APPENDIX 8D-2

WAKE EFFECTS

Ship Wake Effects on Shorelines

One of the concerns raised in the EA review process is on the potential impact of ship wakes on shorelines. The concern is that either the increased energy associated with ship wakes impinging on shoreline or the change in wave character that would alter shoreline habitat.

<u>Ship Wakes Background</u>
Two types of wave are generated by ships (Fig. 1): *Primary waves* (sometimes referred to as stern waves or long-crested waves) and *Secondary waves* (sometimes referred to as bow waves or short-crested waves). Wave heights associated with *primary waves* decrease exponentially away form the ships track (Kim and Lee 2009), and most of the energy propogating from the ship is in the from of short-crested secondary waves. For the common range of ship speeds from 5 to 15 knots, the maximum wave heights generated by a vessel and measured near the vessel typically range between 0.2 and 0.9 m (Sorenson 1993). Wave heights vary depending on ship characteristics, vessel speed and water depths, where shallow-water tends to heighten effects of ship wakes. Secondary waves typically have periods of 1-4 seconds (Parnell *et al* 2007).

<u>Wakes and Shore Erosion</u>
A number of researchers have documented the effects of ship wakes on shore erosion, particularly in low energy environments (see Bradbury 2005; Didenkulova *et al* 2011; Parnell *et al* 2007; Shuttrumpf 2006; Soomre *et al* 2009). Many of these studies have related to the introduction of high-speed catamaran ferries that create *soliton* wave types. Bradbury (2005) and Parnell *et al* (2007) document shoreline erosion caused by ship wakes in relatively protected environments. In the Gordon River estuary of Tasmania, relatively fine shoreline sediments (mud) and narrow channels resulted in transit speeds of most ships being reduced to <6 knots, which resulted in ship wake of less than 7 cm (Bradbury 2005); this speed resulted in wakes that created minimal erosion. Parnell *et al* (2007) noted that the introduction of fast-ferries in New Zealand initially changed shorelines relatively rapidly but then stabilized. Fine-grained shorelines were categorized to be most sensitive to wake effects.

<u>Summary of Reviews</u>
The most likely waves to affect beaches along the proposed shipping routes are the short-crested secondary waves. Wave periods are short and most likely will be in the range of 2-4 seconds. Wave heights near the vessel are likely to be relatively low, less than 0.9m and more likely 0.5m near the ship; the presence of ice during most of the year will have an additional dampening effect that is not well documented in the literature. Shorelines most sensitive to ship-wake disturbance are fine sediment shorelines (e.g., muds and sands) and shorelines close to the ship track.

Approach

Our approach to addressing the concern about ship wake effects on shorelines is to:(a) examine the wave energy contribution of ships versus the ambient open-water wave climate. (b) examine the shore types in general in terms of sensitivity to erosion, and (c) examine specific shores in the predicted zone of ship-wake influence.

Ship-Generated Wave compared to Ambient Wave Climate

Many research papers on this topic had modeling approaches which did not allow the estimation of wave height or did not allow estimates for very large vessels. The simplest and most widely applicable method was described by Kriebel *et al* (2003). This model was used in our assessment of wave height generated by an ore carrier; it does not account for shoaling or wind-wave effects.

The Kriebel *et al*. (2003) model estimates the lateral surface wave height produced by a vessel of a certain size and shape, at a specific speed, and at a specific water depth. The vessel size and shape was based on the description of the Cape-size ore carrier provided in the DEIS. We modeled surface wave heights at two vessel speeds: 14 and 20 knots, which correspond to the transit speed in open-water noted in the DEIS and an assumed maximum speed of the ore carrier, respectively. Modeling the ore carrier at a speed of 20 knots is considered conservative because the ore carrier is not expected to travel at speeds greater than 14 knots in the Regional Study Area. For modeling purposes, a water depth of 25 m which is 5 m deeper than the draft of the proposed Cape-size ore carrier was assumed. This is considered conservative because water depths are generally much greater along the proposed shipping route. Estimates of wave height at increasing lateral ranges (5 m interval) from the vessel were estimated. The distances from the shipping lane that produced wave heights at 0.05 m height intervals were derived and used in a GIS to create zones along the shipping lane corresponding to different wave heights.

