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GLACIAL HISTORY AND QUATERNARY GEOLOGY OF THE WHITE BAY REGION

S.J. McCuaig
Geochemistry, Geophysics and Terrain Sciences Section

ABSTRACT

Evidence of the last (late Wisconsinan) glaciation was found in the White Bay area. During ice build up, ice flowed toward, but not across, White Bay from the Long Range Mountains. At the glacial maximum, ice flowed north-northeastward along the bay. Later, as ice thinned, ice caps developed on peninsular uplands that flank the bay. Calving and drawdown in White Bay occurred at the same time. The change in ice source areas brought about a gradual change in ice-flow directions, until ice was flowing into White Bay from either side. Ice flowed actively during retreat in most of the study area.

Till deposited during the late Wisconsinan is generally thin and discontinuous, and is almost non-existent along the shoreline. An exception is the Micmac Pond area, where till is thicker and locally, hummocky; large boulders litter the surface over much of this area. As ice retreated and thinned, glaciofluvial and glaciomarine sediments were laid down; however, the volume of these deposits in comparison to till is minor. Isostatic rebound during deglaciation caused relative sea level to fall as these deposits formed.

Raised deltas, glaciomarine terraces and beach ridges were formed during several different sea-level stands, ranging from a high of 70 m above sea level (asl) to a low of 10 m asl. Sea-level highstands identified at 40 and 30 m asl on the west side of the bay occurred 11 200 ± 100 and 10 200 ± 100 radiocarbon (^{14}C) years ago respectively.

Modern sediments include minor fluvial and mass-wasting deposits. Rockfalls are particularly active along the steep shores of White Bay.

INTRODUCTION

The White Bay area of northeastern Newfoundland was extensively and likely repeatedly glaciated during the Pleistocene (MacClintock and Twenhofel, 1940; Vanderveer and Taylor, 1987; Liverman and St. Croix, 1989). It has also been an area of interest for gold exploration from 1889 (Betz, 1948) to present. Gold, copper, fluorite, molybdenum and lead occurrences have been identified on the west side of White Bay, while gold, titanium, copper and lead have been found on the east side of the bay (Davenport *et al*., 1999). Lake-sediment geochemistry (Davenport *et al*., *op. cit.*) has identified areas showing anomalous values of Zn, Pb, Mo, Mn, Cr, Cu, Ni, Au, Ag and U.

The presence of mineralization, along with a complex ice-flow history (Vanderveer and Taylor, 1987; Liverman, 1992), make the White Bay area an attractive place for Quaternary geology investigation. An improved understanding of the regional ice-flow history is important for overall ice-sheet reconstruction in Newfoundland. On a smaller scale, an understanding of the Quaternary geology is helpful to companies engaged in drift prospecting, especially if till samples are taken.

Thus, the Quaternary geology of NTS map areas 12H/10 and 12H/15 was mapped. The region was also sampled for till geochemistry and ice-flow indicators were measured and recorded.

PHYSIOGRAPHY

White Bay separates the Great Northern and Baie Verte peninsulas. It is a long, narrow, north-northeast-trending bay that narrows to a point in the south (Figure 1). Its rocky shores consist of steeply sloping bedrock cliffs, upon which numerous rockfalls have occurred. The Long Range Mountains in the northwestern part of the map area reach a maximum elevation of 509 m asl (metres above sea level) and form a hilly plateau. Rolling linear hills and valleys on both sides of the bay take their shape from bedrock structure, which also trends north-northeast. An exception to this is

