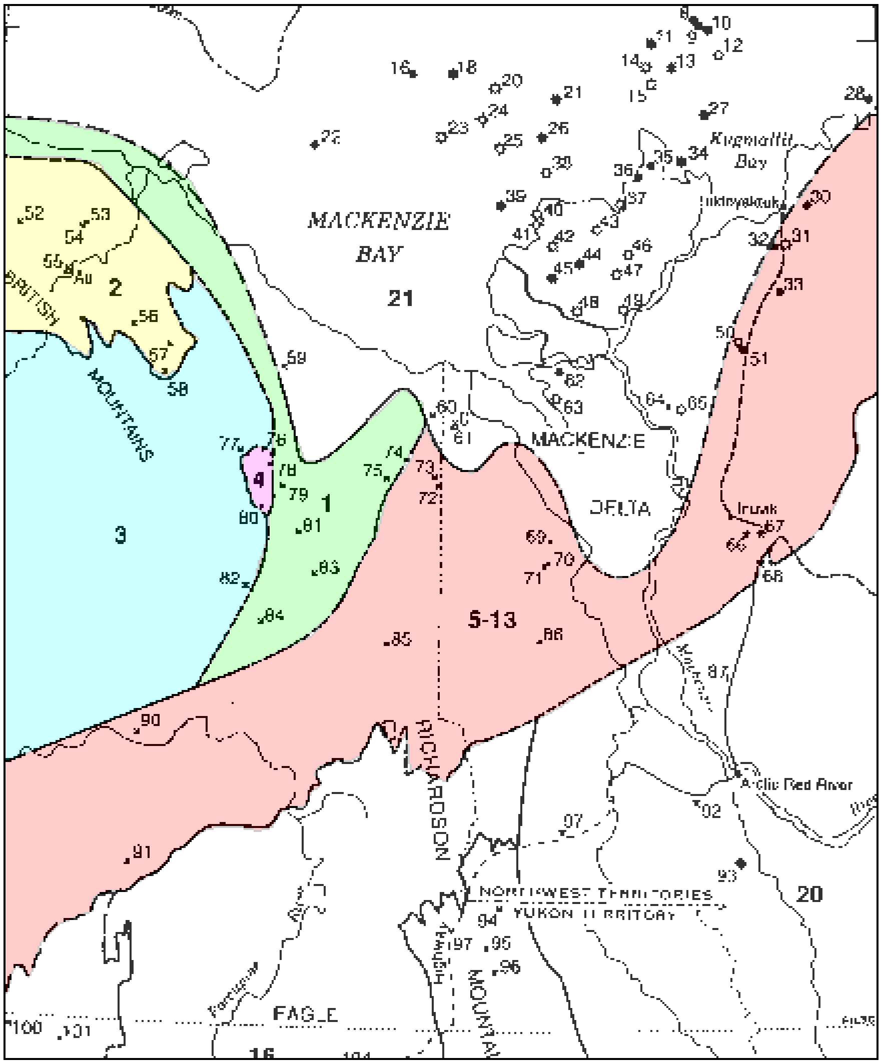


Figure 8: Tectonic elements which drain into the Mackenzie-Beaufort MPAs host a limited suite of potential mineral deposits.

1. Romanzof Uplift

2. Old Crow-Babbage Depression

3. Barn Uplift

4. Rapid Depression

5. Aklavik Arch Complex

After Norris and Hughes, 1997.

The source of the placer gold is unknown, but the gold appears to be far travelled (Norris and Hughes, 1997). It is also worthwhile to note that the recent successes of exploration for diamonds in the Yellowknife region and to the North has resulted in exploration moving towards the Mackenzie Delta region, 300 km north of Norman Wells and an equal distance from the Delta (Terry Halifax, Northern News Services, Inuvik, Feb 14/03).

4 MINERAL ASSESSMENT

4.1 Positioning and boundary issues

The boundaries of the MPAs were based on the Beaufort Sea Beluga Management Plan Zone 1a areas. The digital files provided by DFO Winnipeg contained the following information on the lineage of these files:

> "The Beluga Management Zones were on screen digitized from updated locations provided in the management plans. The basemap was the digital 1:250k NTS series. The data provided included a map with Lat/Long locations in DMS. Occasionally small compromises had to be made between the values given and the boundaries on the map (most notably in Husky Bay, Banks Island). In these situations, the "spatial" location on the map prevailed, in that the DMS was ignored and the "spirit" of the map was reproduced. All of the values were within 0.001 DD (3.6 degree seconds) of the given location, so it was felt that the accuracy remained good, both to the spirit of the paper map as well as the DMS locations. The BMZ areas were checked against the previous areas that had been digitized under SPANS, and again, they seemed true. In those areas where the BMZs bordered coastlines, the coastline was extracted and used as the border."

The abbreviations in the quote refer to: degrees, minutes and seconds ("DMS"), decimal degrees ("DD"), Beluga Management Zone ("BMZ"); SPANS is a type of geographic information systems software.

The use of existing coastlines to define the border means that the actual geographic position of the borders of the MPAs is in error (Figure 9) because:

1. the coastline along the MPA is dynamic and changes on the order of 10s to 100s of metres have occurred since the maps were developed and
2. the coastlines as defined on NTS sheets and CHS charts are only accurate to within 100-300 m.

The position of the boundaries of the MPA may need to be redefined based on the latest positioning and imagery (preferably, the Tarin 2000 orthophoto database where it is available) or surveyed based on the legal requirements of the MPA and Oceans Act legislation. The base that was used to define the boundaries coincides with the 1:250,000 NTS mapsheets and is incorrectly positioned by 100-300 m, however the differences are variable.

Erosion also affects the position of the MPA boundary if is it defined by the low tide line. Changes occur very rapidly along the Beaufort Sea coast, with erosion and coastal retreat dominating over much of the coastline. Recent changes (over the past 30-50 years) will affect the boundaries of the MPAs (i.e. the position of the low water line) and the mapped location of some of the potential mineral deposits. Examples of rapid coastal change are found at the NW tip of Tent Island (300 m in 22 years), the northern tip of Pelly Island 350-450 m over 28 years), the southern shore of Kugmallit Bay (160 m in 28 years) and the spits off the NW end of Garry Island (> 100 m of retreat over 28 year). As described below, changing shoreline positions influence potential volumes and quality of offshore aggregate materials.

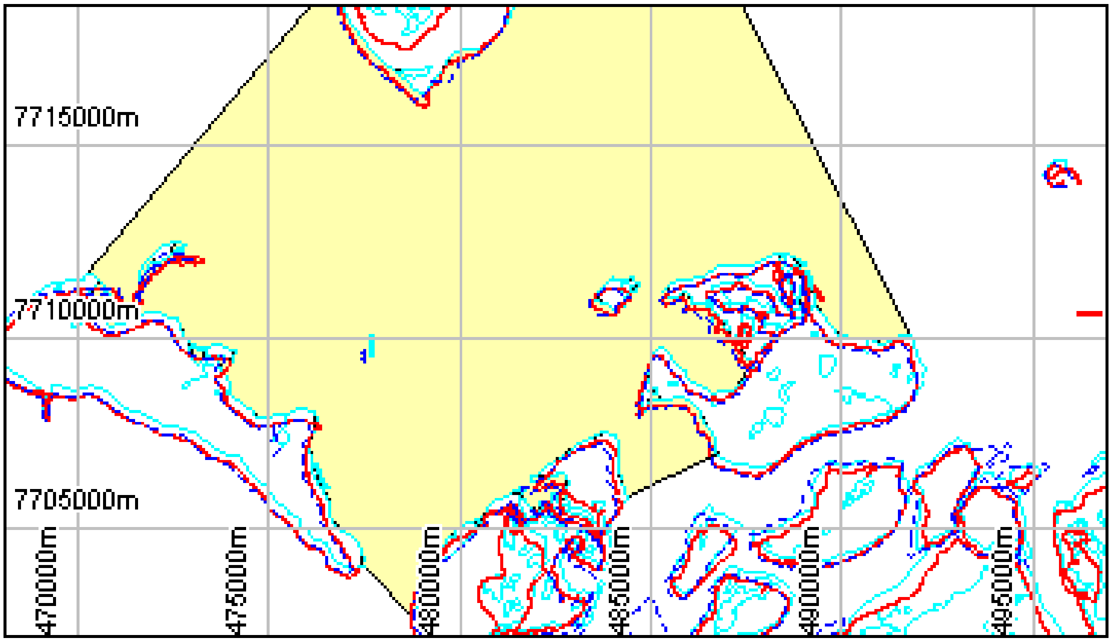


Figure 9: Erosion and mapping inaccuracies combine to generate differences between various available coastlines and the MPA boundaries. In this example from the Kendall Island MPA, the red line is a high water line generated using orthophotos acquired in 2000 (Tarin database – 1: 50000), the blue dashed line is from the CHS chart 7662 (1:150000), the cyan line is from the 1:250000 NTS. The MPA boundary was supplied by DFO Winnipeg. Except for erosion, the CHS and Tarin files are similar, however the MPA boundary differs by about 200-300 m. (Grid is UTM, zone 8 northings and eastings, NAD83).

4.2 Data Base

4.2.1 Sediment Texture

Sediment sampling in the nearshore region within the study area commenced in 1969 with a series of scientific cruises largely directed from the Bedford Institute of Oceanography. Much of the data was collected in order to develop a better understanding of the geological conditions in the region in support of hydrocarbon exploration. The results of surficial geology studies were published in two reports (Pelletier, 1975; Pelletier, 1984). These reports summarize the general sediment texture and mineralogy of the Beaufort Shelf. Vilks et al (1979) describe the marine environment of the Beaufort Shelf, with an emphasis on micropaleontology using the same sample set as Pelletier. Fifty-six surficial sediment sample locations were collected within the proposed MPAs (Pelletier, 1984); however, detailed textural analyses are only available for a subset of those locations. No cores within the proposed MPAs or adjacent shallow waters were obtained during the 1970s sampling period. Similarly, seismic and acoustic investigations of the stratigaphy were confined to water depths greater than 10 m (outside the proposed MPAs and related shallow waters).

In the 1980s the Northern Oil and Gas Action Program (NOGAP) spurred a new round of data collection. Sampling, coring and seismic/acoustic data collection in shallower water was enabled by the use of new ships and instrumentation with much of the work being done in water depths of 5-10 m (just beyond the boundaries of the proposed MPAs). The results of the NOGAP are summarized in Hill et al. (1990) and reported in several papers (Hill et al, 2001; Héquette and Hill, 1989). Additional sampling and coring in shallow water was performed in the 1990s at the end of the NOGAP program in the vicinity of North Head and as part of coastal programs funded largely by climate change concerns. Some of these data have been reported by Solomon and others (Solomon et al, 1992; Solomon and Forbes, 1993; Solomon, 1993; Dallimore et al, 1996; Wolfe et al, 1998).