Figures 2 and 3 show the estimated wave heights generated by a Cape-size ore carrier travelling at 14 and 20 knots, respectively, along the shipping lane in northern Foxe Basin. At a vessel speed of 14 knots, waves are estimated to be 0.20, 0.15, 0.10 and 0.05 m high within 60, 140, 480 and 3,865 m of the vessel, respectively. At a vessel speed of 20 knots, waves are estimated to be 2.0, 1.5, 1.0, 0.5, 0.4, 0.3, 0.2 m high within 0.06, 0.14, 0.48, 3.86, 7.54, 17.9, 60.4 km of the vessel, respectively.

Wave heights are predicted to quickly dampen as they move laterally away from the vessel - particularly at the slower vessel speed. At the expected transit speed (14 knots) of the ore carrier in Foxe Basin during the open-water period, ship wakes of >0.05 m are likely to touch the shoreline at only a few locations (Fig. 2). For comparison purposes only, at the unlikely vessel speed of 20 knots, wave heights are predicted to be >0.3 m at a few coastal locations in Steensby Inlet and on Koch Island (Fig. 3).

It is instructive to compare wave heights generated by vessels transiting the area with expected wind wave amplitudes during open water conditions. Much of the shipping route lies in broad, open water areas with fetches commonly of 100 km or more. In Foxe Basin maximum hourly winds at Hall Beach and Igloolik in September are about 14-15

ms^{-1} (Canadian Climate Normals, Environment Canada). At Cape Dorset in western Hudson Strait, maximum hourly winds in September and October are about 25 ms^{-1} (Canadian Climate Normals, Environment Canada). Table 1 presents the wave period and "energy-based significant wave height" for various fetch distances corresponding to sustained 10, 15 and 25 ms^{-1} winds; these values are based on Figures II-2-23 and 24 in the US Army Corps of Engineers Coastal Engineering Manual. It can be seen that even a 10 ms^{-1} wind with a 10 km fetch would produce a 0.7 m wave, considerably larger, by a factor of about ten, than anticipated wave heights from a passing vessel. A wind speed of 25 ms^{-1}, as often occurs in Hudson Strait, would create a 6.8 m wave with a period of 8.6 s over very long fetches common in the area.

The hindcast waves indicate that ambient storm events that occur within Steensby Inlet and Foxe Basin are capable of generating waves during open-water of comparable size and period to ship wakes. And because storms events typically occur over many hours, rather than just a few minutes (as does a ship wake), energy expenditure on the shoreline is much higher.

Steensby Inlet – Shore Types

Different shorelines respond differently to ship wakes with finer sediment shorelines being most sensitive (Bradbury 2005; Parnell et al 2007). Smaller grain sizes have lower thresholds for suspension so are more likely to be sensitive.

Shore types within Steensby Inlet were mapped from 2007 high resolution videography and photography. Seven shore types are described for Steensby Inlet (Harper and Morris 2008). Table 2 summarizes an generic assessment of sensitivity of the various shore types to ship wakes. In general, it is expected the shore sensitivity to ship wake-caused erosion is *low* because (a) most shorelines have a coarse cobble-boulder armour that limits sediment movement (Table 2), (b) almost all shorelines in Steensby Inlet are advancing (as opposed to retreating) due to post glacial isostatic rebound and (c) ship wakes are in the same range or smaller than those that occur during moderate storm events.

Biotic habitats that could be affected by ship wakes include salt marshes, intertidal and shallow subtidal rock weed beds and nearshore kelp beds (Harper and Morris 2008). Salt marshes occur in the upper intertidal zone and supratidal zone of low-energy shorelines, predominantly within bays, lagoons and estuaries. In general, it is unlikely that ship wakes will reach these protected lagoons and bays due to sheltering and shoaling effects; marshes naturally occur in very low-energy environments that are protected from larger waves. While there are some open coast estuaries (e.g., the Rowley River), low gradients of these areas will cause loss of ship-wake energy from shoaling, where the waves are likely to reach the shore as surges or spilling waves with a substantially reduced erosion potential. In the case of the Rowley River estuary, this estuary is also protected by a number of offshore islands. Given that ship wakes are similar in height and wave period to wind-waves generated during moderate storm events, it is assumed that rockweed and kelp are acclimated to current action associated with locally-generated storm waves and would not be adversely affected.