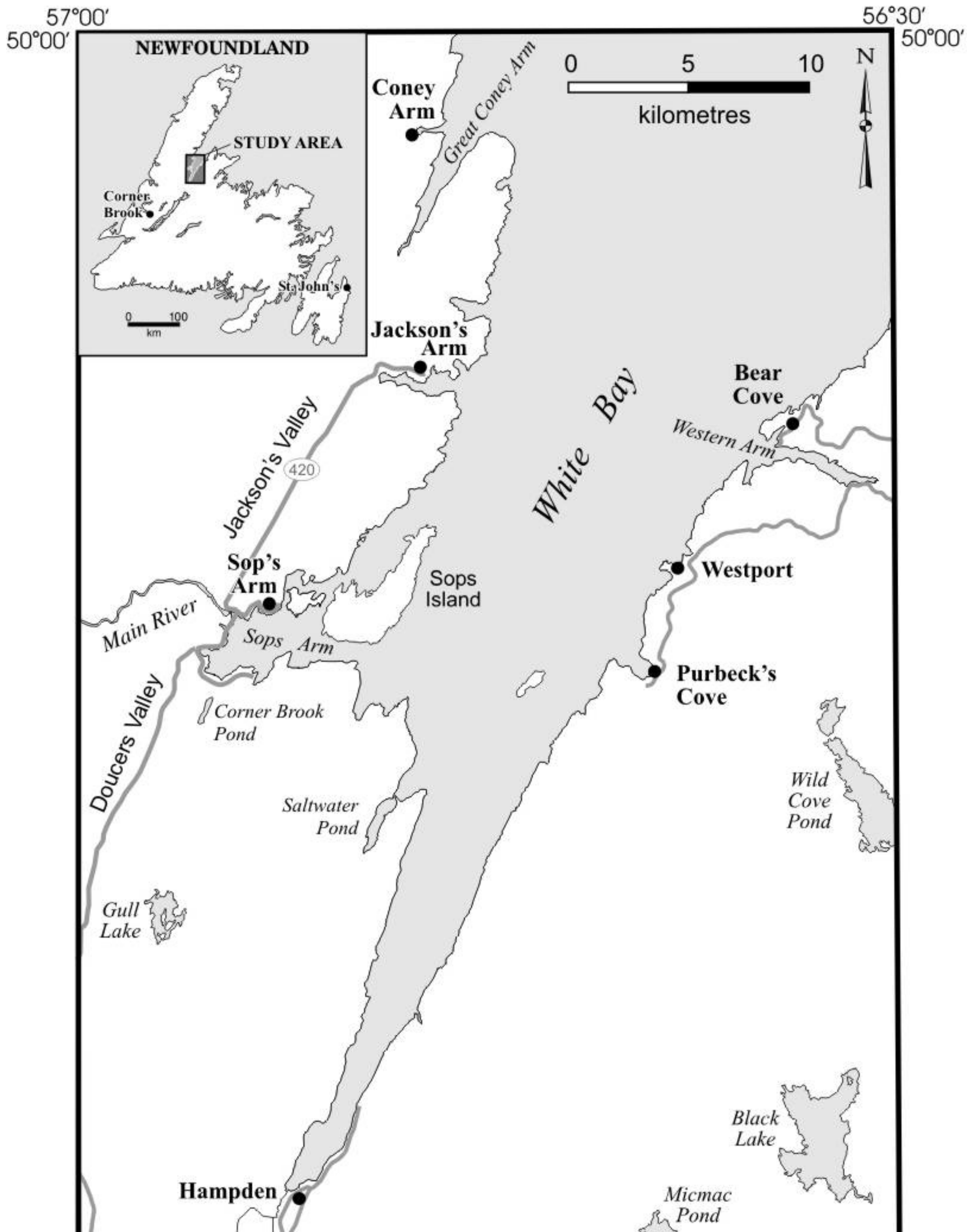

Figure 1. *Location map, White Bay area.*

Purbeck's Fiord (near Purbeck's Cove), a curving fiord that cuts through the bedrock structure. In the southeastern part of the region, near Micmac Pond, glacial sediments are thicker; they hide much of the bedrock and create a locally subdued hummocky topography. Drainage patterns are directly related to bedrock geology, except in the southeastern part of the study area, where the sediments are thicker. Narrow beaches are located in sheltered coves and at river mouths, but they are uncommon.

BEDROCK GEOLOGY

The bedrock geology of the study area is complex (Figure 2). The region is dominated by rocks of the Humber

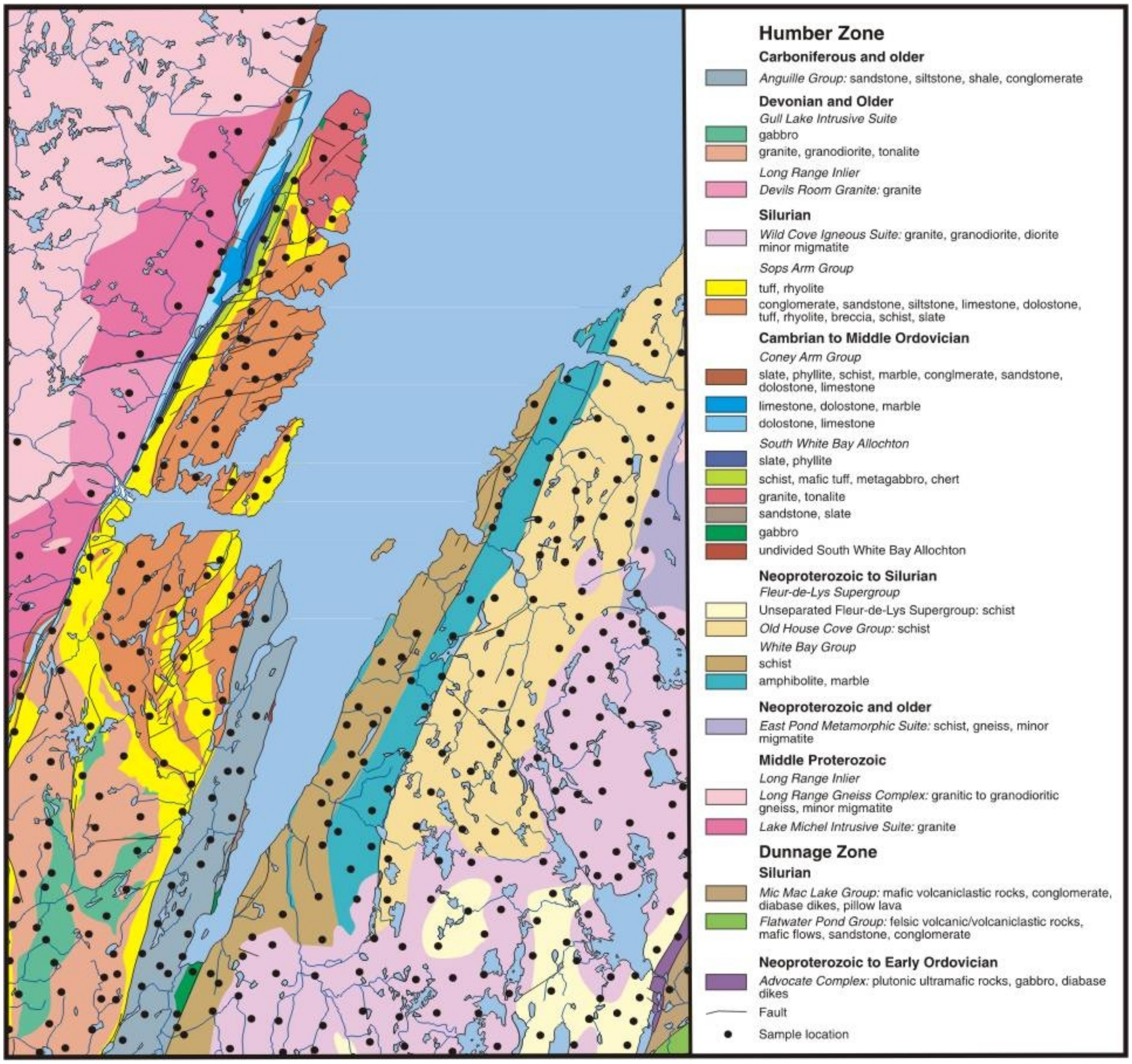

Figure 2. *White Bay geology and till sample locations.*

Zone, although Dunnage Zone rocks outcrop in the south-eastern corner of the study area. The Humber Zone was once the margin of the early Paleozoic continent Laurentia (Williams, 1979). The Dunnage Zone contains mostly volcanic oceanic rocks that were thrust over Humber Zone rocks when the Iapetus Ocean closed (Hibbard, 1983).