A complete shallow water surficial and core database was developed for this assessment (Figure 10). Considerable time was spent in order to sort out problems related to old data and database issues. Textural data from original hand-written spreadsheets and computer printouts were obtained from original data holders, but many of the original sample locations had not been included in the newly developed sample database at the Geological Survey of Canada (Atlantic). In order to find locations for as many samples as possible efforts were made to acquire original navigation data from cruises and, where that was impossible to incorporate sample locations from older maps. Samples from the following sources or cruises have been compiled (Table 2).

Table 2: Names of marine and coastal surveys which included sediment sampling

LEVINSON70	70MACKENZIE-HELICOPTER
70RICHARDSON	70PARIZEAU
71ARCTIC_HELICOPTER	71PARIZEAU
RADIUM EXPRESS76	87NAHIDIK
71PARIZEAU	90HILL
ARKTOS91	95301
96303	97303
2001303	

Sample locations for all of the cruises except LEVINSON70 and RadiumExpress76 were obtained from documents provided by Dr. B. Pelletier or from the GSC (Atlantic) database. LEVINSON70 samples were located by digitizing sample locations from a map in Dewis (1971). RadiumExpress76 samples were located using offsets from transponder locations found in a field notebook provided by Dr. H. Kerfoot. In the former case, there are uncertainties in positioning because of the map scale and the lack of information about horizontal datum and projection used. Samples could be incorrect by several hundred metres. In the latter case, it was necessary to assume that transponder coordinates provided by the Canadian Hydrographic Survey were the correct ones for the Radium Express Survey (there is good reason to believe they are correct). Additional uncertainties are associated with a lack of information provided in the field notebooks regarding the side of the baseline from which the offsets were calculated. However, despite the uncertainties, bathymetric corroboration was achieved for several distinctive sample locations (e.g. located in a confined and unique deep water location), which

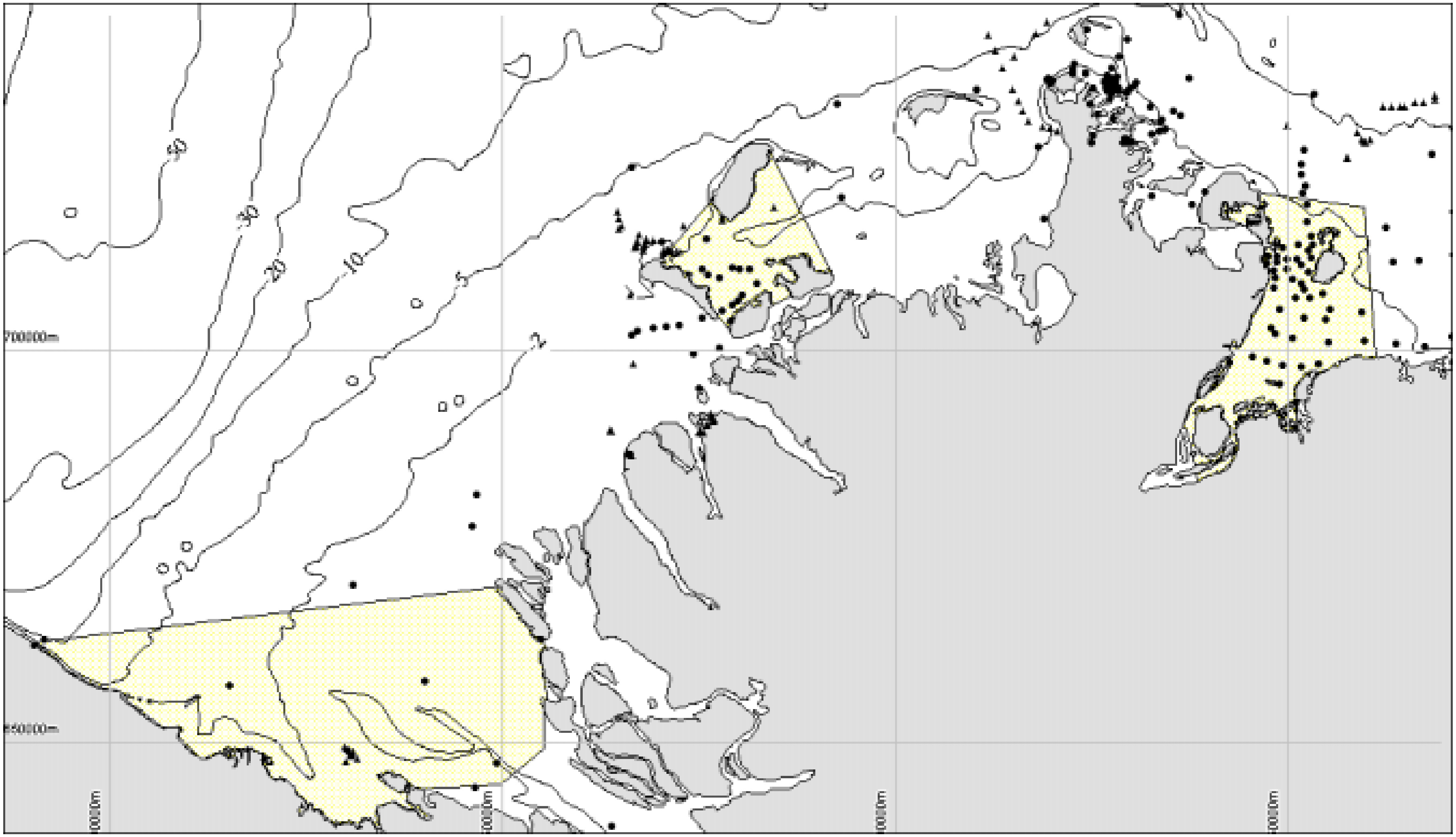


Figure 10: Cores (triangles) and surface grabs (circles) were collected in water depths of less than 5 m for a variety of purposes over the past 40 years. These were used as the basis for the analysis of mineral resources in the MPAs.

provides some confidence in the location of most of the samples. A total of 215 surficial grab samples with textural information were compiled from water depths of 5 m or less. Of these, 5 samples were located in the Mackenzie Bay MPA (1165 km^2), 13 samples from the Kendall MPA (205 km^2), and 40 samples from the Kugmallit Bay MPA (379 km^2). Sampling density is obviously very low.

An additional dataset of sediment core locations and textural analysis was obtained from Indian and Northern Affairs Canada (INAC) (triangles in Figure 10). This database was compiled as part of an effort to preserve aggregate data acquired largely through industry assessment activities during the height of the oil exploration that occurred in the 1970s and 1980s. The database was known to have problems and we found that some of the textural data had been corrupted. Careful comparison with original industry reports revealed the source of the problem and it was corrected for a subset of the data relevant to this assessment. This dataset is extremely important in that it contains information about textural variations with depth. Some additional core data from the 1990s was provided by Dr. P. Hill and his students at Université Québec à Rimouski and from jet drilling undertaken by the GSC (Judge et al, 1976; MacAulay et al, 1977)).

Nine boreholes with textural data from the INAC industry dataset were located within the Kendall MPA; only one very shallow (< 1 m) borehole is located in the Kugmallit Bay and 7 boreholes are located in the Mackenzie Bay MPA. A series of jet-drilled boreholes just to the southeast of the Mackenzie Bay MPA and just to the west of the Kendall MPA provide some additional qualitative information on texture in those regions.

We have assumed that textural data which are reported as percentages of gravel (> 2mm), sand (>0.625 mm), silt (> 0.0039 mm) and clay (<0.0039 mm) use the Udden-Wentworth Scale (Blatt, Middleton and Murray, 1972, p. 46). However, different methods were used to produce the textural analysis data, so there is some uncertainty when comparing results, especially for the clay-sized fraction. Percentage of sand for any given sample are probably directly comparable, however, it is possible that coarser material may be under-represented by grab samples taken with relatively small samplers. The fraction of sand in surficial samples has been mapped (Figure 11). Most of the samples within MPAs are less than 75% sand and many are less than 25% sand. The highest sand concentrations are associated with eroding headlands around North Head.

4.2.2 Heavy minerals

Heavy minerals were examined from samples within the Mackenzie Bay and Kugmallit Bay as part of a sediment dispersal study in the 1970s (Costaschuk, 1980; Pelletier, 1984). The analyses were undertaken on the sand fraction of 166 selected samples and involved quantification of the light, heavy mineral and magnetic fractions. Mineral counts were performed on 30 of the residues from different regions across the Beaufort Shelf. Nine samples from within the Mackenzie Bay MPA and 3 samples from within the Kugmallit Bay MPA were examined for total heavy minerals (none from the Kendall Island MPA). Sand fractions of these samples contained less than 3% heavy mineral (Figure 12). The light fraction includes quartz, feldspar, mica, carbonates and organic

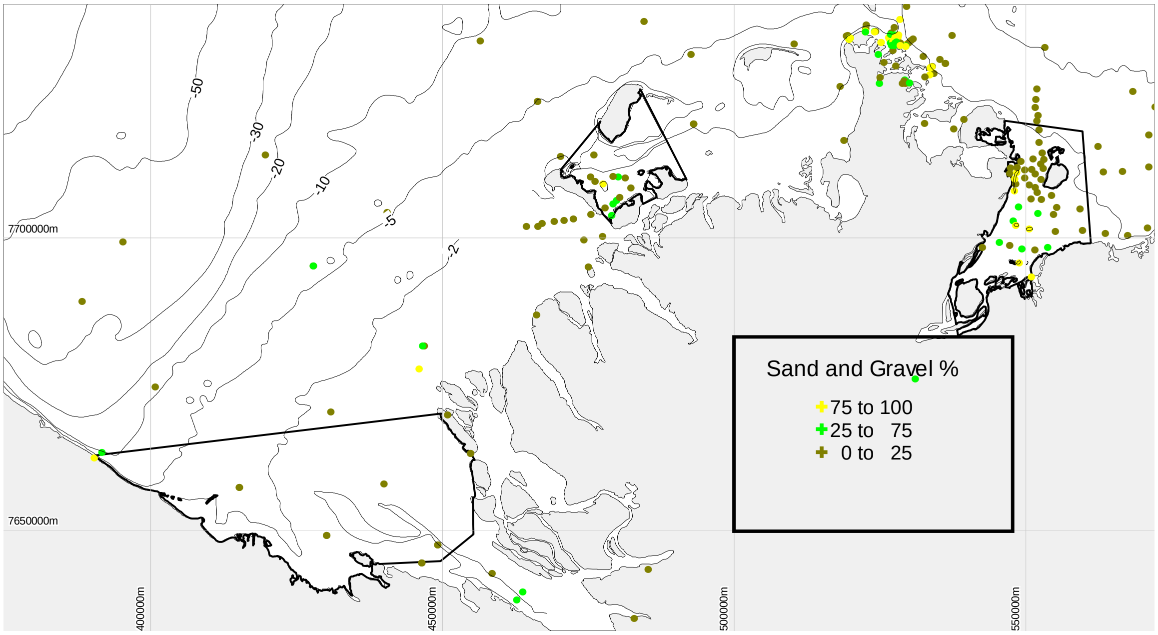


Figure 11: Surface grab samples in the MPAs and in the region are dominated by mud.

