ICE CONDITIONS USED AS A DESIGN BASIS FOR THE VOISEY'S BAY DEVELOPMENT

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ABSTRACT

This paper reviews the range of nearshore ice conditions encountered along the winter shipping route serving the Voisey's Bay (VBNC) mine site in Labrador. The geographic scope focuses on the area beginning with the offshore approaches to Nain near 60° West Longitude, and ending at the dock site. Material draws primarily on the authors' experience with a series of studies in 1996 and 1997, and sections prepared for the VBNC Environmental Impact Statement (1997).

The historic time scale of the ice review varies according to the source data, but generally ranges from 1972 through 1997. Accounts of the Moravian Mission (1795 to 1917) were used to construct an older record for comparison with modern data.

The paper summarizes the following ice parameters:

- Freeze-up and break-up trends
- Fast ice extent
- Spatial variability of ice and snow depth along the route
- General pack ice characteristics

INTRODUCTION AND BACKGROUND

This paper describes ice conditions on the approaches to the port site in Edward's Cove, Anaktalak Bay, serving the Voisey's Bay mining development on the coast of Labrador, Canada. The focus is on the nearshore fast ice[1] environment but consideration is also given to general pack ice trends. Much of the material is drawn from the Voisey's Bay Mine/Mill Project Environmental Impact Statement, Chapter 9.1 (VBNC, 1997) and supporting documents prepared by the authors during the development phases of the project (Dickins 1996,1997a; Cormorant 1997).

[1] Ice that forms between the shore and sina (ice edge), also known as land fast ice.

Importance of the Ice Environment

Sea ice, in the words of Hare (1950), "is not merely a consequence of winter cold; it is also a climatic factor in its own right, drastically changing the climate of the whole year". Along the northern coast of Labrador, ice is a prominent, highly variable feature of the landscape. The fast ice acts as an extension of the land for over five months of the year. For animals such as ringed seals, the fast ice provides habitat for breeding and whelping. It also serves as a surface for travel by local residents and caribou. People living in the communities of the Northern Coast are highly knowledgeable about the ice environment; using the fast ice for recreation, travel to neighbouring communities for social visits, and access to resource harvesting areas. In addition, the ice environment greatly affects many aspects of project design and operation, including: scheduling, stockpile storage, port design, winter navigation, safety issues, vessel selection and chartering, project economics.

Geographic Scope and Boundaries

Shipping activity will take place along a defined corridor within the fast ice from Edward's Cove to the fast ice edge. The focus of the environmental assessment was on the nearshore ice immediately along and adjacent to the shipping route (Fig. 1). Also shown are a range of historic fast ice edges mapped from satellite images during the months of January to early June, from 1974 to 1997, closely matching the boundaries mapped by Nain residents (Williamson 1997).