Foxe Basin – Hudson Strait Shore Types

A more regional shoreline mapping effort was undertaken within Foxe Basin to characterize shore types in terms of oil spill sensitivity (Harper 2010). In that inventory, six shore types were mapped using a combination of Google Earth satellite imagery and approximately 100,000 shoreline photos collected opportunistically during polar bear shoreline surveys. The shore types (Table 3) follow the shore types of Harper and Morris (2008) and sensitivities of Table 2. The occurrence of these shore types are summarized in Figure 4.

Foxe Basin and Hudson Strait shorelines are expected to have a *low* sensitivity to ship wake erosion because (a) most are coarse sediment shorelines that are naturally resistant to erosion, (b) shorelines are isostatically rebounding, so are generally advancing rather than eroding and (c) ship wakes produce waves that are similar in height to wind-generated storm waves, which are comparatively common during fall months.

<u>Shorelines Closest to Ship Route</u>

Although most ship wakes are likely to be very small, wakes associated with a 20 knot ship speed where wakes might exceed 0.5 m in height are identified in Figure 3 (red shoreline; Locations A and B). Figures 5 and 6 show aerial photos of Location A on a small islet within Steensby Inlet. The shoreline here is wave-cut rock platform with boulder-cobble-pebble berms in the upper intertidal zone. Such bedrock shores have a low sensitivity to wake erosion due to the anchoring nature of the bedrock and boulders, the low-gradient offshore slope and the fact that islets are still rebounding, as evidenced by raised beach features in the backshore. No sensitive habitats (e.g., saltmarshes are present along the outer shores of these islets).

Figures 7 and 8 show the shore to the south of the proposed port (see Fig. 3, Location B) where wakes are likely to higher than other areas of Foxe Basin. These aerial photos show a typical section of shoreline which includes some bedrock control, wide beaches of cobble-boulder armor interspersed with some sand patches in the lower intertidal. While the sand patches may be more sensitive to wake disturbance, the vast majority of wakes will be small (<0.5m) and within the range of normal storm-wave activity.

<u>Summary of Wake Effects on Shorelines</u>

Information on ship wakes generated from ore carriers indicate that most wakes are likely to be very small, especially where vessel speeds of less 15 knots occur. Ship wakes along the shore are likely to be less than 0.5 m in height and last less than a few minutes per ship transit. Wake heights are predicted to be of similar size or smaller than typical fall storms that occur prior to freeze-up; ship wakes have a relatively short duration (minutes per transit where storms wave occur over many hours. The presence of sea ice cover during most of the year is expected to reduce ship wake heights.

Most shorelines in Foxe Basin are advancing rather than retreating due to isostatic rebound. Bedrock–controlled shorelines are common and most alluvial fan shorelines include boulder-cobble armor across much of the intertidal zone. As such, most shorelines are resistant to wake effects, which are known to be more important on soft-sediment shorelines (muds and sands).

Sensitive habitats include salt marshes, rockweed beds and kelp beds. Salt marshes do not occur along the open coast shorelines that are likely to be subjected to wake wash; they primarily occur in protected bays and lagoons so are unlikely to be affected. Rockweed and kelp beds are common (see Fig. 7, 8) but are assumed to be acclimated to the existing wave climate, which includes waves of greater heights and for longer durations than ship-generated waves.

Wave modeling data and observed morphology and habitat features indicate that ship wakes are unlikely to cause any measureable erosion or habitat alteration along the proposed shipping routes.

Table 1. Wave Periods and Wave Heights as a Function of Wind Speed and Fetch

Wind Speed (ms^{-1})	**Fetch (km)**	**Wave Period (s)**	**Significant Wave Height (m)**
10	**10**	2.5	0.7
	20	3	1.1
	30	3.5	1.2
	50	4.1	1.4
	100	5.2	2.0
	200	6.5	2.2
15	**10**	2.7	0.8
	20	3.3	1.2
	30	3.7	1.3
	50	4.4	1.9
	100	5.3	2.3
	200	7.0	3.1
25	**10**	3.2	1.4
	20	4.0	2.0
	30	4.4	2.3
	50	5.4	3.0
	100	6.9	4.7
	200	8.6	6.8

Table 2. Steensby Inlet Shore Types[1]