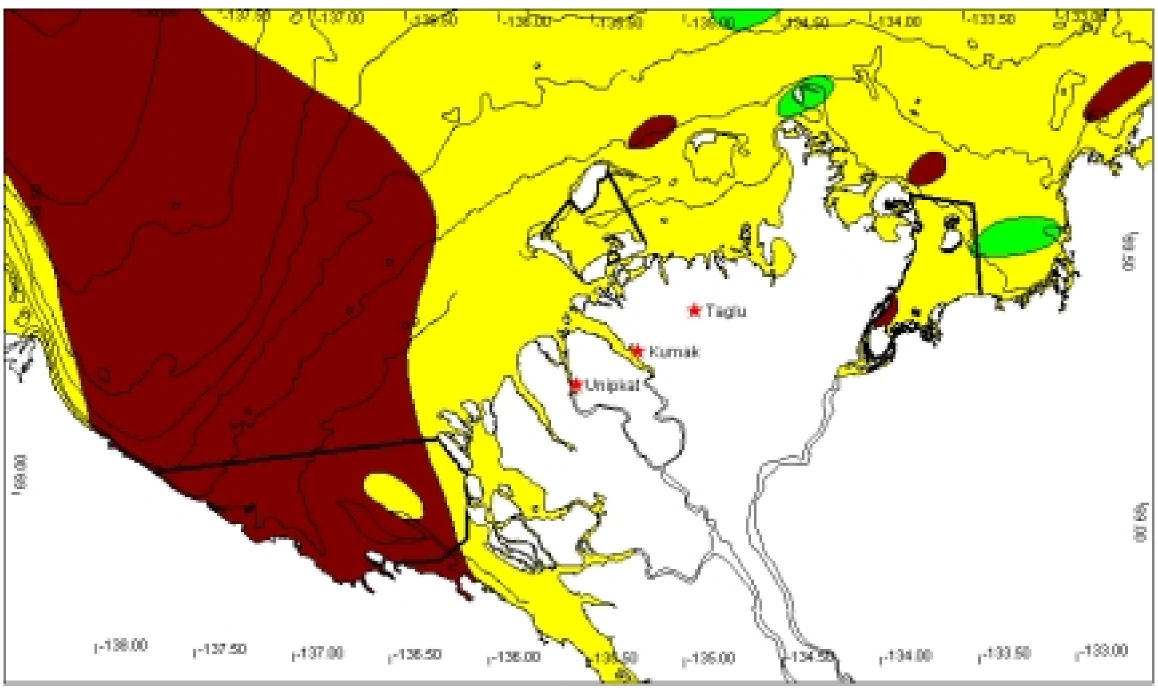


Figure 12: Percentages of heavy minerals in the offshore grab samples (after Pelletier, 1984).

carbon (including coal). The magnetic component is composed of magnetite and ilmenite. The non-magnetic heavy component includes clinopyroxenes, clinoamphiboles, garnet, kyanite, sillimanite, andalusite, apatite, epidote, mica, orthoamphibole, staurolite, zircon, tourmaline, rutile, lazulite, limonite, pyrite, and hematite. Costaschuk (1980) concluded that the cordillera is the main source of heavy minerals west of the Mackenzie Delta and the Canadian Shield is the main source to the east. In general, the marine and coastal sediments are relatively immature suggesting either a lack of reworking or a mixing of a combination of more mature, but mineralogically diverse suite of source materials (i.e. erosion of various glacial and glaciofluvial sediments).

Heavy minerals were analysed in 3 deep boreholes from a transect drilled across the Delta in 1993 (Dallimore and Matthews, 1997). Unfortunately, the total percentage of heavy minerals in the boreholes was not reported. The uppermost sample (1.96 m below the Delta surface) from the Unipkat borehole was characterized by a heavy fraction (> 3.3 specific gravity), which was dominated by siderite (44%). Significant percentages of goethite, orthopyroxene and garnet were also present. Siderite is associated with iron-bearing formations in Lower Cretaceous rocks along the Yukon-NWT border (Rapid Depression); these may be the source of the siderite found at Unipkat. A heavy mineral analysis of a sample from 8.08 m depth from the Kumak borehole was also dominated by iron bearing minerals (siderite – 39%, goethite- 7%, pyrite – 3% and hematite – 2%). No shallow (< 20 m) samples were reported from the Taglu borehole.

Borehole samples from 5 locations in the vicinity of North Head were analysed for heavy minerals (Dallimore et al, 1991). The abundance of heavy minerals as a percent of the total sample was not reported, however, scientists responsible for core logging did not identify heavy mineral accumulations as an important component in the upper portions of the cores. Garnet is the dominant heavy mineral constituent in all of the sand units intersected. Hypersthene, ilmenite and epidote were also important components.

Samples from massive ice and melt-out tills on Summer Island (off North Head) are dominated by goethite and pyrite with lesser amounts of siderite, hematite, garnet and ilmenite (Murton, pers. comm.). Samples from sand wedges on Summer and Hadwen Islands are dominated by garnet, ilmenite, goethite, and hematite (Murton, 1996)

Heavy mineral analyses from samples in the Kidluit and Kittigazuit Formations in the region are referenced by Dallimore et al (1997), but details of the analyses are not available.

4.3 Depositional models, coastal dynamics, and potential sources of aggregate to the shallow nearshore

The proposed MPAs span a range of coastal and nearshore environments with varying potential to host mineral resources. The lack of intensive sampling, the difficulty in obtaining geophysical data in the shallow water environment and the lack of borehole data requires the use of conceptual models to assess the likelihood of existence of various resources. As described in the previous sections, the delta and adjacent upland areas are dominated by unstable coastal cliffs and bluffs with coastal retreat rates of 1 m a^{-1} to more than 20 m a^{-1}. Local areas of deposition include the mouths of some active distributary channels, spits and barrier beaches down-drift from eroding headlands. Much of the modern delta front is erosional, but since the sediments are composed mostly of silt and organic material, there is little coarse sediment released for redistribution.

In general, the environments which characterize the 3 proposed MPAs can be classified based on their onshore source material, the dynamics (erosional or depositional), and their proximity to the surf-zone environment. We identify four settings: three surf-zone proximal settings (two of which are erosional, one depositional) and one distal setting. These are:

1. Upland-backed erosional
2. Delta-backed erosional
3. Deltaic-depositional/channel mouth
4. Nearshore

4.3.1 Upland-backed erosional setting

The upland-backed erosional environment is characterised by a terrestrial and backshore environment that is dominated by older Pleistocene upland terrain of glacial and glacio-fluvial origin. The western section of the Mackenzie Bay MPA (west of the Blow River Delta), most of the Kendall Island MPA and much of the Kugmallit Bay MPA are in this category. These environments are described by Ruz et al (1992); Dallimore et al (1996) Héquette and Ruz (1991) and by Hill and Solomon (1999). Despite considerable variability in the details, these environments share several characteristics (Figure 13). The backshore consists of a steep unvegetated bluff or infrequently a vegetated slope fronted by a narrow to moderately wide fringing beach. Backshore materials are usually fine sand or a stony diamict with variable amounts of ground ice. The beaches are usually composed of a mixture of cobbles, gravel and sand. Beach deposits tend to be thin (1-2 m at most) and are often observed to pinch out at the low tide line (Héquette and Ruz, 1991; Hill and Solomon, 1999). Extensive spits tend to form where prominent headlands exist and these spits may become detached to form barriers (Figure 14) (Ruz et al. 1992). The nearshore profiles in these environments tend to be fairly steep within the surf zone, and then flatten out at depths ranging from 2-4 m in more sheltered locations (and most surveyed locations within the influence of the Mackenzie River Plume). At other locations farther removed from the plume, and/or more exposed or more sediment-limited, shoreface profiles flatten out at greater depths (i.e. 8-10 m). These types of profiles are more characteristic of the Yukon coast west of the proposed MPAs. Sand and gravel deposits characterize the inner foreshore and surf zone environments, with a rapid offshore gradation to silts in the outer foreshore, beyond the typical storm wave base of 3-4 to 8-10 m. Spit and barrier thickness depends on the depth of water into which they are migrating, so can be 3 m or more in thickness (Héquette and Ruz, 1991).

As relative sea level has risen over the past several millennia, the coarse materials which form the beaches, spits and the inner foreshore are buried by the fine sediments associated with the adjacent deeper waters. Surveys and samples along several moderate-energy coastal reaches within the influence of the Mackenzie River plume show that the transition from sand and gravel to silt occurs in water depths of 2.5-4.5 m. This transition depth almost surely varies with the ambient wave and current conditions and will be

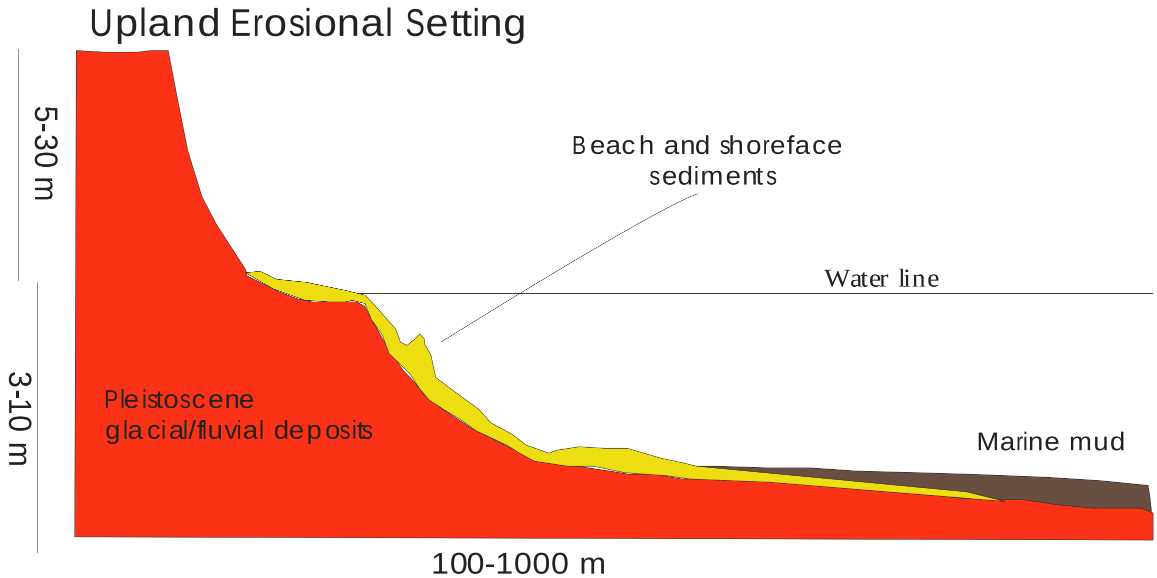


Figure 13: The Upland erosion setting hosts potential deposits in the wave-influenced environment where sand and gravel are found in the Pleistocene coastal bluffs. The transition from sand to marine mud usually occurs in water depths less than 5 m and less than 500 m from the low-tide line.