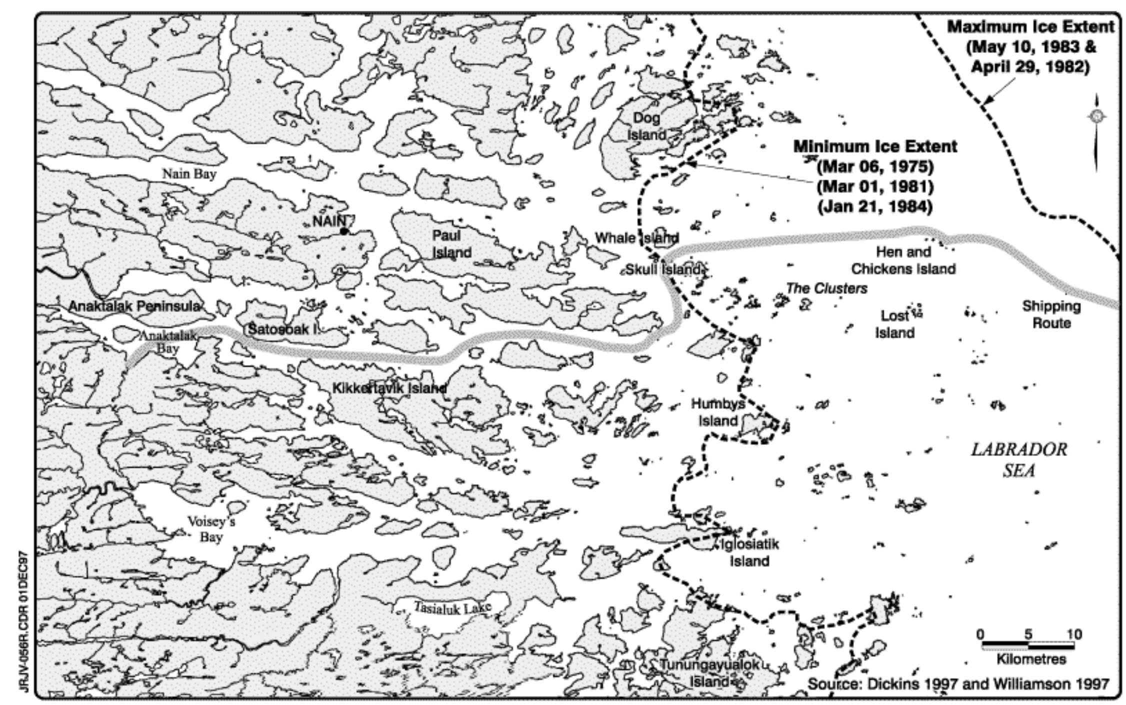

Figure 1 Ice Assessment Area and Historic Range in Fast Ice Extent

METHODS AND SOURCES

The extensive knowledge base on ice conditions for the Voisey's Bay Project was derived from three main types of sources:

- Publicly available technical references and historical documents, e.g.: Canadian Ice Service (1996 and 1992), Allen (1977), Elton and Asburner (1980),
- Project-specific studies commissioned by VBNC, e.g.: Dickins 1996 and 1997), JWEL 1997), Cormorant Ltd. (1997), and
- Inuit knowledge of ice conditions in the Nain area (e.g., Williamson 1997).

The original ice characterization was based on a 25-year record of ice conditions consisting of ice charts, Landsat imagery, surface measurements, aerial reconnaissance, and climate analysis. The Canadian radar satellite (Radarsat 1) available since 1996, overcomes many of the weather limitations associated with visual imagery. Radarsat was extensively used in carrying out ice evaluations along the shipping route in 1996 and 1997 (Dickins, 1996a; Cormorant, 1997). Subsequent studies after 1997 (unpublished) include: an additional winter ice monitoring program (Cormorant, 1998 for VBNC), and the development of a ship ice transit database covering the complete shipping route (Dickins, 2002 for AMEC).

ICE CONDITIONS

On a broad scale, there are three important kinds of ice which impact various aspects of the Voisey's Bay Project: fast ice which freezes in-situ along the coast among the islands and in the bays, inlets, and fjords; pack ice which flows outside the winter land fast ice, coming from Hudson Strait and Baffin Bay; and icebergs, which have calved off the glaciers of Greenland and Ellesmere Island.

In northern Labrador, fast ice usually forms between late November and early January, progressing from north to south. Violent winds during the freeze-up period can delay the formation of permanent fast ice for several weeks, often resulting in a rough final ice surface. A sudden cold snap in autumn, accompanied by an extended period of calm weather, on the other hand, will bring on an early and rapid formation of relatively smooth fast ice. Once a stable sheet takes hold, it remains throughout the winter, becoming like the land, soon covered with snow in sheltered places and scoured clean in others by the strong winds channeled out of the bays and fjords. The break-up period usually lasts three weeks, terminating consistently in the month of June. The onset of onshore winds can keep the pack ice inshore and delay navigation for a month or more.

Field studies by Cormorant (1997) documented several distinct bands or zones of ice associated with the transition from stable fast ice to the dynamic offshore pack ice visible in Fig. 2. This transition region can include areas of heavily rafted and deformed ice created as the fast ice edge expands eastwards during cold, calm periods and then compresses as the winds shift to onshore. This band of rough ice is relatively narrow, in the order of 10-15 km in east-west extent, and after February is normally incorporated as a rougher, thicker part of an expanded landfast zone.