Rocks on the east and west sides of White Bay are significantly different from each other. Clast lithology can thus be used to help determine ice-flow directions in this area. The bedrock geology is described in detail in the following section.

HUMBER ZONE ROCKS

The oldest rocks, which have been subjected to high-grade metamorphism, belong to the Long Range Inlier of the Great Northern Peninsula (Owen, 1991). They form the Mesoproterozoic Long Range Gneiss Complex, composed of granitic to granodioritic gneiss and minor migmatite. They were intruded first by the Paleoproterozoic Lake Michel Intrusive Suite (Aspy and Main River granites) and much later by the Devonian Devils Room granite (Owen, *op. cit.*).

The Proterozoic rocks are unconformably overlain by much younger sandstone, conglomerate, dolostone, limestone, slate, schist, phyllite and marble of the Cambrian to Middle Ordovician Coney Arm Group; ophiolitic volcanic/volcaniclastic rocks, sandstone, slate, phyllite, granite, tonalite and gabbro of the Cambrian to Middle Ordovician Southern White Bay Allochton; and conglomerate, felsic tuff, rhyolite, breccia, sandstone, siltstone, dolostone, limestone, schist and slate of the Silurian Sops Arm Group (Smyth and Schillereff, 1982). The Devonian and older Gull Lake Intrusive Suite lies to the south of these rocks and consists of gabbro, granodiorite, tonalite and granite (Smyth and Schillereff, 1982). The Carboniferous Anguille Group borders southern White Bay, east of the Sops Arm Group and the Gull Lake Intrusive Suite and is mainly sandstone and shale (Smyth and Schillereff, 1982).

The Doucers Valley fault complex separates the Grenvillian rocks in the west and the younger Sops Arm and Coney Arm groups to the east, and extends from Doucers Valley to Great Coney Arm (Tuach, 1987). The northern extension of the fault complex falls in a valley, which is informally named 'Jackson's Valley'. The Birchy Ridge strike–slip fault and the Cabot–Hampden fault separate the Anguille and Sops Arm groups (Smyth and Schillereff, 1982; Tuach, 1987).

Rocks outcropping on the Baie Verte Peninsula include the Neoproterozoic to Silurian Fleur-de-Lys Supergroup, the highly deformed, Neoproterozoic or older East Pond Metamorphic Suite and the Silurian Wild Cove Pond Igneous Suite (Hibbard, 1983; Cawood *et al*., 1994). Schistose rocks dominate the Fleur-de-Lys Supergroup, which is mainly continental and is less deformed than the East Pond Suite. The Fleur-de-Lys Supergroup is subdivided into the White Bay Group, which contains schist, amphibolite and marble, and the Old House Cove Group, which consists of schist (Hibbard, 1983). The East Pond Metamorphic Suite includes banded and granitic gneiss, schist and minor migmatite (Hibbard, 1983) and is intruded by the Wild Cove Pond Igneous Suite, which is composed of diorite, granodiorite, granite, and minor migmatite (Hibbard, 1983).

DUNNAGE ZONE ROCKS

The oceanic rocks in the southeastern-most portion of the study area include Neoproterozoic to Early Ordovician plutonic ultramafic rocks, gabbro and diabase dykes of the Advocate Complex (Hibbard, 1983). A younger Silurian sequence consists of mafic volcaniclastic rocks, conglomerate, diabase dykes and pillow lava of the Mic Mac Lake group and felsic volcanic–volcaniclastic rocks, sandstone, conglomerate and mafic flows of the Flatwater Pond Group (Hibbard, 1983).

ECONOMIC GEOLOGY

A number of mineral occurrences have been described in the region. The Mineral Occurrence Data System (MODS) database of the Geological Survey of Newfoundland and Labrador identifies one past-producing gold mine, two past producers of marble, three gold prospects and one limestone prospect within the study area. Other showings or indications include gold, copper, iron, molybdenum, lead, zinc, silver, titanium, barium and fluorine, of which the first four are the most common.

Gold mineralization is found in shear zones in the Aspy Granite, in the Sops Arm Group, and along the Doucers Valley fault complex (Owen, 1991; Tuach, 1987). Arsenic and antimony are pathfinders for gold in lake sediments in these areas (Davenport and Nolan, 1989; McConnell and Honarvar, 1989). Browning's Mine, near Sops Arm, was one of Newfoundland's first gold mines, and operated for a year in 1903-04 (Betz, 1948).

Localized fluorite and molybdenite are found in the Devils Room granite (Smyth and Schillereff, 1982) and in the Gull Lake Intrusive Suite (Tuach, 1987). Fluorite-bearing breccia is exposed along the forestry road on the Main River's north bank. Lead is found in limestone and rhyolite in the fault zone at the western edge of the Gull Lake Intrusive Suite, as well as minor copper and uranium (Tuach, 1987).

PREVIOUS WORK

QUATERNARY GEOLOGY

The Island of Newfoundland maintained an independent ice cap or caps during the late Wisconsinan; the Laurentide Ice Sheet reached only the tip of the Great Northern Peninsula (Grant, 1977, 1992). Ice-flow directions in Newfoundland changed through time as the influence of individual ice caps increased or decreased (*see* for example St. Croix and Taylor, 1991).

Heyl (1937) and MacClintock and Twenhofel (1940) provide the earliest descriptions of glacial geology in the White Bay area. They mention the presence of abundant erratics, ice-scoured and stossed bedrock, U-shaped valleys and patchy glacial sediment. MacClintock and Twenhofel (*op. cit.*) concluded that the uplands on both sides of the southern part of White Bay were glaciated. They also identified thick glacial deposits extending from Grand Lake to White Bay. Heyl (*op. cit.*) noted that glacial deposits had caused the damming of several ponds and a reversal of the drainage from Taylor Pond, which drains southward rather than northward to Sops Arm. He also suggested that White Bay is a major fault zone that was scoured deeper by glaciation.