Figure 14: The north end of the Garry Islands spit and barrier is composed of sand and gravel and have been migrating land(south)ward. There are likely similar relict deposits to the north. (The grid is easting and northings, zone 8, NAD83).

found at greater depths following a storm and in more exposed location. The silt veneer thickens with distance from the shore despite the very slight seabed gradient. Examples of the depth of the transition from sand to mud: 3.5 m on the NW side of North Head, 2.5- 3 m on the NE side of North Head and 4-4.5 m at Tuktoyaktuk. The width of the sand and gravel dominated materials ranges from 500 m to more than 1000 m. The beach and upper shoreface deposits are thus found exposed at the seabed surface in a narrow zone (500 m to more than 1000 m in more exposed environments, probably less in more sheltered locations). The aggregate deposits formed in this setting will likely be relatively thin (1-3 m thick) interfingered and covered with finer material in deeper water. In areas where spits and barriers have transgressed into deeper water (e.g. a former lagoon or lake basin), sand and gravel can be deposited as washover lobes. This setting may produce thicker lensoid sand and gravel bodies with intervening layers of silt and clay.

The quality of the aggregate deposits found in the Upland-backed erosional setting depends in part on the degree of exposure of the site to wave attack, along with the type of materials which compose the backshore environment. Locations which are sheltered from direct attack by waves will not have an opportunity for significant sorting of materials, so if the backshore materials are poorly sorted, the beach and nearshore may be as well. Sheltered locations may also provide a site for deposition of fine materials in intertidal flats (e.g. Whale and Kendall Islands). Sites that are exposed to higher energy from waves will exhibit better sorting as fines are removed. Similar types of deposits may also be present where remnants of upland areas remain as shoals further from shore. The offshore Issigak borrow site is interpreted as such a remnant (Lewis in Macleod, 1993)

Heavy minerals, if present in the source materials, may be concentrated in beach and spit environments, however, informal observations of researchers in the field suggest that this is not common (L. Dyke, P. Hill, S. Dallimore, D. Forbes pers. comm.). The degree of concentration is in part a function of the concentration in the source materials and in part a function of the energy in the environment (Emory-Moore, 1993).

4.3.2 Delta-backed erosional setting

The Delta-backed erosional setting consists of backshore deposits dominated by silt and organic-rich, very low (1-2 m) bluffs of modern alluvium (Figure 15). Most of the coast of the Mackenzie Bay MPA is characterized by this environment. The lack of sand and gravel as a source of aggregate in the backshore results in beach and nearshore deposits of detrital organics and silt with minor amounts of sand. Coastal and nearshore aggregate deposits are poorly developed in this setting. A transect of boreholes drilled to a maximum of 5 m bsl were acquired by the author in the Arvoknar Channel area of the modern delta. Unpublished field notes describing boreholes in water depths of about 1 m reveal that surficial sediments are dominated by silt to very fine sand. The thickest interval of sand-dominated sediments were found at a depth of about 1 m below the seabed (2 m below the ice surface) and consisted of 1.5 m of ripple cross-laminated and massive very fine grained sand to the bottom of the borehole. This borehole was more than 500 m from the shoreline; silty materials with occasional slightly coarser beds dominated boreholes closer to the shore.

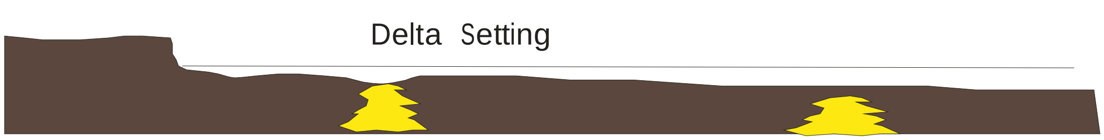


Figure 15: The delta setting includes the low (< 2 m) erosional bluff and the nearshore channel mouth settings. The bluffs contain little sand or gravel so there is usually only a detrital peat beach. Sands (in yellow) are associated with distributary mouth bars and abandoned channels.

4.3.3 Deltaic-depositional and channel mouth setting

In general, the delta plain environment consists of stable, anastamosing channels comprising about 20% of the surface and small, interconnected systems of lakes which occupy 30-50% of the surface. Broad interchannel vegetated flats comprise the remainder of the delta plain surface (Hill et al, 2001). Sediment facies in the delta plain environment are dominated by silt and clay deposits with smaller amounts of sand found as channel fills and small bars.

The channel mouth environment in the vicinity of the Mackenzie Bay MPA is described by Jenner (1989) and Jenner and Hill (1998). Primary channels up to 5 m deep extend across the subaqueous delta platform up to 15 km from the shoreline. These deep channels do not freeze during the winter while smaller, shallower channels freeze to the bed. In the model presented by Jenner and Hill (1998) broad lobate bars are deposited in a frictionally dominated setting. Both the emergent bars and the channel fills are composed of fine sand grading upwards to silt and clay. The best-sorted sand is associated with the channel fill section and with a ubiquitous storm bed. Grain size analyses of the sediments in these facies associations are a maximum of about 0.3 mm size with most of the sand closer to 0.1 mm (very fine to fine sand range). The shallow water subaqueous delta facies is found in water depths of about 0-2 m, in the zone of bottom-fast ice. The dominant lithology is fine to very fine sand with some silt.

4.3.4 Nearshore

The nearshore setting is seaward of the influence of most shoaling and breaking waves, although the setting is influenced by storm waves. Water depths are somewhat deeper than those found in the other settings and distance from the shore is greater. This setting includes the subaqueous delta environment which is found seaward of (and adjacent to) the channel mouths and, in the vicinity of Shallow Bay on the west side of the delta, is composed of platform and prodelta/deep water facies (Hill et al., 2001). In water depths of 2-5 m, sediments fine to graded beds of very fine sand and silt. These beds show evidence of both erosion and deposition. The prodelta/deep-water facies (water depths greater than 5 m) is characterized by silt and mud beds with little evidence of erosion, and increasing amounts of bioturbation. Most of the MPAs are in water depths of < 5 m and therefore should be within the zone characterized by the delta platform facies.

Investigations by Hill and Nadeau (1989) in the wave-exposed environment north of North Head suggest a decrease in wave energy from a maximum in 4.2-5.5 m water depth to lower energies in 2.5-4.2 m. However, in that environment, sediment grain size did not change appreciably, in both zones silt was the dominant component. The thickness and types of bedding varied from thick in the deeper zone to thin in shallower zone. The authors also reported thick sand beds deposited close to shore (water depths of less than 2 m).

In somewhat higher wave energy settings farther offshore from the Mackenzie River than the MPAs, surficial sediments consist of sand and gravel to depths of nearly 5 m (Héquette and Hill, 1989). In greater water depths there is a veneer of mud over the sand which increases in thickness as water depth increases. The nearshore environment may also host relict aggregate or heavy mineral deposits which were formed in higher energy settings (beach, spit and barrier islands) and then drowned as a result of rising relative sea level (Figure 16) (Blasco in MacLeod, 1993). Relict Pleistocene sands and gravels will also be present beneath variable thicknesses of modern marine muds.

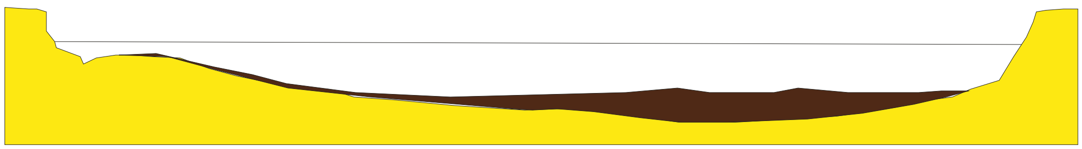


Figure 16: Pleistocene sands and gravels (yellow) may be present close to the seabed surface in the Kendall Island MPA beneath a variable (decimetres to metres) layer of marine mud.

4.4 Sand and Aggregate Potential

4.4.1 Mackenzie Bay MPA (Figure 17)

The Mackenzie Bay MPA is divided into 3 sectors: (1) MB_west_coast and (2) MB_east_coast and (3) MB_nearshore.

MB_west comprises the coastal and nearshore zones west of the Blow River Delta to 5 m water depth and is characterized as Upland-erosional setting. The section of shoreline is 26 km long and includes Shingle Point and the associated spits and barriers of Escape Reef. The presence of these long-lived sand and gravel beaches, spits and barriers (first documented by Franklin, 1828) indicates a consistent updrift (western) source of coarse materials. The only sampling in this sector was at the extreme western end. One sample in 4 m of the water contained more than 90% sand (positioning and mapping inaccuracies place this sample on shore). A sample 1 km offshore (10 m water depth) contained 50% sand. Further west, at the King Point Barrier, sand is present at the seabed surface in water depths of 8-10 m, 600 m from shore (O'Connor and Assoc, 1986). Further west, at Stokes Point, sand is present on the seabed surface in water depths of 3.7 m, approximately 200 m from shore (Forbes, 1997). Based on these data, we expect that the sand and gravel present on the beaches extend below the water line to depths of a least 4-5 m and are buried beneath Mackenzie River silts beyond that depth. Based on the CHS chart 7661, the 5 m contour is an average of about 300 m offshore and typical shoreface deposits are 1 m thick, this section of coast may contain approximately *8×10^6 m^3 of sand and gravel* below the present water line, and exposed at the seabed surface.