Further to the east, an area of unstable but relatively static ice is often found inshore of the thicker, rougher offshore pack. For much of the winter (January to March), this area is dominated by broken new and young ice as shown in the March satellite image example (Fig. 2). Along the eastern edge of this transition area, a sharply defined, continuous ice shear wall can form at the boundary with the more rapidly moving offshore pack (Cormorant, 1997).

Timing of Fast Ice

Fall storms play a major role in determining when the fast ice becomes established sufficiently to remain through the winter. The 1996/1997 winter is a good example of the often-complex sequence of events leading to a stable fast ice cover. New ice was observed forming in protected bays near Nain as early as mid-November 1996; one month later there was still no stable ice cover across the main channels. The initial sheet of new ice across Edward's Cove (the new port site) was broken by strong winds in late December. A second new ice sheet was then submerged by a heavy snowfall at the end of Dec (forming a condition locally referred to as "slob" ice). Freeze-up in the main shipping channel finally occurred in the last week of January, after a period of strong outflow (westerly) winds on January 18-19 broke up the initial fast ice in that area (Cormorant Ltd. 1997).

At its seaward edge, the fast ice arches between successive islands, shoals and islets running roughly north/south from Dog Island to Tunungayualok Island. Depending on the pressure of the offshore pack, the ice edge may remain inshore near Whale Island or expand seaward to encompass an area of small islets, the Hen and Chickens and Lost Islands (Fig. 1). The area between the minimum and maximum envelopes of likely edge positions is subject to fracturing and movement when pressured by onshore winds and tidal movements. When followed by a strong sustained westerly wind, large sections of fast ice can break-off and drift offshore, leaving a broad north/south flaw lead or band of thin ice between the offshore pack and fast ice.

Canadian ice charts can be used to estimate break-up and freeze-up dates (Table 1).

Nearshore waters inside of Paul Island are often clear of ice within 7-10 days of the break-up dates defined in Table 1. In some years, such as 1996, high concentrations of pack ice and fast ice remnants can persist along the shipping route for up to six weeks following break-up.

Table 1 Fast Ice Freeze-up and Break-up: Satosoak Island 1980 to 1996

	Start of Fast Ice [1] (1979-1996)	**Break-up (1972-1996)**	**Duration of Fast Ice**
Earliest or Minimum	November 25, 1979	May 31, 1979 & 86	139 days (1996)
Latest or Maximum	January 20, 1996	July 7, 1991	210 days (1991)
Mean	December 15	June 17	183 days

[1] "Start of Fast Ice" means the first appearance of a complete ice cover. Ice often occurs in protected areas along the shoreline a month ahead of the start of fast ice.
[2] "Break-up" is interpreted as the first date when ice charts report that an area formerly mapped as fast ice contains 9/10 or less concentration (90% ice by area).

Moravian mission accounts together with a diary of George MacMillan's voyage to Labrador in 1927-1928 contain much older records of ice freeze-up and break-up in the area (Elton and Asburner 1980; MacMillan 1928 in Leacock and Rothschild 1994). Old and new databases were combined to produce a record spanning 200 or more years (from 1820 for freeze-up and 1795 for ice clearing). Data from the 1800's display greater variability than the modern record and indicate only slight shifts in the timing of the ice season since that time. Mission accounts in the 1800s point to a somewhat earlier freeze-up (by one to two weeks) together with a slightly later break-up. The average ice season during the period 1820-1890 may have been 10 to 15 days longer than the present day, indicating somewhat colder winters and thicker ice.
The variability in timing of travel on the ice is summarized in Table 2 (Allen, 1977). Similar timing of on-ice travel is described in Williamson (1997).