On the Baie Verte Peninsula, till is thin and discontinuous (Grant, 1986), especially near the coast (Liverman and Scott, 1990). Thicker deposits are found in the southern part of the peninsula and in lowlands and valley bottoms (Liverman and Scott, 1990; Liverman, 1992). Lodgement, supraglacial melt-out and basal melt-out till are all present, but there is generally only one stratigraphic unit of till (Liverman and St. Croix, 1989; Liverman, 1992). Glaciofluvial deposits are rare and include braided outwash plains, kames, eskers (Liverman and Scott, 1990; Liverman, 1992) and deltas (Liverman and St. Croix, 1989). Thick glaciolacustrine deposits have been found in the Indian Brook area (Liverman and St. Croix, *op. cit.*) and glaciomarine sediments are found near the coast (Liverman and Scott, 1990).

Vanderveer and Taylor (1987) mapped in the Sops Arm area. They found till up to 10 m thick, as well as glaciomarine silt–clay grading upward to glaciofluvial sand and gravel.

Ice Flow

MacClintock and Twenhofel (1940) suggested that ice moved northward through White Bay. Heyl (1937) found north-northeastward flow south of Sops Arm and east-southeastward flow north of it. Vanderveer and Taylor (1987) found two ice-flow events in the same area: early eastward flow from the Long Range Mountains was followed by northeastward flow, which came from an ice centre southwest of Gull Pond.

Liverman (1992) identified four phases of ice flow on the Baie Verte Peninsula. Phase 1 was a southeastward flow from the Long Range Mountains at the last glacial maximum. This flow may have deflected northward-flowing ice from central Newfoundland to the east across the Baie Verte Peninsula. Ice flowed northwestward toward White Bay in Phase 2, from an ice divide extending along the central part of the Baie Verte Peninsula. It may then have been deflected northeastward along White Bay. In Phases 3 and 4, an isolated ice cap developed over the southern Baie Verte Peninsula, after ice retreated completely from the northern part of the peninsula. Ice flow from the Baie Verte ice cap was radial (northwest into White Bay) (Liverman, 1992). This ice cap stagnated sometime between 12 000 and 11 700 years BP (Liverman and Scott, 1990). Clast lithology studies show that transport distances were short on the Baie Verte Peninsula (Liverman and Scott, *op. cit.*), whereas they were longer on the west side of White Bay (Vanderveer and Taylor, 1987).

Sea Level

Liverman (1994) showed that the White Bay area had a type-B sea-level curve (following the terminology of Quinlan and Beaumont, 1981): rapid sea-level fall was followed by lesser sea-level rise caused by forebulge migration; sea level fell below present between 10 000 and 9500 years BP (Liverman, 1994).

Flint (1940) notes a raised beach at 32 m in Sops Arm. *Mya truncata* shells collected from a 30 m asl site in the Corner Brook Pond area, just south of Sop's Arm, yielded a ^{14}C date of 10 200 ± 100 years BP (GSC-4023, Blake, 1988). Grant (*in* Blake, 1988) interprets the site as having formed at the margin of a southward-retreating ice lobe. A date of 11 200 ± 100 years BP (GSC-4247) on *Mya truncata* shells at Jackson's Arm is interpreted as being from a major delta that gives a 41 m marine limit. Grant (*op. cit.*) suggests that both sites may represent a Younger Dryas stillstand.

METHODS

The area has an extensive network of woods roads, which, along with the three main roads, provide a reasonable amount of vehicle access (4x4 truck and ATV); the remainder of the area was reached by helicopter. Surficial sediments were mapped at numerous field sites and were recorded on air photos for later interpretation.

Ice-flow directions were determined by measuring striation, rôche moutonnée and crag-and-tail orientations. Nine striae were measured at each striation site and the median orientation was recorded. Direction was determined by stoss–lee relationships (micro- and macro-scale), crosscutting relationships and by preservation of older striae in the lee of younger ones. Clast provenance was also used to support ice-flow information.

Till samples were taken for geochemical analysis. The region was sampled at a spacing of about 1 sample per 4 km^2, except for the Long Range Mountains, which were sampled only near the roads, as till was scarce in that area (Figure 2). The sample target was C-horizon till. Most of the samples were taken from hand-dug pits at depths commonly in the 40 to 60 cm range and from road-cuts. Road-cut sample depths average 100 cm below the soil surface. Mudboils were sampled at shallower depths (average 25 cm) and in areas of thin till, samples were taken near the bedrock-till interface. A number of B- and BC-horizon samples were taken in areas where the soil was too thin for a C-horizon to be present or where till was too bouldery to penetrate to greater depths. Nevertheless, 81 percent of all samples are either from the BC- or C-horizon (45 percent are from the C-horizon). Samples were placed in paper bags and weigh about 1 kg each. Three hundred and fifty-five samples were taken and the silt–clay fraction will be analyzed for trace-element content. The Geological Survey laboratory will complete ICP and AAS analyses, and INAA analyses will be done externally.

At many sites, the various rock types present in the till were recorded; these were not quantified.

RESULTS

QUATERNARY GEOLOGY

The surficial geology of the area is dominated by thin till deposits. However, minor glaciofluvial and glaciomarine sediments are also present. Modern deposits include fluvial, marine, bog and rockfall sediments.