MB_east includes the coastal areas below the low-tide line and immediately adjacent to the Mackenzie and Blow River Delta coasts (mostly water depth <1m). This sector is dominated by low (1-2 m) erosional bluffs in silt and peat with some areas of bar deposition on the east side. It includes both delta-backed erosional and delta depositional settings. In general, the sector is considered to have a low potential to host aggregates based on the lack of sand and gravel for source material and the abundance of silt and clay being delivered by the Mackenzie River through Shallow Bay. The only limited sampling in the coastal zone suggests the possibility of sandy storm beds on emergent bars and at the mouths of distributaries in the vicinity of the Ellice Islands (Jenner, 1989; Jenner and Hill, 1998). Distributary channel fill is composed of sand and therefore the submarine channels may be floored with sand. There is insufficient data to estimate the quantities of aggregate in that sector.

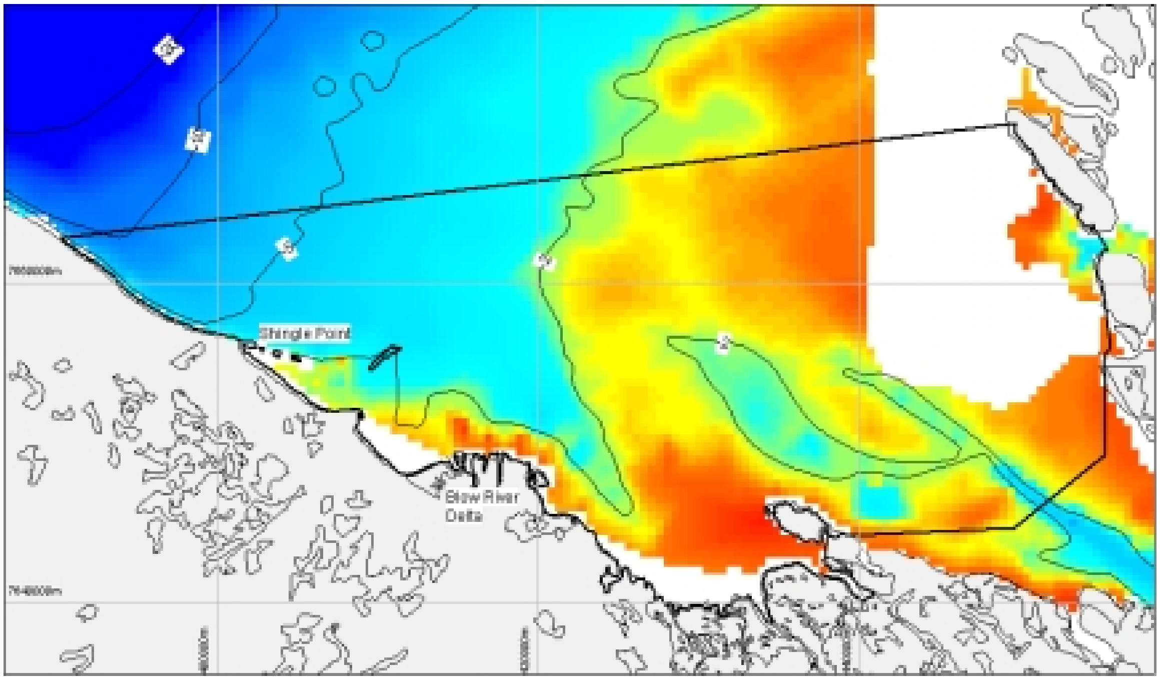


Figure 17: Mackenzie Bay MPA. White areas show coastal areas with insufficient data for incorporation into the digital elevation model (DEM). Colour shading ranges from less than 1 m water depth (orange) to 25 m water depth (dark blue). All surface samples in the MPA are dominated by mud. Aggregate resources are confined to the shoreface within 1 km of the shoreline west of the Blow River delta. Other possible aggregate resources may exist in channels, at channel mouths and buried beneath marine mud

The MB_nearshore sector is defined as the areas offshore from the first two sectors. All of the samples collected in this sector are dominantly silt and clay (80-90% silt). A cluster of boreholes in the sector contain silt-dominated lithologies to a depth of more than 12 m. Upstream from the MPA in Shallow Bay jet-drilled boreholes are also characterized by a predominance of silt to depths of more than 100 feet (30 m) (MacAulay et al, 1977). This sector is considered to have a low potential for sand and even less of a potential to host gravel deposits.
Aggregate potential (Speculative/known): 8 x 10^6 m^3 of sand and gravel. There may be additional aggregate deposits associated with distributary mouth bars, and channel-fill, but there is insufficient data to evaluate them.

4.4.2 Kendall Island MPA (Figure 18)
The Kendall Island MPA is an embayment defined by the islands which surround it: Garry, Pelly, Kendall and Whale (Figure 1), all of which are mostly composed of Pleistocene sediments with varying amounts of sand and gravel. The Upland-backed tundra shore therefore dominates the depositional setting. Within the boundaries of the MPA, spits and detached barriers composed of sand and gravel are present off of Garry and Pelly Islands. Fringing beaches are several 10s of metres wide and composed of sand and gravel (based on aerial video mapping) derived from erosion of the surrounding tundra cliffs.

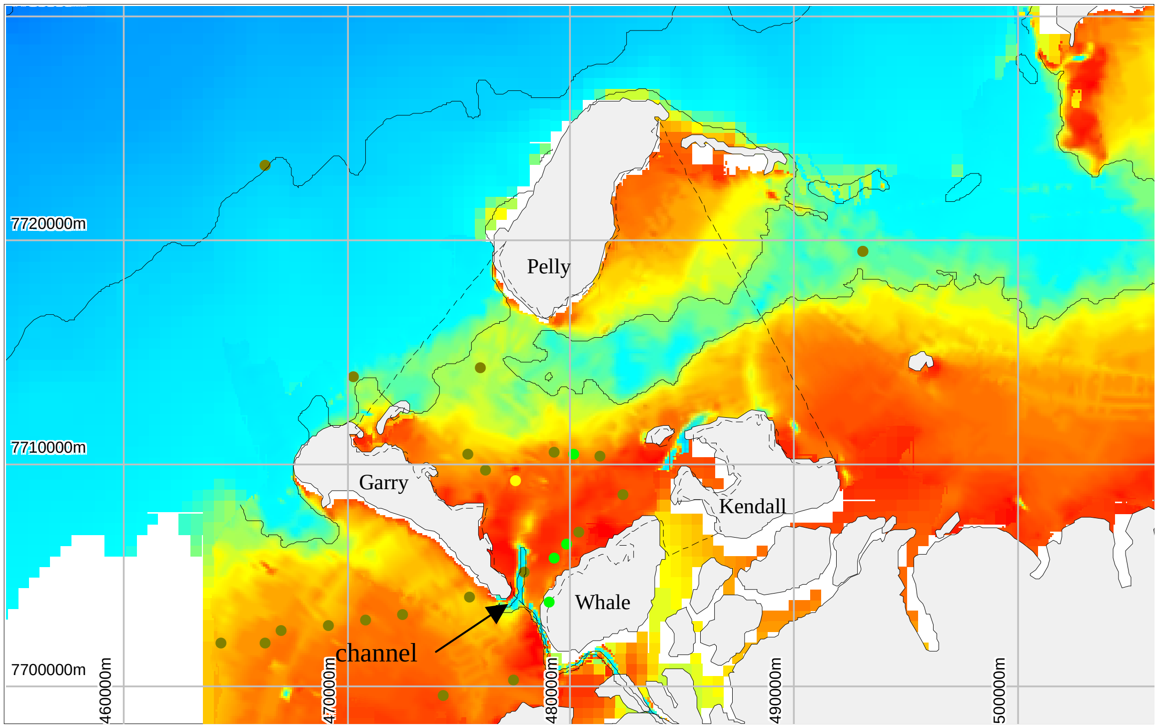


Figure 18: the Kendall Island MPA is surrounded by islands composed of Pleistocene upland deposits (mostly sand and gravel). The shoals which occupy the southern half of the MPA may be underlain by relict sand and gravel deposits. Coastal shoreface and spit/barrier settings may also host sand and gravel deposits. Most surface samples contain less than 25% sand (olive circles), but several contain 25-75% (green circles) and one more than 75% sand (yellow).

No direct information about wave or current conditions is available within this MPA. Openings between the surrounding islands are over 10 km wide, so that there should be little impediment to waves and currents impacting the shorelines or seabed. The most significant factor affecting waves in the region is the very shallow water, which limits maximum wave heights and periods.

Water depths within the MPA are invariably less than 3 m with the southern half mostly less than 2 m deep. The deeper area which separates Pelly Island from the shoals to the south is channel-like with a width of 3-4 km. The feature may be the remains of a series of thermokarst lakes or basins which have been inundated by rising sea level. A narrow submarine distributary channel meanders up along the coast of Whale Island and enters the MPA between Garry and Whale with maximum water depths in the channel of more than 4 m.

Surface samples from the MPA are dominated by silt; however some samples contain 10-30% sand. A single grab sample from the middle of the embayment in 1 m water depth is composed entirely of sand. It may be related to end of the submarine channel as a mouth bar deposit. CHS chart 7662 shows a mixture of sand, mud and gravel on the surface of a submarine shoal abutting the channel in the northwest. The morphology of the shoal suggests it is formed by currents entering the MPA embayment from the south through the channel. Currents that are strong enough to transport sand in the surf and nearshore zones are therefore implied. The one sample taken within the distributary channel was described as "silty clay" (H. Kerfoot, pers. comm.).

There are known deposits of sand and gravel at the northern edge of the MPA just north of the Garry Island spit and barrier complex. Boreholes reveal 50-100% sand and gravel at depths of 2 m below the seabed off the east end of Garry Island spit and north of the barrier island. Additional sand and gravel are present at depths of 7-15 m below seabed off the north end of Garry Island (outside of the MPA) in water depths of about 3 m. The few analyses from samples taken closer to the seabed surface are dominated by silt. The coarse deposits at depth are probably related to the erosion of Garry Island, having been originally deposited in beach or spit environments. Their present positions 1.5 to 2 km north of the present shoreline of Garry Island and current rates of erosion (~1 m a^{-1} from 1972-2000) suggests they were formed 1500-2000 years BP at sea levels which were 1-4 m below the present sea level. Boreholes off the southern shore of Pelly Island also show a dominance of silt above 2 m below seabed and one analysis with more than 50% sand below 2 m. Further to east and south of Pelly Island (at the site of an abandoned artificial island (Pelly B-35), gravel and sand are found at depths of more than 8 m below the present seabed.