Table 2 Timing of On-ice Travel at Hopedale, 1965-74

Ice Condition	Range in Dates
First permanent ice	November 26 to December 19
Complete freeze-over	December 1 to December 28
Ice safe for traffic	December 9 to January 9
Ice unsafe for traffic	May 12 to June 10
Water clear of ice	May 29 to June 28

Source: Hopedale Records 1965-1974 (Allen 1977)

The available ice databases demonstrate the extreme annual variability both in dates of formation and rates of ice growth along the Labrador Coast. Local residents have observed recent changes in the natural ice cycle, noting that the ice: takes longer to freeze, accumulates less snow cover, breaks-up earlier, and is thinner at the end of the winter (Williamson, 1997). Future ice studies need to consider potential changes to the ice environment that could result from climate change (including the potential for even greater variability)

Fast Ice Extent

Fast ice edges were mapped from 18 historical Landsat images in three different winter periods: January; February to March; and April to June (Figure 2). A similar number of Radarsat images were collected during the 1997 ice season to provide a detailed chronology of fast ice extent from January to May (Cormorant Ltd. 1997).

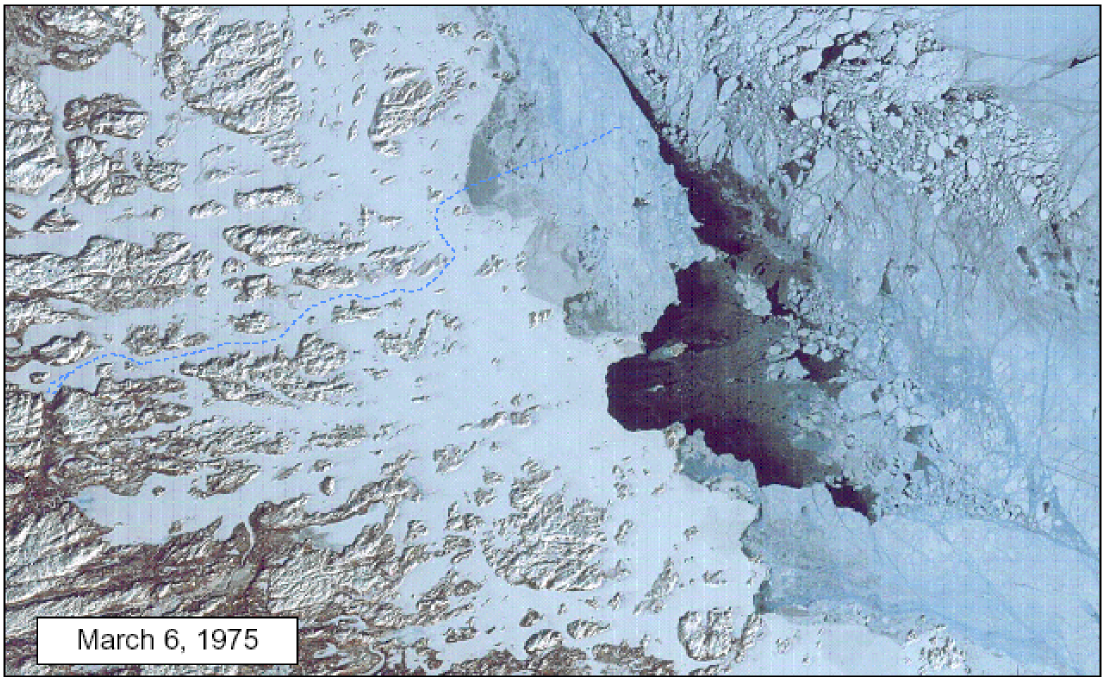

Figure 2 Landsat image showing fast ice, shear zone and pack ice on the approaches to Nain, March 6 1975. Shipping route as dashed line.

Figure 3 shows an example of fast ice edges in months of February and March mapped from Landsat images in six different years.

Fast Ice Thickness

The expected growth and thickness of fast ice along the shipping route was compiled from three sources: historical measurements at Hopedale (no records are available for Nain), 1997 field measurements along the shipping route, and hindcast modeling based on historical freezing-degree day accumulations. Periodic measurements collected at Hopedale harbour over a 24-year period (1961 to 1984) show mean, maximum and minimum thickness of 107, 135 and 80 cm, respectively. In an average year, fast ice reached its maximum thickness in the last week of April, and the first measurable loss in ice due to melt occurred at the end of the first week of May (Canadian Ice Service 1992). Average snow accumulation at the end of the winter was 27 cm. The Hopedale record is representative of fast ice found in the Nain area (demonstrated by concurrent measurements in 1997 at both locations).