Shore Type	Physical Description	% Occurrence in Steensby	Sensitivity to Ship Wakes
Rock cliff	Rock cliffs without beaches. Slopes range from steep (>30) to ramped. Generally heights are moderate in Steensby Inlet. Intertidal zone widths less than 10m. Most common on the east shore from proposed port site south to Cape Jensen.	5	*Low* sensitive to ship wakes. Attached biota relatively rare and capable of surviving ice contact, fall storms.
Rock cliff with beach	Rock cliff or ramp backshore with poorly sorted sand-cobble-boulder beaches in the intertidal. Boulder ridges in the intertidal are common. Intertidal widths usually less than 30m. Most common on the east shore of Steensby Inlet from head of Inlet south to Cape Jensen.	14	The armoring of most beaches with a cobble-boulder armor makes this shore type relatively insensitive to wakes effects and shoreline erosion. *Low* sensitivity.
Alluvial Fans	There are areas of till and glacial outwash that are termed *Alluvial Fans.* Backshore slopes are moderate and usually include a tundra vegetation cover. Associated intertidal areas are usually moderate to narrow coarse sediment beaches of boulder, cobble, pebble sand. Bounder ridging tends to be common.	20	Generally armored by cobble-boulder in the lower intertidal; may include pebble berms. Presence of boulder-cobble armoring in mid and lower intertidal reduces sensitivity to erosion; boulders especially cause wave breaking to reduce energy as wave cross intertidal. Assumed *Low* sensitivity to wake effects because of armoring.
Eroding Cliffs	There are some locations of eroding, unconsolidated sediments that produce steep cliffs with sand and gravel beaches. Generally the shoreline of the Inlet is progradational due to isostatic rebound but at a few locations eroding cliffs are noted. Intertidal zone widths vary but are comparatively narrow (<30m). These cliffs occur at isolated locations with limited extent.	2	May be sensitive to wave effects but this shore type is rare (2% of shoreline). Assumed to be *Moderate* sensitivity.
Wide Flats	Low gradient shorelines with flat backshores and foreshores. Raised beach ridge deposits are common in the backshore. Wide intertidal flats (unconsolidated) or rock platforms (sedimentary bedrock) occur; widths up to 1 km. Beaches typically consist of pebble-cobble and include supratidal storm berms and intertidal berms and beach faces. Common on offshore islets in Steensby Inlet and along the west shore of the inlet.	31	Low gradients of nearshore likely to dissipate energy of wakes as they propagate into shallow water. Ship wakes likely to reach shorelines as a surge rather than a breaking wave. Attached kelps observed offshore are assumed to be tolerant to wind wave-generated currents so not likely affected by wakes. Assumed sensitivity to wake impacts is *Low*.
Delta Flats	Delta flats and channel complexes associated with larger streams (e.g., Rowley River). Wide intertidal flats comprised of sand are bifurcated by distributary channels. Salt marsh occurs locally. Intertidal zone widths may be up to 1 km. Delta flats are most common on the east shore of Steensby Inlet.	2	Low gradients of nearshore likely to dissipate energy of wakes as they propagate into shallow water. Ship wakes likely to reach shorelines as a surge rather than a breaking wave. However, sediments are usually fine so may be likely more sensitive - *Moderate*.
Lagoon Complexes	Lagoon complexes are low gradient shorelines primarily in the northern portion of Steensby Inlet. The "shoreline" is extremely complex. Coastal gradients are very low with "backshores" only a few centimeters above the intertidal zone. Coarse boulder-cobble veneers dominate the intertidal. Finer sediments may occur in the shallow subtidal, where ice-gouging was commonly noted. White subtidal mats are interpreted as *Beggiatoa* and indicate anaerobic seabed conditions occur locally. Brine pools were noted in some isolated lagoon basins.	26	This shore type is not presence in ship wake areas. Intertidal areas are typically coarse, cobble-boulder armour.

Notes:[1] Shore types as described in Harper and Morris 2008, Table 1.

Table 3. Foxe Basin Shore Types [1,2]

Foxe Basin Mapping Shore Types	Description	% Occurrence	Sensitivity to Ship Wakes
Bedrock	bedrock control, usually narrow and steep. May include some coarse sediment pocket beaches	32.6	Low
Beach	mostly coarse sediment, boulder-cobble over sand matrix but lower energy beaches may include silt. Usually <50 m wide. May include salt marsh in low energy areas.	30.2	Low
Tidal flats	wide intertidal flats – often >1 km in width. Discontinuous coarse sediment (boulder-cobble) over sand. Upper intertidal coarse sediment beach	21.6	Low
Tidal Flats w Ridge & Swale	wide intertidal flats, often >1 km in width. Discontinuous coarse sediment (boulder-cobble) over sand. Upper intertidal includes berms. Ridge and swale lagoons in backshore with salt marshes in swales.,	5.8	Low
Delta Complexes	River-mouth areas with delta flats and distributary channels, frequently with large salt marsh areas. Estuaries are major conduit for anadromous fish.	7.0	Moderate
Lagoon Complexes	lagoon complex areas with high crenulated, complex shorelines. Salt marshes are common. Very low wave energy levels	3.7	Low