The sampling to date indicates that most of the surface of the seabed in this MPA is composed of silt. Sand and gravel at the surface is likely to be present along the modern shoreline, but the lack of samples or any profile data does not permit an appraisal of the quantities. The most prospective areas for aggregate are associated with the spits and barriers. These features are composed of sand and gravel and are actively migrating landward. Washover deposits will be found in their lee, probably interbedded with silt layers deposited between the storms responsible for the washover. On the seaward side of the spits, platforms of sand and gravel may be present several hundred metres from the present shoreline, and off the ends of the features.

Estimating potential amounts of sand and gravel at the surface of the MPA is highly speculative.
Shoreface deposits:
5×10^3 m x 150 m width x 1 m thickness = 7.5×10^6 m^3

Deposits associated with Garry north spit and barrier
5×10^6 m^2 area x 1.5 m thickness = 7.5×10^6 m^3.

Possible channel mouth sands
1.5×10^6 m^2 area x 1.5 m thickness = 2.3×10^6 m^3

This shows that there may be as much 17.3×10^6 m^3 of sand and gravel at or close to the surface of the MPA. Based on the very limited borehole data and the morphology of the seabed in the MPA, it is possible that much of the MPA is underlain by Pleistocene sand and gravel deposits similar to those found on adjacent upland surfaces. Given that they represent lowland surfaces (since they were inundated before the adjacent uplands), they would also be expected to contain lacustrine and tundra peat deposits. All of these deposits are likely also covered by at least a veneer of silt; however, the borehole data suggests 1-8 m of silt. If we assume that only the shoal areas less than 2 m deep are underlain with sands and gravels and the deeper locations are probably filled in large part with lacustrine deposits, then that represents an area of about 150 x 10^6 m^2. We do not have any information on the thickness of the sand and gravel deposits below the water line, but it could be several metres. Therefore up to 150 to 450 x 10^6 m^3 of sand and gravel could be present beneath variable thicknesses of silt in the MPA.

Aggregate potential
Speculative: 150-450 x 10^6 m^3
Known: 17.3 x 10^6 m^3

4.4.3 Kugmallit Bay MPA (Figure 19)

The Kugmallit Bay MPA is characterized by 4 distinctive sedimentary/coastal environments.

East Channel mouth

The East Channel mouth extends from the upstream margin of the MPA to the outermost subaerial distributary islands and emergent bars. This area includes a portion of the more confined channel environment as well as the delta-backed erosional setting. There are no known samples or textural analyses in this region. Sand is noted on CHS chart 6431 as sand shoals along riverbanks, and between bars. Sand may also be present on the channel bottoms (Hill et al, 2001), but the quality and thickness are unknown. The vegetated subaerial bars are erosional on their seaward side and have an elevation of up to 1 m. The islands and associated intertidal banks and levees are composed of interbedded fine sand and silt with organic particulates (P. Hill, pers., comm.). Beaches are narrow to non-existent. The easternmost islands and intertidal flats have expanded over the past 50 years and observations by local elders suggest infilling of previously navigable channels has occurred in the vicinity of the Kitigaaryuit National Historical site (Solomon, 2002). Aggregate potential is probably greatest in the channels, but there may be lenses and beds of finer material. It is not possible to quantify the aggregate potential for this environment.

Aggregate potential: speculative in channels and bars

East coast of Richards Island

The coastline on the east side of Richards Island (west coast of Kugmallit Bay) within the MPA is characterized by low coastal bluffs generally 3-5 m in elevation, with stretches of drowned tundra and wetlands. The backshore is fronted by fringing beaches (10-20 m wide) composed of sand and gravel. The surficial geology is gravely and sandy hills and ridges. This coastal segment is generally protected from westerly storms, so that during storm surges, wave energy is weaker than on the west facing shores. Thus, although the morphology of the shoreline is erosional, the retreat rates are relatively low (< 0.5 m a^{-1}). There are no reports of beach or nearshore surveys on this coastal segment, so we do not know the texture of the materials immediate offshore from the beaches. Since this segment of coast is in a relatively sheltered position compared to locations to the north, we assume that the width of the nearshore zone with sand and gravel will be narrower.

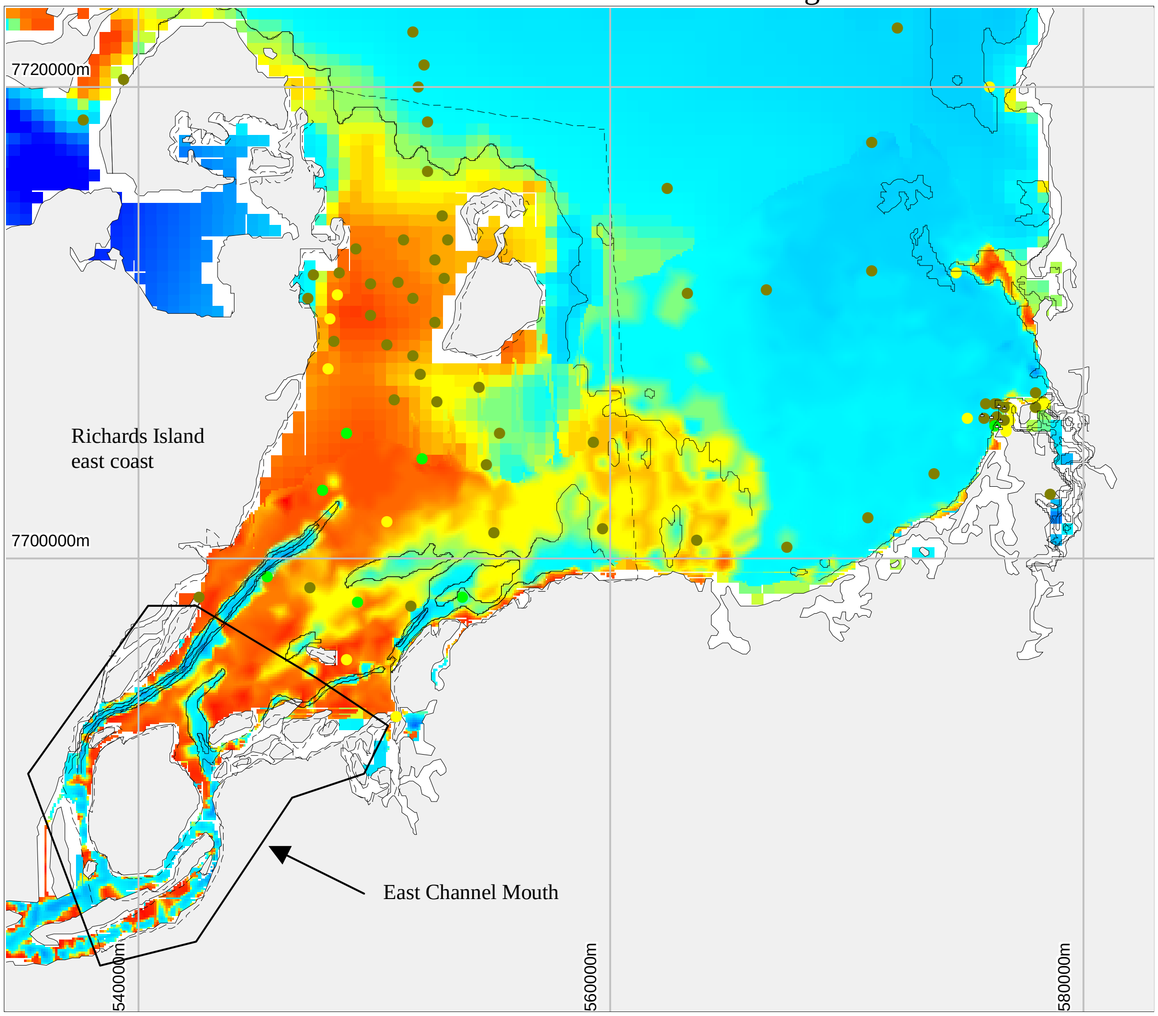


Figure 19: The Kugmallit Bay MPA may contain sand in its channelized southern portion. Shoreface aggregates are probably present along the east and west coasts. Several surface samples in the central portions of the MPA are composed of more than 75% sand (yellow circles). These may be related to relict or active distributary mouth bar deposits. Active delta channels may also host aggregate deposits, but no samples have been acquired.

The length of the coastal segment is 26 km and we assume that the width of sand and gravel in the nearshore will be between 100-500 m and deposits are 1 m thick, then the aggregate potential is 2.6-13 x 10^9 m^3. The quality will vary along the coastal segment. The best and most extensive quantities are expected at the northernmost part of the MPA along the Richards Island coast (the southern part of Summer Island) where sediments are being transported southward from rapidly eroding coastal bluffs.

Aggregate potential: speculative along the coast adjacent to sand and gravel beach deposits - 2.6-13 x 10^6 m^3 based on geological assumptions (no data)

West Coast of Tuktoyaktuk Peninsula and the Kitigaaryuit National Historical site

Along the west coast of the Tuktoyaktuk Peninsula seaward and inshore of the emergent bars and islands, the MPA is backed by a mixture of gravel and sand ridges and lacustrine deposits (Figure 7). This configuration is characterized as an upland-backed erosional setting. The coastline consists of moderate to wide fringing beaches backed occasionally by salt marshes and wetlands. The beaches are sand and gravel with rare concentrations of boulders. The shoreline is eroding slowly along the southern part of the sector (< 1 m a^{-1}) where the backshore consists of high sand-dominated ridges. Toward the north the backshore consists of low (3 m or less) bluffs composed of ice-rich lacustrine silt, sand and organics and is characterized by very rapid erosion (> 5 m a^{-1}). The more southerly parts of this coastline are partially sheltered by shallow intertidal sand flats, but towards the north the nearshore waters are deeper. Recent reconnaissance work on coastal stability has been undertaken in conjunction with archaeological studies in the vicinity of Kitigaaryuit National Historical site (Solomon, 2002). The shallow intertidal and subtidal zone adjacent to the southern beaches are characterized by oblique bars composed of fine sand (Figure 20); the bars are extensively exposed (up to 100 m wide) during low water associated with offshore winds. These bars are a potential source of aggregate. Since the bars are quite flat, small changes in their elevation/depth with respect to the tides will have a considerable impact on what portion lies within the MPA. Surveys performed in 2001 were tied to a somewhat inaccurate pressure gauge (±10 cm) and they indicate that most of the bars lie above the chart datum (lowest astronomical tide) meaning that they are technically outside of the MPA (as defined, but not necessarily as mapped. The flats and bars adjacent to the National Historical site may contain 0.25 to 0.5 x 10^6 m^3 of fine to very fine sand, likely underlain by thin beach sand and gravel. This estimate is based on an assumed sand thickness on the bars of 0.5 to 1.5 m; no coring has been done. A restricted area of shallow water is strewn with rounded boulders up to 1 m in diameter. Along the coast to the north, sand and gravel deposits are found on beaches and are likely to be found in the nearshore below the water line. No data has been acquired in this segment. The distance from the shoreline to the 2 m isobath is about 300 m in this area based on the CHS river chart 6431 and the length of the coastline is 15 km. Based on the width of sand and gravel zones from other more energetic locations which vary from 500-1000 m, we assume that the distance to the 2 m isobath is a reasonable assumption for the width at this location. Thus, based on an assumption of 1 m thickness of sand and gravel, there is a potential for about 4.5 x 10^6 m^3 of sand and gravel along this section of coast.