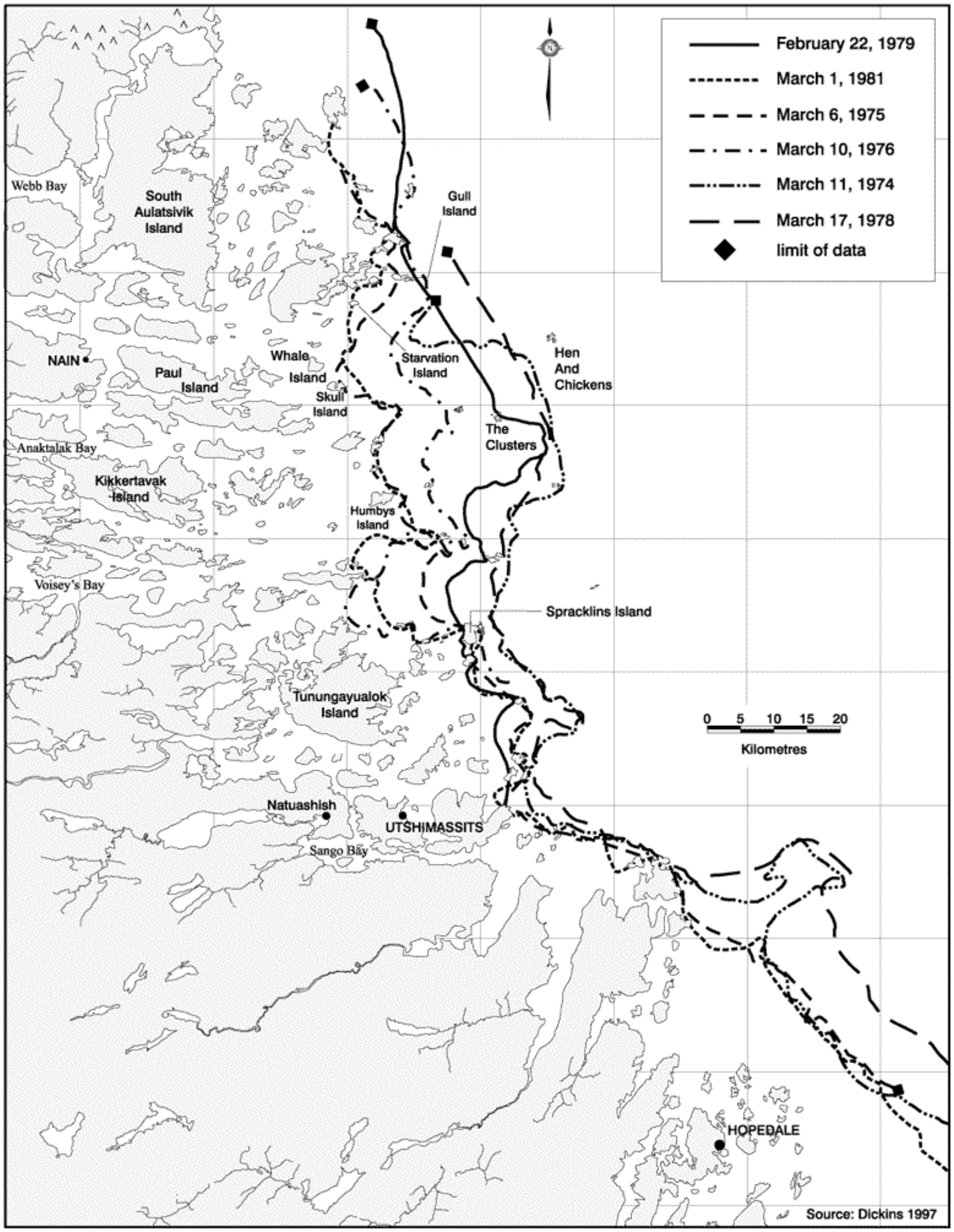

Figure 3 Fast ice edges mapped from satellite imagery in February and March

Snow and ice thickness were measured at over fifty points along the shipping route from January to May 1997 (Cormorant, 1977). Results showed that even after an extremely late freeze-up, interrupted by storms in late December and mid-January, the fast ice grew to between 115-130 cm along the route by May 7 (compared with a long term estimated mean thickness of 107 cm). Peak values at several stations exceeded 140 cm. Typical snow depths on the ice ranged from 5 to 25 cm from January to mid-March, increasing to between 30-40 cm in late March and April (peak values were over 50 cm). Areas of thicker ice generally coincided with lower tidal currents.