Note: [1] After Harper 2010, Table 3
[2]Total shoreline length = 35,511 km

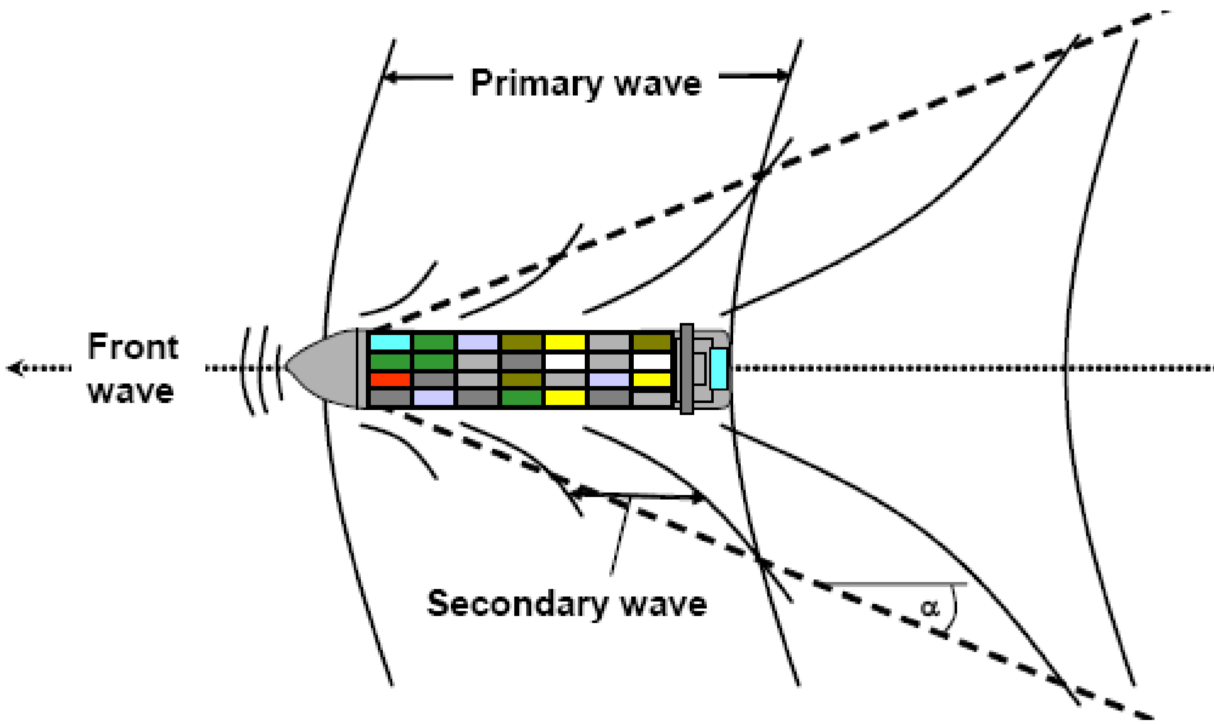

Figure 1. Schematic of ship wake terminology (from Schuttrumpf 2006)

Figure 2. Wake heights resulting from a 14 knot ship transit speed (after Kreibel 2003 and Appendix 8D-1 Figures 8D-1.1 – 8D-1.4).