Aggregate potential (known occurrence – oblique nearshore bars): 0.25 to 0.5 x 10^6 m^3 of fine to very fine sand

Aggregate potential: speculative along the coast adjacent to sand and gravel beach deposits – 4.5 x 10^6 m^3 based on geological assumptions (no data).

Figure 20: Transverse bars of very fine sand are present in the intertidal and shallow subtidal environment offshore from the Kitigaaryuit National Historical Site (see close-up in Figure 6). The grid coordinates are UTM zone 8, NAD83.

Inner Bay

The inner bay areas are in a nearshore setting. They are seaward of the channel mouth and beach-foreshore settings, but still well within the confines of Kugmallit Bay and are thus relatively sheltered (although less so than the East Channel Mouth). Water depths vary from 5-6 m in a few deep channels to an average of 1-2 m in the surrounding waters. Depths are shallower on the west side of the bay than on the east. Surface sediment samples collected during the course of several field campaigns (mostly in the 1970s) are on average, composed of silt (67%) with lesser amounts of sand and gravel (16%) and clay (17%). Five samples contain more than 75% sand with very small amounts of gravel. Most of the sand-dominated samples are located on the west side of the bay, but the reason for this is not apparent. Three of the samples are located in <1 m water depth within 1.5 km of the shoreline in a relatively protected area between Richards and Hendricksen's Islands. The other sand-dominated surface samples are close to offshore shoals or the end of an offshore extension of the primary distributary channel of the East Channel. The only core obtained within the boundary of the MPA was at the end of this channel as it shoaled to < 2 m water depth. The surface sample was silt, but a 17 cm sand bed was present 32 cm below the surface; the total core length was 57 cm (Kauppaymuthoo, 1997). Outside of the MPA, the nearest boreholes are in water depths of 3-5 m. Silt is the largest component in the upper several metres, and then sand dominates often down to the base of the borehole (10-20 m). In some cases silt and clay are found below the sand.

In the sheltered setting occupied by the Inner Bay environment, we anticipate that sand deposits will be localized in areas where there is either an active source of sand, a lack of fines to cover previously deposited materials or sand and/or gravel will be buried beneath a cap of silt and clay. Active sources of sand are in the submarine channels and associated with the bars which develop at their termination. Thus lenses of sand should be associated with the present and former positions of the submarine channel and along the bottom of the channel (Hill et al, 2001 and Hill pers. comm.). Offshore bars are another source of sand which is being winnowed by waves as they erode. The presence of a single sand-dominated sample at the south end of the Bay may be related to its proximity to an eroding offshore bar. The bar itself has not been sampled. It may have a surficial sand cap overlying interbedded silt and sand. The sand dominated nearshore samples on the sheltered west side of the bay may be an example of a location where current activity may be enhanced and fines are not deposited, however, we have no evidence for that.

Aggregate potential: speculative/known – there are identified samples with more than 75% sand at the surface or within 1 m of the seabed, but we do not have sufficient information to quantify the amount.

4.5 Heavy mineral potential

Heavy mineral potential of the sediments within the MPAs is based on the available information about the sources of heavy minerals (i.e. the local glacial and glaciofluvial deposits), the potential concentrating mechanisms and the analyses of the sediments themselves. The heavy mineral potential of the MPA is considered to be low to very low based on the following reasons:

1. The MPAs are not located adjacent to or coincident with any known bedrock mineral deposits. Previous sections have described the bedrock geology of the region. The nearest bedrock outcrops are 50 to 100 km distant. Thus any heavy mineral placers will be of the allochthonous variety, meaning they would be derived through a process of grain sorting at some distance from the primary mineral sources.
2. The Mackenzie and Blow Rivers do not supply large amounts of coarse-grained material to the coast – nearly all of the material is suspended load in the silt and clay fractions.
3. The glacial and glaciofluvial sediments which represent the source materials for marine and beach placers do not contain identified heavy mineral placers or enriched zones themselves. This observation is based largely on informal observations by geologists working in the field. As such, we consider these materials as being disseminated sources of heavy minerals. It should be noted that there have been no heavy mineral analyses which specifically quantified the bulk percentage of heavy minerals in samples of the source sediments.
4. The heavy mineral suites from outcrop and borehole samples do not contain indicators of specific precious metals or diamonds. The presence and in some cases importance of metallic minerals such as garnet and ilmenite in the heavy mineral suite suggests that given suitable conditions, heavy mineral placers could form from these sources. Although no precious metals or diamonds have been reported in the heavy mineral separates, it is not possible to rule out the potential completely given that primary sources are known to exist in the region.
5. The energy available to sort eroded glacial and glaciofluvial sediment is limited. While waves are the primary cause of erosion of coastal bluffs, the absolute energy of the waves along the Beaufort Sea coast is relatively small in comparison with open ocean coasts where significant beach placers have been identified (e.g. black sand placers on the Oregon coast – Li and Komar, 1992). In addition, the combination of sea level rise and rapid erosion means that the time available for reworking and concentration of heavy minerals from coastal materials under high energy conditions is limited.

6. The seabed surface samples only contain small amounts (<3%) of heavy minerals (Pelletier, 1984). It should be noted that the number of samples analyzed are small and not necessarily chosen for their heavy mineral potential.

5.0 SUMMARY AND DISCUSSION

The available data on sedimentary texture and mineralogy and interpretations of geological history and sedimentary processes were compiled in support of an assessment of the mineral resource potential of the Marine Protected Areas proposed for the Beaufort Sea. The proposed MPAs are in very shallow water locations, so that many of the usual surveys required for this type of analysis have not been undertaken. In particular, there are no useable high resolution seismic or sidescan sonar surveys within the MPAs. This limits our understanding of subsurface and surficial conditions to only those specific locations where samples or boreholes have been collected. Extrapolation between samples and boreholes had to be undertaken by analogy with other locations and/or based on our understanding of sedimentary processes and depositional models in those environments.

Heavy mineral potential of the MPAs is considered to be low to very low based primarily on the lack of observed heavy mineral concentrations in either source material or marine sediments and the relative lack of marine energy available for sorting and concentrating minerals. However, the presence of precious metals and diamonds in the region and the relative paucity of directed sampling efforts indicate that the possibility cannot be ruled out.

Aggregate resources in the form of sand and lesser amounts of gravel are known to occur on beaches and in the offshore regions of the Beaufort Shelf. There are potentially exploitable deposits of sand and gravel in the MPAs. In all cases, there was insufficient data to quantify either the extent or quality of the potential resource, therefore, they are classified either as known or speculative occurrences. Table 3 summarizes the estimated quantities of materials in the know occurrences for each MPA.

Additional potential deposits which are more speculative in nature include the channels and bars in the mouth of East Channel and isolated surficial sand samples in Kugmallit Bay which may indicate a resource, but it cannot be quantified. These known and speculative occurrences are largely based on geological settings and information gleaned from surveys in analogous locations along the Beaufort coast. Considerable additional work would be required to quantify those occurrences with some confidence. In most cases, we have quantified potential resources in waters adjacent to beaches. Exploitation of those types of deposits would cause rapid and potentially severe erosion of the adjoining subaerial deposits. In addition, we anticipate that any deposits in water depths of less than 1-1.2 m are likely to be ice-bonded within 1-2 m of the seabed.

In order to put these estimates in perspective, we can compare the estimated aggregate resources from locations on the Beaufort Sea shelf (Macleod, 1993). The terminology shown in Table 4 is similar to the terms used in this report (shown in brackets).

Table 3: Aggregate potential in the proposed MPAs

MPA	Known Occurrence
Mackenzie Bay	8×10^6 m^3
Kendall Island	17×10^6 m^3
Kugmallit Bay	3 to 13×10^6 m^3 0.25 to 0.5×10^6 m^3 4.5×10^6 m^3
Total	33 to 43×10^6 m^3 (conservative estimate) 183 to 493×10^6 m^3 (speculative)

Table 4: Beaufort Shelf Aggregate Resources (From MacLeod, 1993)

Area	Proven (quantified) m^{3}x10^6	Probable (known) m^{3}x10^6	Prospective (speculative) m^{3}x10^6	Author
Yukon Shelf (0-10m)	na	na	444-740	Lewis
Herschel area shelf	10	na	41	Quinn
Issigak	3.3	5.8	5.1	MacLeod
Isserk	45	63	80 (+40-816)	Lewis
Ersak	720	8000-14000	19000	Lewis
Total	778	8100-14100	20000	

The scale of the individual estimated MPA resources are generally similar to the scale of some of the offshore resources. In particular, the Issigak deposit, located offshore from the Kendall Island MPA, may actually be an example of a drowned coastal deposit. However, they are an order of magnitude smaller than the 2600 km^2 Ersak borrow block. The MPAs in total cover approximately 1750 km^2.

More accurate and complete assessment of the non-hydrocarbon resources within the proposed MPAs and adjacent nearshore waters will require a significant investment in surveying and sampling. Shallow waters with acoustically “hard” bottoms associated with sand and permafrost are notoriously difficult environments for geophysical surveying. However, given the paucity of surface samples and cores in the proposed MPAs, we would recommend that efforts be made to improve the sampling density both for aggregate and for geotechnical purposes.

6.0 ACKNOWLEDGEMENTS

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Gordon Fader (author of the MPA assessment of the Gully – Fader, 2003) and Margo Burgess provided advice on the process. Robert Taylor and Margo Burgess reviewed the report and provided useful comments.