Figure 4 shows the cycle and variability of ice thickness along the shipping route from Edwards Cove (left) to the east end of Paul Island (right) during the winter of 1997.

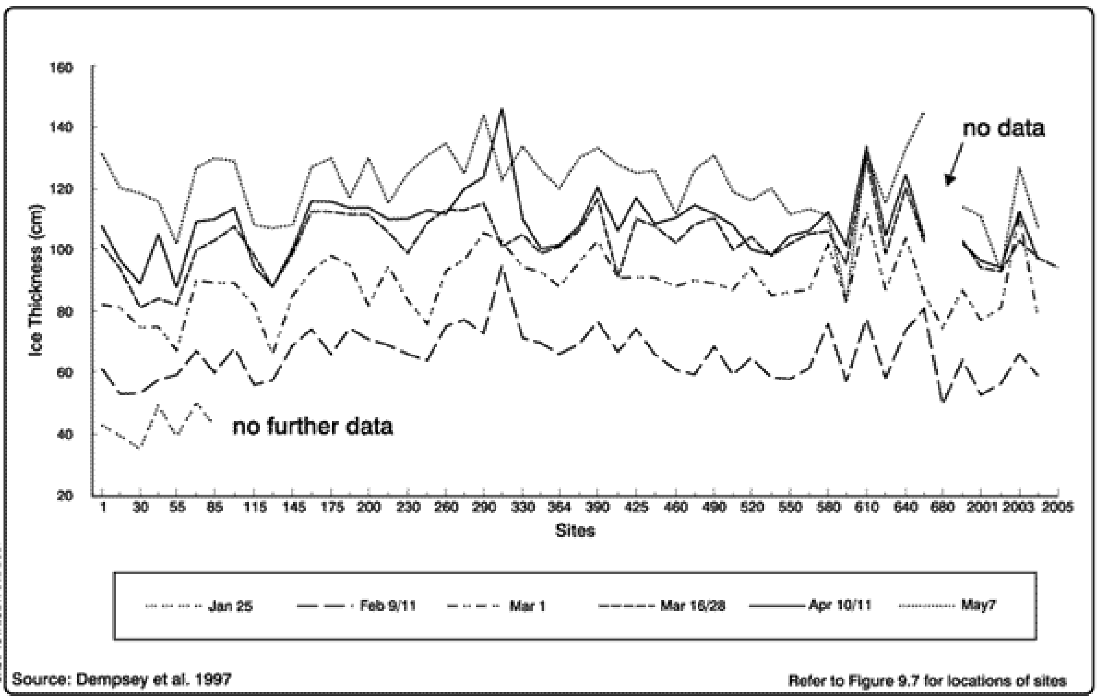

Figure 4 Variability in ice thickness along the winter shipping route, January to May 1997 (Cormorant, 1997)

Hindcast modeling was used to estimate the ice growth that likely occurred in previous winters, based on freezing and thawing records. Snow cover was not considered directly. Coefficients in the empirical ice growth formula were selected such that the predicted curve closely matched the Hopedale mean ice thickness when the model was run using the average Hopedale freezing records. The same formula was then applied to predict likely thickness values along the shipping route, using Nain climate records for a given winter. The results agreed closely with 1997 measurements (to within 10 cm) when the model was run with climate data collected from a temporary automated weather station at the east end of Paul Island (Cormorant, 1997).

Summary of Pack Ice Conditions

The historical (1972-96) mid-winter width of the pack ice zone at the latitude of Nain varies from as little as 40 km to almost 200 km (Dickins 1997). The ice concentrations within the pack alternate between compact and open depending on the prevailing winter winds (generally westerly from December to March, with infrequent states of extreme pressure when the pack is driven into the coast shore by onshore winds (easterlies).