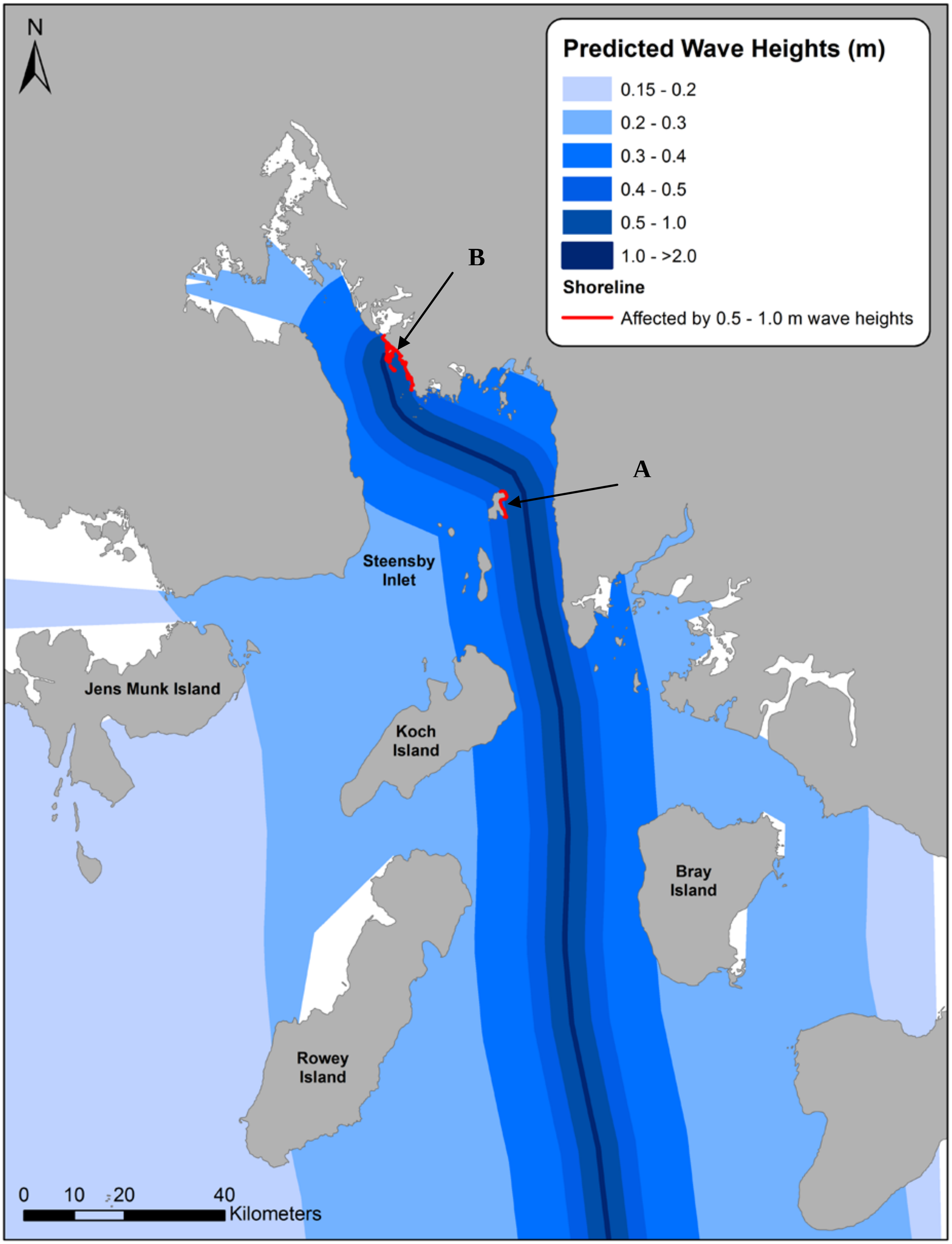

Figure 3. Wake heights resulting from a 20 knot ship transit speed (after Kreibel 2003 and Appendix 8D-1 Figures 8D-1.1 – 8D-1.4). Red shoreline indicates possible 0.5 to 1 m wake heights.