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APPENDIX 1
Terms of Reference

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Draft Terms of Reference

The proposed Beaufort Sea Beluga Marine Protected Area:

An assessment of the probable distribution of mineral and hydrocarbon resources, their economic and strategic value (September 2002)

Background

The Government of Canada, Inuvialuit organizations pursuant to the Inuvialuit Final Agreement, and industry as represented by CAPP, have formed a Working Group and Senior Management Committee for the Beaufort Sea Integrated Management Planning Initiative (BSIMPI). One priority of the BSIMPI is evaluating three areas classified as Zone 1(a) under the Beaufort Sea Beluga Management Plan (BSBMP) for potential Marine Protected Area (MPA) status under the authority of S. 35(1) *Oceans Act*.

The traditional ecological knowledge of the Inuvialuit identifies these areas as very important habitat for beluga. Scientists know these areas to be important areas for ecological productivity and biomass. They further conclude that these areas are of considerable importance to beluga because they return to them each summer. The Beaufort Sea Beluga Management Plan (BSBMP) established protective guidelines for the Zone 1(a) areas in 1994. Parties to this plan include the Fisheries Joint Management Committee (FJMC), the six community Hunters and Trappers Committees (HTCs) and Fisheries and Oceans Canada (DFO). BSBMP guidelines exclude oil and gas exploration, production or related construction, and mining activities in the Zone 1(a) areas. They also address shipping routes and the development of commercial fishing proposals.

Over time, the intent of the BSBMP has been respected. At the request of the Inuvialuit, the federal government (INAC) has voluntarily not offered these areas for lease. Also the Environmental Impact Screening Committee has, to date, recommended against activities, for which they have a responsibility for screening, going ahead in these area. However, there has been sustained pressure on the Inuvialuit by the petroleum industry to open these areas to allow some level of activity. Consequently, consideration of the magnitude of potential hydrocarbon development scenarios in the Beaufort Sea, have led members of the FJMC and Inuvialuit beneficiaries to express a wish to examine the potential of having the BSBMP guidelines for three Zone 1(a) areas formalized through the establishment of an MPA.

Rationale

The *National Framework for Establishing and Managing Marine Protected Areas* (1999) requires that socio-economic assessments be conducted as part of the MPA evaluation process. These assessments include an evaluation of mineral, aggregate and hydrocarbon resource potential. The *Government of Canada Regulatory Policy* requires that the costs and benefits of any proposed regulation be evaluated prior to submission to Governor in Council. Additional government policies specify that non-renewable resources be

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considered when making land use decisions. These include the *Minerals and Metals Policy of the Government of Canada*, the *Federal Land Use Policy* and the *Cabinet Directive on the Environmental Assessment of Policy, Plan and Program Proposals*

Purpose

These Terms of Reference formally recognize participants, their expertise and describe the process whereby mineral and hydrocarbon resource potential in Zone 1(a) areas will be evaluated. The completed assessment will serve two primary functions. First, the assessment will ensure that, in making recommendations to designate Zone 1(a) areas as a MPA, the Minister of Fisheries and Oceans is apprised of the economic and strategic value of mineral and hydrocarbon accumulations in the area. Second, it will support the analysis of the cost and benefits of the proposed regulation, should the decision be made to proceed to establish a regulation for the MPA.

The resource assessment should evaluate the following options:

1. Status quo -- The three Zone 1a areas identified in the Beaufort Sea Beluga Management Plan (BSBMP) remain closed to all oil and gas development.
2. MPA regulation – development of a regulation based on conservation objectives, including prohibition of activities that are not consistent with meeting the conservation objectives.

The proposed analysis and documentation will provide a common set of facts regarding hydrocarbon potential and the economic value, on which the Governor in Council would be able to make a decision regarding a regulation.

Geographic Scope

For the purposes of this assessment, the core study area has been defined to encompass the proposed MPA Area of Interest which includes three areas designated in the Beaufort Sea Beluga Management Plan as Zone 1(a) areas. These areas are as follows: Mackenzie Bay at 1,160 km^2; the Kendall Island area at 193 km^2; and Kugmallit Bay at 363 km^2. The total area of the three is 1,716 km^2. They are identical with the areas zoned as 1(a) in the BSBMP. (See Attached Map.) In order to understand the relative value of the resources within the core study area, a broad understanding of resource values in the Beaufort Sea/Mackenzie River delta will be required.

For those portions of the assessment that require geological comparisons with other accumulations in the region, the Beaufort Sea/Mackenzie River delta will be the area of comparison. For economic and operational comparisons, particularly for minerals and aggregates, it may be necessary to review the experience from other jurisdictions.

Participants and Roles:

It is anticipated that the overall non-renewable resource assessment will be undertaken in two stages. Initially, the extent, distribution and overall value of resources within the

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study area will be determined. Once the proposed regulation for the MPA has been clearly defined, it will then be possible to make a determination with respect to any potential costs as well as benefits of the regulation with respect to exploiting the resources within the study area.

- Natural Resources Canada, NRCan –will provide the leadership to assemble the available information to determine the extent of deposits of minerals, aggregates and oil and gas resources within the Zone 1a areas and the Southern Beaufort Sea. NRCan will also provide the expertise to undertake economic analysis of the potential costs of any proposed regulation
- Indian and Northern Affairs Canada, INAC – may be called upon to provide specific information and expertise to NRCan.
- National Energy Board, NEB – may be called upon to provide specific information and expertise to NRCan, particularly, modelling expertise to extrapolate resources estimates for non-conventional hydrocarbons
- Fisheries and Oceans Canada, DFO – will work within the Beaufort Sea Integrated management Planning Initiative Working Group to identify the possible regulatory requirements for a proposed MPA, which will, in turn, inform the economic analysis of the effects of the regulation.
- Inuvialuit Organizations (Inuvialuit Regional Corporation (IRC), Inuvialuit Game Council(IGC), Fisheries Joint Management Committee (FJMC)) – will work within the Beaufort Sea Integrated Management Planning Initiative Working Group to identify the possible regulatory requirements for a proposed MPA, which will, in turn, inform the economic analysis of the effects of the regulation. The IRC will also review the draft assessment along with other members of the BSIMPI Management Committee.

Statement of Work

1. Conduct an inventory of existing public and private data of the total resources within the three Zone 1(a) areas. This inventory will include: conventional petroleum, oil and gas; unconventional petroleum resources such as natural gas hydrates; and earth minerals /industrial minerals for construction materials.
2. Complete a description of geological conditions.
3. Provide a rating of the three proposed MPA areas and the resource potential as a proportion of the entire Beaufort Sea/Mackenzie River Delta in order to understand the relative (~~known and~~ potential) quantity and economic value of the resources in the Zone 1a areas as compared to the rest of the Beaufort/Delta. This would also include the relative exploitability of the various identified resources.

Deliverables

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PART I: REPORT – by January 30, 2003

A technical report for public distribution based on published documents and grey literature will include:

- a summary, analysis and interpretation of existing public and private data concerning the likely distribution of the known and predicted accumulations of commercial resources within the region and those resources specifically attributable to the three Zone 1(a) areas using the adjusted NEB resource model; and

- an assessment of what portion of the geological resource is economic and operationally feasible. This will include an examination of operating flexibility (e.g. directional drilling, low impact winter seismic etc.).

This report will include an Executive Summary, a Plain Language Summary, and a digital scaled summary map (GIS) documenting the probable distribution of discovered and undiscovered petroleum potential for both conventional and gas hydrate petroleum resources throughout the region such that the resources attributable to the in the three Zone 1 (a) areas is described.

PART II: ADDITIONAL DOCUMENTS – by February 28, 2002

Assessment of the economic value of the potential resources to the region.
Assessment of the strategic value of the resource (in the local, regional, national and continental context).

These two documents will be concise (not more than five pages each).

Timelines
PART I is to be completed by January 30, 2003.
PART II is to be completed by February, 28 2003.

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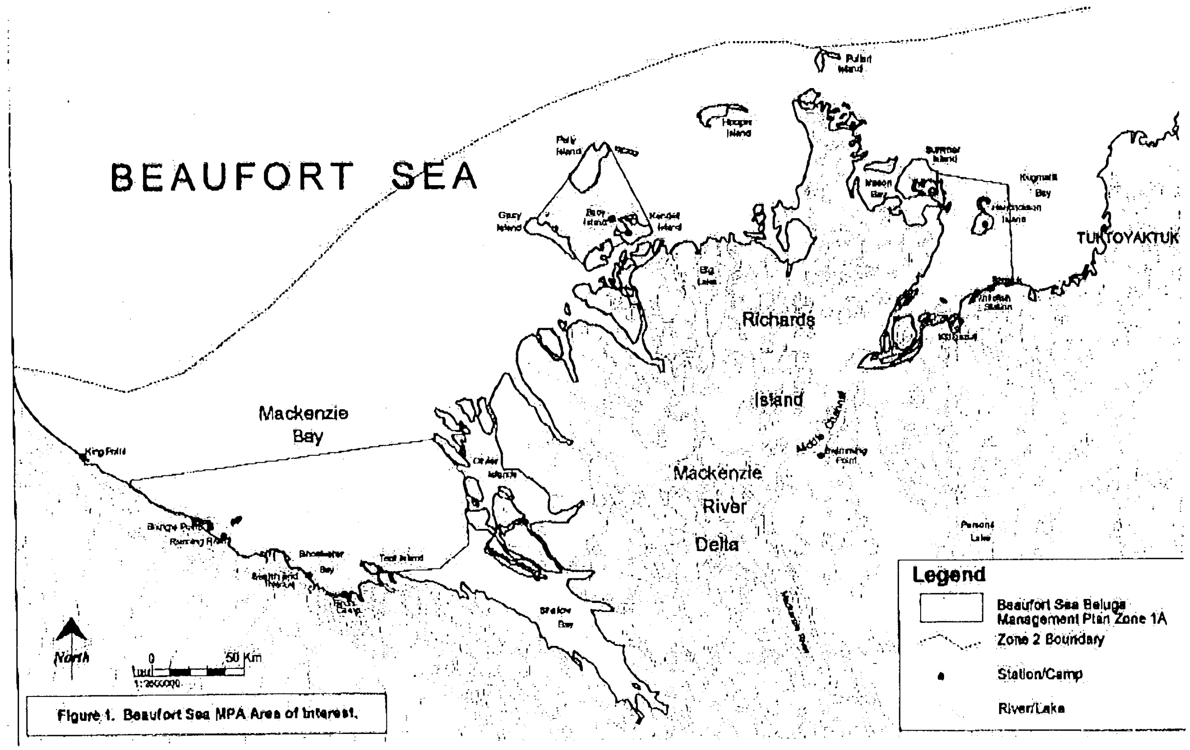

Figure 1. The proposed MPA for the southeastern Beaufort Sea.