Till

Plate 1. *Large boulders on surface of till, Micmac Pond area. Helicopter for scale.*

In most areas, till distribution is thin and discontinuous; only a single stratigraphic unit of till was noted. Bedrock outcrop is common, especially at higher elevations and along the coastline. Till thickness increases in the southeastern part of the study area, where large hummocks are common. The clast lithology within the till is variable and reflects ice flow from a variety of source areas. The till is commonly massive, matrix-supported, and very poorly sorted; the matrix ranges from silt to very coarse sand, and is calcareous in Doucers and Jackson's valleys (Figure 1). Clast sizes range from granule to boulder and are generally subround to very angular. Very large clasts (boulders that average 100 cm in diameter) are quite common and can be up to 12 m in diameter. Boulders 2 to 4 m in width are not uncommon, especially in the southeastern portion of the study area, where the till is thickest. The largest boulders are generally found in the upper part of the till and on the surface (Plates 1 and 2); these boulders may represent the englacial load of the glacier and were thus the last debris to be released from the melting ice sheet.

Plate 2. *Large boulders are more common near the surface of till deposits, Wild Cove Pond area.*

Glaciofluvial Sediments

Glaciofluvial sediments are uncommon and are found only in a few valley bottoms; both ice-contact and ice-distal deposits are present. Two eskers were identified in the southern part of the map area, but most other glaciofluvial sediments are subaerially deposited outwash plains that generally terminate near the sea, at deltas that are elevated above current sea level. A few ice-contact deltas are also present.

Glaciofluvial braidplain or outwash sediments are poorly to moderately sorted, horizontally or irregularly bedded and either clast- or matrix-supported. Clast size ranges from granule gravel to boulder gravel and the deposits have a sand or granule gravel matrix. Also present are medium to very coarse sand and gravelly sand beds. Overall, the clasts are subround to angular but generally are subangular.

Deltaic sediments, found on both sides of White Bay, are thick (up to 20 m exposed) and contain topset and/or foreset beds that are generally well stratified. The deposits comprise moderately to well sorted beds of granule gravel to boulder gravel set in a matrix of sand, granule or pebble gravel. Well to very well sorted sand beds and laminations are commonly present (Plate 3) and may contain heavy mineral concentrations. Beds are 10 to 70 cm thick and clast- and matrix-supported beds are both common. Rounding ranges from subrounded to angular, however, subrounded and subangular clasts dominate the deposits. Dipping beds/laminations of fine gravel, granules and very fine to coarse sand commonly comprise the foreset beds, which become coarser toward the delta surface, eventually giving way to horizontal cobble and boulder gravel topset beds. Foreset beds have planar or tangential dips. Contacts are sharp and sigmoid and planar crossbeds are common, while scoured beds are less so (e.g., coarse sand scoured into fine sand). Ripple cross stratification was only seen at a delta northwest of Corner Brook Pond.

One delta or fan, perched 40 m above the Main River, contains very large subround boulders (up to 2 m diameter) in its uppermost crudely stratified beds. At Corner Brook Pond, a delta with distinct topset and foreset beds indicates water flow into the valley rather than out toward the sea (informally named the 'Backwards Delta', Plate 4). It is moderately to well sorted and has finer grained beds at lower stratigraphic levels as well as to the southwest. The topset and foreset beds consist of interbedded silty fine to coarse sand, sandy pebble gravel, sandy granule gravel, pebble gravel and cobble gravel. Clasts are subangular (range subround to very angular), indicating a short transport distance.

An ice-proximal delta at Jackson's Arm consists mostly of sandy pebble gravel, cobble gravel, fine and medium sand beds, and a few poorly sorted diamicton beds; some of the sand beds contain recumbent folds.

An esker in the southeastern part of the study area has irregular horizontal beds of matrix-supported, poorly to moderately sorted, imbricate granule to boulder gravel set in a fine- to medium-sand matrix. Pebble and cobble gravel are most common as are subangular clasts. However, there are also beds of fine and medium sand, and clast roundness ranges from round to angular. A wide variety of rock types are present. The deposits form a discontinuous esker complex less than 10 m high and aeolian blowouts are common on the surface. Unlike the surrounding till, there are no large boulders on the esker surface.

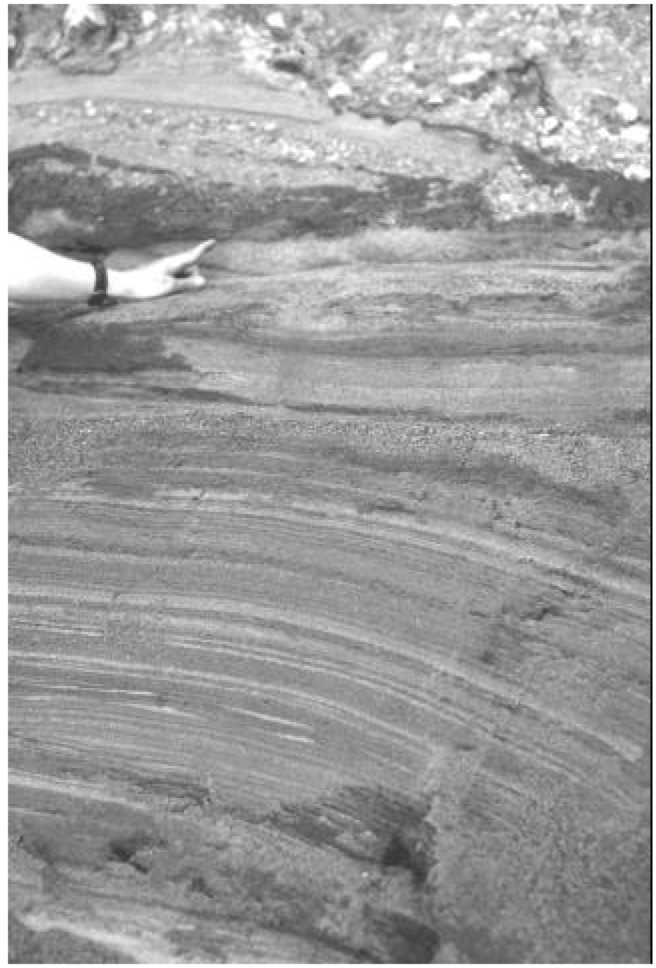

Plate 3. *Very fine sand/fine sand laminations underlying coarser beds, Sops Arm 60 m delta. Person is pointing to contact between the two.*

Plate 4. *'Backwards Delta'. Foreset beds dip up valley (to the southwest) rather than towards the sea.*

Glaciomarine Sediments

There are two types of marine sediments in the White Bay area; these are glaciomarine diamicton and raised beach deposits. The glaciomarine diamictons are found below marine limit, commonly close to sea level and often seaward of glaciomarine deltas. They have a finer matrix than the till typical of the region (clay to fine sand) and clast content is low (about 30 percent). As a result, glaciomarine diamictons are fully matrix-supported. They are also massive or crudely stratified, poorly sorted, and contain granule- to boulder-sized clasts, however, granules and pebbles dominate. Clasts are generally subangular, but range from subround to very angular and represent a variety of rock types.