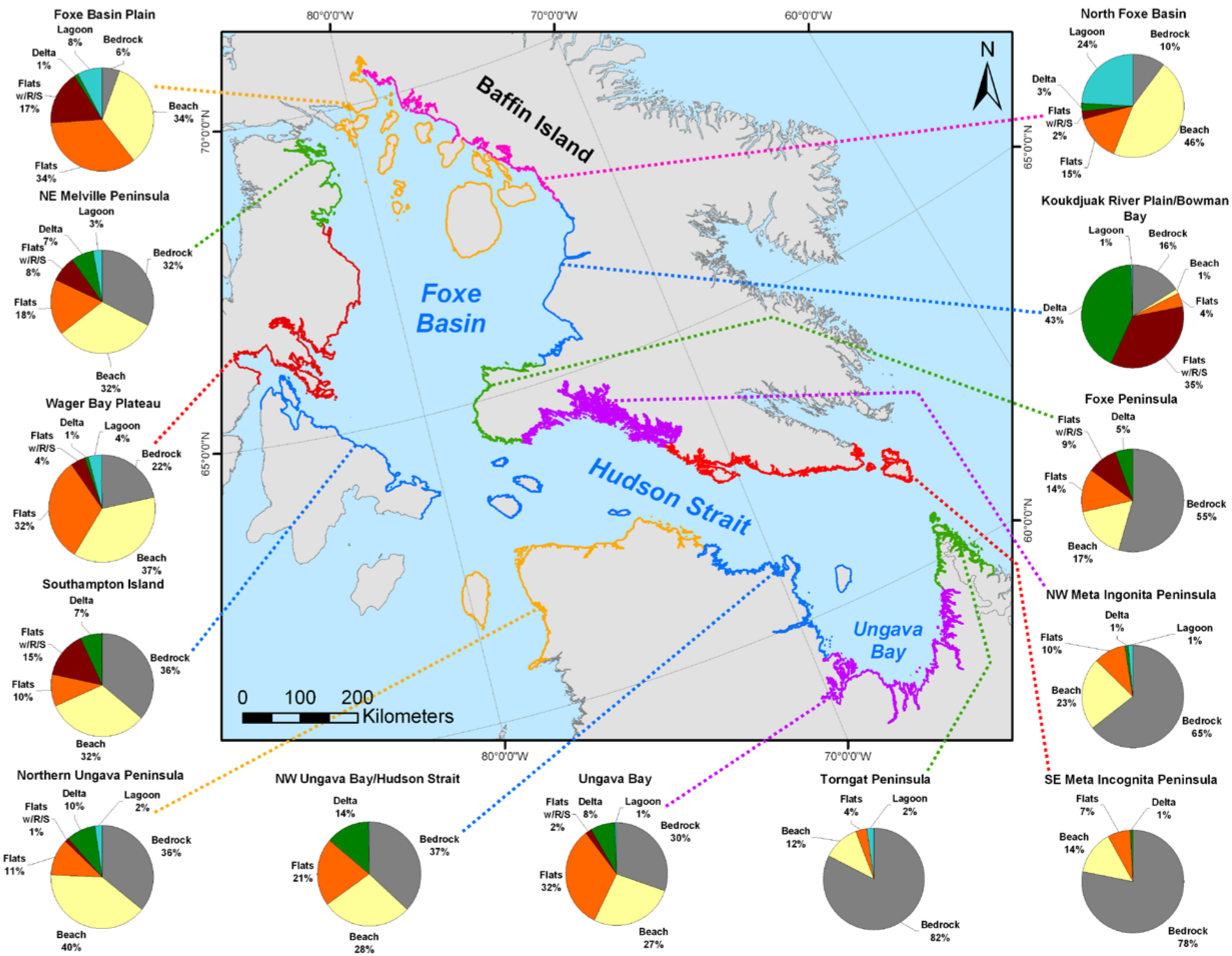

Figure 4 Summary of coastal habitat occurrence in Foxe Basin. The summaries are based on 36,000 km of imagery classification (see Harper 2010 for details).

Figure 5. Point closest to shipping route on offshore islet (Location A, Fig. 3). The shallow, subtidal is a wave-cut rock platform with coarse sediment berms in the upper intertidal. Isostatic rebound has caused berms to be uplifted (further inland).

Figure 6. Close-up of upper intertidal in Figure 5. Note sedimentary bedrock in lower frame, coarse boulder-cobble near the base of the beach and the pebble berm in upper frame. Sediments are unlikely to be sensitive to wake wash.

Figure 7. Aerial photo of typical shoreline immediately south of the proposed port area (Location B, Fig. 3). the upper intertidal zone is boulder and the lower intertidal zone is a mixture of boulder to sand-sized sediment. Rockweed (*fucus*) covers the boulders in the lower intertidal. While some intertidal sands exist, the boulder cover 40-50% cover) is likely to anchor the shoreline from any significant erosion. Raised beaches in the backshore indicate the shore is isostatically rising.

Figure 8. Very low elevation (~20 m altitude) photo near Fig. 7 showing boulder cover and rockweed. The lineation (upper left to lower right) is most likely due to bedrock that is near the surface of the beach. Beaches and flats are very commonly armored with cobble-boulder veneers.

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