Pack ice often moves rapidly south along the coast. For example, a beacon deployed off the coast near Nain (58ºW) drifted at an average rate of 50 km/day for 10 days (Prinsenberg, 1988). Another beacon deployed at the same time but closer to the fast ice edge moved at about one-third the speed, characteristic of the slower moving more protected inshore area separating the fast ice and offshore pack (Fig. 2). LeDrew and Gustajtis (1979) quote ice speeds in 1977 as high as 120 km/day in the main pack ice stream, with 75 percent of the measurements showing rates in excess of 20 km/day.

Older, multi-year ice drifting south from Baffin Bay makes up a small proportion of the overall pack (usually much less than 10 percent). In addition, icebergs can be encountered year round on the approaches to the fast edge.

Historical measurements of pack ice thickness off the Labrador coast are limited in number and accuracy. Fenco (1976) studied five rough Arctic floes near 56°N. Mean thickness ranged from 5.5 to 8.2 m, with floe sizes tending towards elliptical in the range of 50-90 m. Fenco's 1975 and 1976 April data were reinterpreted ten years later to arrive at an estimated mean undeformed first-year floe thickness came of 1.76 m. This value compares remarkably well with the overall average of 1.86 m computed by Holladay and Moucha (1998) from over 400 km of ice thickness profiles flown off Cartwright in 1994 (a year with colder than average temperatures and lower than average snowfall). The 1994 field program observed that the ice thickness and concentration increased with increasing distance from shore until the main pack was encountered at about 50 km out. The main pack comprised a mix of very rough consolidated floes made up of thick (over 1.5 m), small floes bonded together, and a few large, smooth thinner floes (40-55 cm thick).

Over 80% of the ice area within the pack ice zone can be deformed with rubble, rafted pans and ridges. This extreme roughness is common in the nearshore areas with active shearing processes between the fast ice and the moving pack. Continuous North/South shear ridges can exceed 5 m in sail height over distances of tens of km, with surrounding roughness features in the range of 3-5 m elevation (Cormorant, 1997). A segment flown in an equivalent rafted/rubble, inshore ice zone off Hopedale in 1994 showed an average ice thickness of 4.5 m over four kilometres (Holladay and Moucha, 1988).

Localized Conditions: *Rattles* and *Ballicaters*

Rattles and *Ballicaters* form localized areas with special characteristics within the fast ice zone, in the first case, areas to avoid when travelling, and in the second case, potential opportunities for seal harvesting.

Rattle is a local term used to describe patches of persistent open water or thin ice, usually associated with narrows and channels with strong tidal action (for example Bridges Passage near Nain). Coastal residents take great care to avoid these areas due to the danger of breaking through the ice.

One *rattle* identified through local workshops is located between a small islet immediately to the south of the shipping route and the Southeast shore of Paul Island. Three ice thickness stations in the 1997 ice monitoring study straddled the area known locally as a rattle at the end of Paul Island. Station (#595), in the area most affected by the tidal flow through the constricted passage, consistently showed thinner ice (by 20 to 30 cm) than the two stations on either side. For example, on February 1, station #595 had 43 cm of ice, while the stations immediately to the east and west had 65 cm of ice. These results show that while thinner than the surrounding fast ice, constricted, fast running passages can still freeze to form a substantial, potentially dangerous ice cover.

Hinge Ice is a term used to describe a particular nearshore geometry of parallel tidal cracks which can lead to the creation of a temporary air cavity beneath the ice foot or ledge (known as the *ballicater*) adhering to steep rocky shorelines. The tidal crack area in shallow water along the shore is used to set seal nets (Williamson 1997).

CONCLUSIONS

The winter ice environment plays a major role in defining many of the engineering design, operational and economic aspects of the Voisey's Bay Mine/Mill Project. This paper presents a synopsis of results from a series of dedicated field programs, and extensive analysis commissioned to support the Voisey's Bay development. These results were validated and supplemented by local knowledge to arrive at a comprehensive understanding of the important features and characteristics of the local ice environment.

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