The raised beach deposits are also matrix-supported, but they are much coarser and are better sorted than the diamicton (moderately to well sorted). The deposits form low (about 3 m high) terraces up to 10 m asl. Sediments are crudely stratified or have well-defined horizontal bedding and common clast sizes are pebbles and cobbles, but granules and boulders are also present. The matrix is medium to very coarse sand; medium to coarse sand beds may also be present. Clasts are subangular to round, but mostly subround, and may be aligned along bedding planes. The upper 70 cm of the deposit can be strongly cemented.

MODERN SEDIMENTS

Mass-Wasting Deposits

Mass wasting is a significant process in the hilly White Bay area. Rockfalls are the most common type of mass wasting, but debris flows and other processes are also active. The scars of both recent and much older rockfalls are evident along the shores of White Bay (Plate 5) and in some areas homes have been built on the base of fan-shaped bouldery rockfall deposits (e.g., the Coney Arm area). The communities of The Beaches and Galeville in southern White Bay are built on rocky beaches originally derived from rockfall deposits. These deposits form narrow, cone-shaped fans that have built out a short distance into White Bay where wave action has smoothed them into level beaches at and near sea level. The presence of old landslide scars above these communities would suggest that these locations are not attractive construction sites.

Fluvial Deposits

Alluvial deposits include horizontally bedded floodplain and fan sediments. Both consist of moderately to well-sorted, matrix- or clast-supported pebble to cobble gravel; some boulder gravel beds are present and a sandy matrix is most common.

Plate 5. *Rockfalls on cliffs (arrowed), Great Coney Arm, looking southeast.*

Floodplain deposits are typically thin. Clasts are rounded to very angular (average subangular), which may be due to colluvial input from steep valley walls.

Fan sediments consist of alternating beds of matrix-supported and weakly imbricate clast-supported beds. Beds are between 10 and 30 cm thick, have irregular contacts and include a few beds of crossbedded or massive sand. Clasts are commonly subangular to very angular, indicating very short transport distances.

Marine and Organic Deposits

Modern beach deposits are located only in sheltered coves and at river mouths and generally consist entirely of coarse, rounded cobble gravel. Most are pocket beaches, but one barachois beach forms a barricade across the end of Saltwater Pond. At Hampden and Sops Arm, muddy tidal flats have developed at the river mouths.

Bogs are abundant in the region, but are generally small; string bogs are present, but rare.

GLACIAL HISTORY

Evidence of the last (late Wisconsinan) glaciation was found in the White Bay area. Ice flowed across the entire study area, changing its flow directions as glaciation and deglaciation progressed. Till was deposited beneath the ice, and was reworked by meltwater in some areas when the ice retreated. In the southern part of the study area, west of Upper Indian and Micmac ponds, eskers are found, which suggests that this is the only part of the study area where ice stagnated during deglaciation; elsewhere, ice flowed actively during glacial retreat. Marine sediments and glaciomarine features such as deltas indicate that there were a number of different deglacial sea-level stands in the region. Ice flow and the sea-level record are discussed in more detail below.

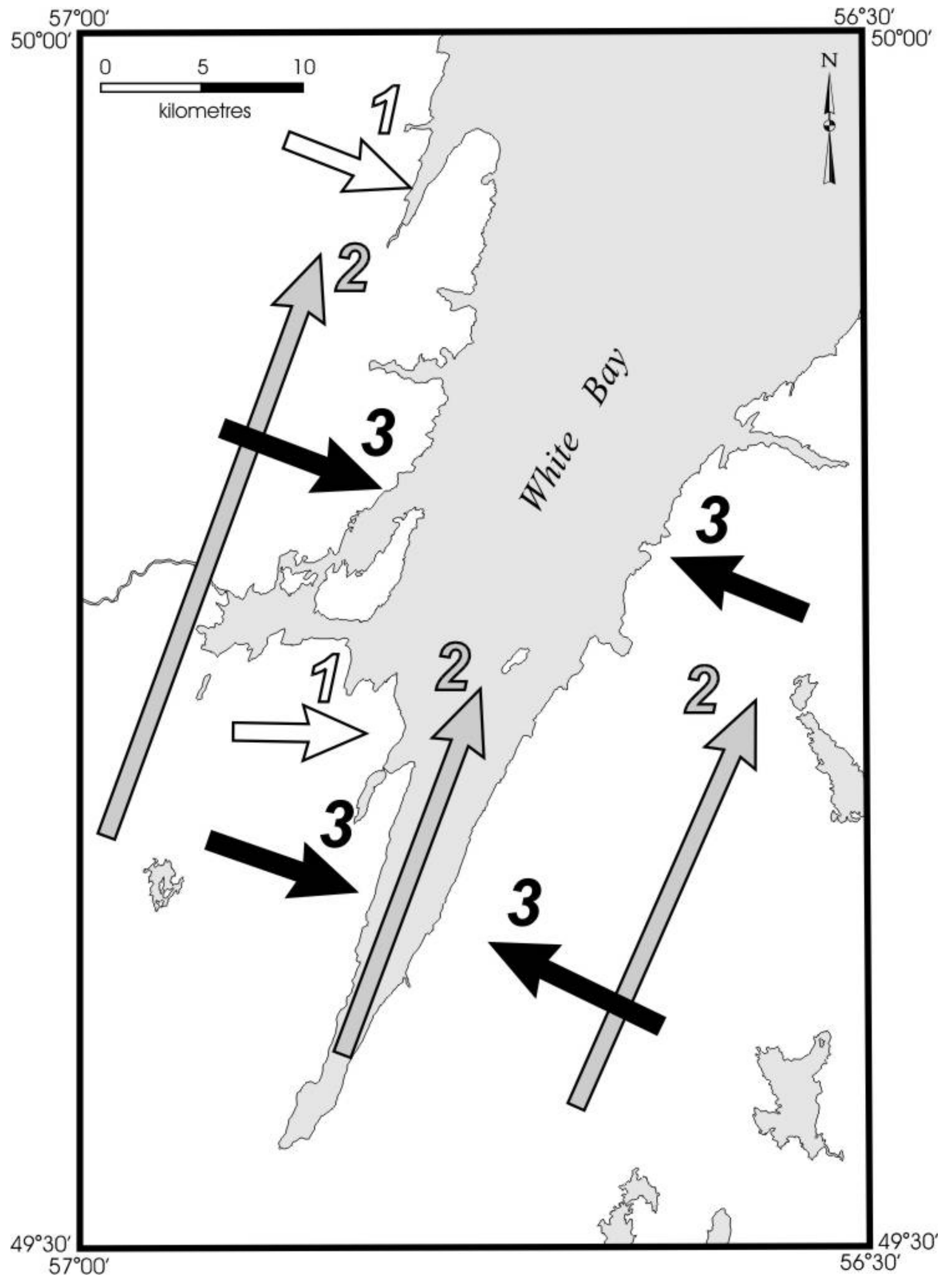

Figure 3. *Former ice-flow directions in the White Bay area, as determined by striation evidence. 1: earliest identified flow direction, 2: later flow from a major ice source to the south, 3: last ice-flow directions, from smaller ice caps centred on Baie Verte and Long Range peninsulas.*

Ice Flow

Ice flow is determined from various ice-flow indicators, including striations and the provenance of clasts within till. Striations in the region occur on fresh, unweathered surfaces, which suggest that they are all related to the most recent glaciation; they are best preserved in fine-grained rocks. In the White Bay region, bedrock bedding or schistosity is commonly vertical, which means that striations are not present in many areas.

The ice-flow history of the surveyed area is complex (Figure 3). The earliest flow (Flow 1) was eastward or southeastward out of the Long Range Mountains but it did not extend across White Bay. If ice had crossed White Bay, then distinctive clasts from the western side of the bay (e.g., carbonates from the Coney Arm Group) should be found in tills east of the bay. However, none were found. All of the erratics and till clasts on the east side of the bay can be ascribed to local bedrock sources. Flow 1 was identified from striations that are older than Flow 2, but, only five such sites were found. As a result, Flow 1 is poorly constrained. A similar early ice-flow event was identified by Liverman (1992) and by Vanderveer and Taylor (1987), however.

The next flow event in the White Bay area was northward and north-northeastward along White Bay (Flow 2, Figure 3). Flow was from a major ice centre south of the study area, so Flow 2 probably represents ice flow at the glacial maximum. Striations marking this flow event are common but much less so than those representing later ice flow.

The last ice-flow phase is shown as Flow 3 (Figure 3). There are 14 striation sites from which the relative age of this event was determined. A gradual drawdown of ice into White Bay (indicated by younger striations that are more strongly oriented toward the bay than older ones), along with overall ice retreat, changed the locations of the major ice caps: they shifted from south of the study area to new locations on the Baie Verte Peninsula and over the Long Range Mountains. This caused ice flow to become northwestward or southeastward into the bay from the surrounding uplands. The change in ice-cap locations was gradual, and ice-flow directions slowly changed as a consequence. This is indicated at several sites that exhibit three separate striation sets, each successive set becoming more strongly oriented toward White Bay.

The evidence of a north-northeastward flow (Flow 2) is in agreement with the findings of previous workers (*see* MacClintock and Twenhofel, 1940; Heyl, 1937; and Vanderveer and Taylor, 1987). Vanderveer and Taylor (*op. cit.*) also identified Flow 1. Flow 2 may be comparable to Liverman's (1992) Phase 2 flow and Flow 3 is the same as his Phase 3 event.

General ice-flow directions as indicated by clast provenance are shown in Figure 4. Bedrock belts are oriented northeast–southwest, and vectors are shown approximately perpendicular to the belts, although actual ice flow may have been at smaller angles to them. The clast lithology ice-flow vectors mainly reflect the last phase of ice flow. They show that Flow 3 was the most dominant mover of debris. The earlier northward flow is rarely apparent, but this may be an artifact of drawing the vectors perpendicular to the belts, thus eliminating most clast provenance evidence for northward flow.

Clast provenance also shows that transport distances were variable (Figure 4), from approximately 1 to 20 km for some vectors that extend off the map area in the east.

Sea Level

In locations bordering White Bay, several geomorphic features record a series of former higher sea-level stands (Figure 5). The highest stand (the regional marine limit) is 70 m above present sea level, which is the elevation of topset beds in a delta near Western Arm. Another delta near the town of Sop's Arm is graded to 60 m asl. Two deltas at Sop's Arm and another at Jackson's Arm formed at the next sea-level stand, which was 40 m asl. This stand occurred at 11 200 ± 100 years BP (marine shells in an ice-proximal delta at Jackson's Arm; Blake, 1988). Sea-level stands of 30 m are indicated by deltas and by marine terraces on both sides of White Bay. This stand is dated at 10 200 ± 100 years BP (based on marine shells southwest of Corner Brook Pond; Blake, 1988) on the west side of the bog. Six different features represent a 20 m stand, mainly terraces cut into glaciomarine sediments. Several raised beach deposits in the Coney Arm and Western Arm/Purbeck's Cove areas are evidence of 10 m stands on both sides of the bay.

The deltaic deposits, in particular, provide much information about the area's sea-level history. A number of raised deltas at different levels at Sop's Arm indicate that meltwater flow was continuous throughout deglaciation and sea-level fall. The paleoflow directions of these deltas are southeast, south and southwest (Figure 5), which is unexpected if the Main River valley was the main source of meltwater. In addition, the 'Backwards Delta' at Corner Brook Pond is problematic. The delta's foreset bed orientation indicates that water flowed upvalley. This is an unusual situation, as glaciers generally retreat upvalley, and their meltwaters flow downvalley toward the sea. The result is a delta with foreset beds that dip towards the ocean. The 'Backwards Delta', however, contains foreset beds that dip away from the ocean.

If there was ice in Sops Arm when the 'Backwards Delta' formed, it would deflect glacial meltwater along Corner Brook Valley, which would account for an upvalley flow direction. The presence of glaciomarine terraces graded to 20 m and a delta graded to 30 m on the opposite side of White Bay indicates that White Bay at least was ice-free during these two sea-level stands. Due to isostatic tilting, these two stands may relate to the 30 m and 40 m stands on the west side of the bay, or perhaps the 40 m and 60 m stands. Either way, the indication is that the entire bay was ice-free during the 40 m stand on the west side of the bay, and likely during the 20 m stand when the Backwards Delta formed. An ice readvance would have to have occurred after the 40 m stand for ice in Sops Arm to be blocking the outlet of the Corner Brook Pond valley. Another possible model is that there was no ice in Sops Arm, but there was another meltwater river issuing from Jackson's Valley. The Main River meltwater river would have flowed to the southeast, as the Main River does today. The Jackson's Valley meltwater river would have flowed to the southwest. The combined

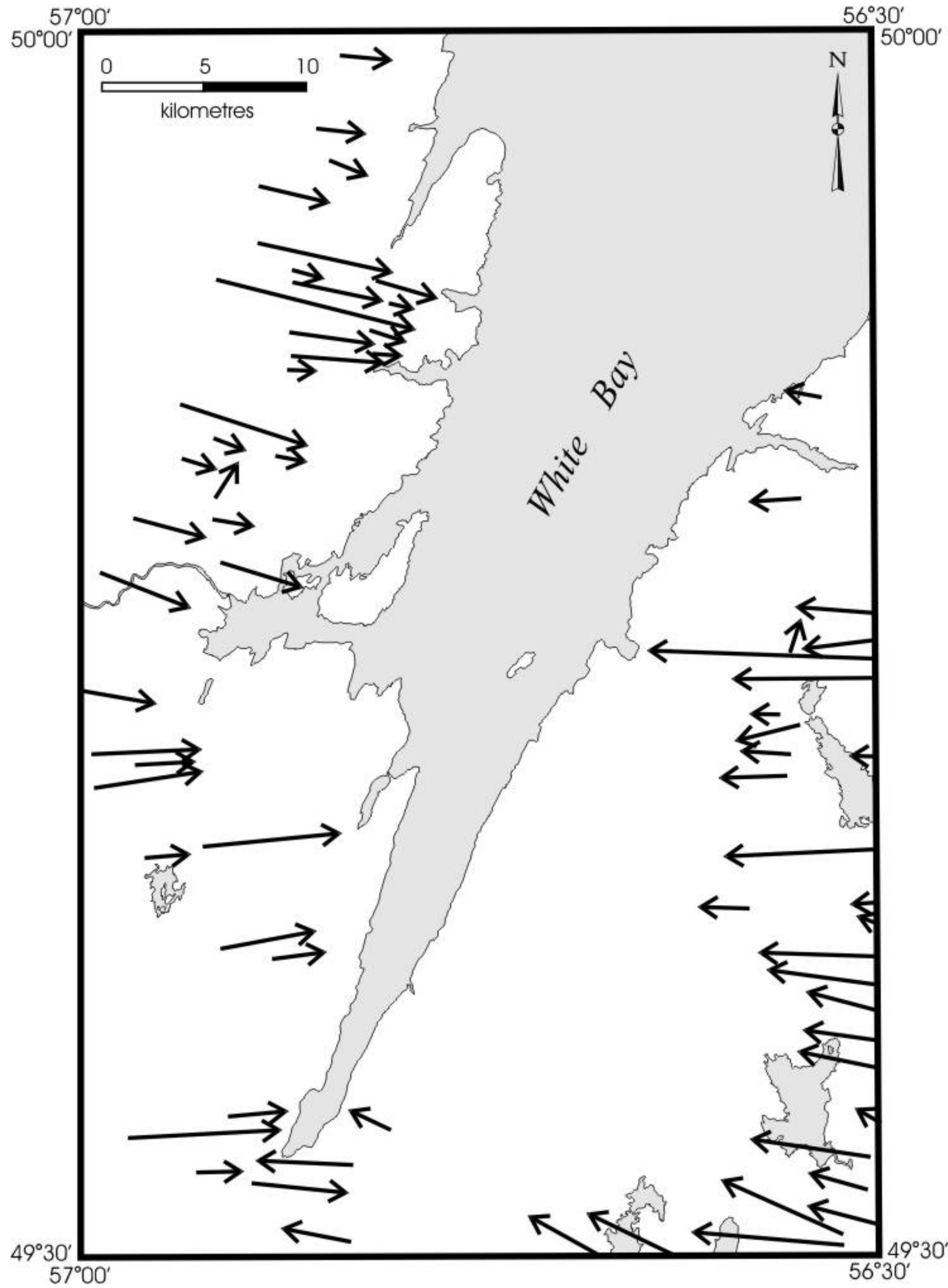

Figure 4. *Former ice-flow directions in the White Bay area, as determined by till clast lithologies. Longer arrows indicate longer (approximate) transport distances. Clast lithologies were not recorded in areas lacking arrows.*

vector flow would have been roughly south, and a very large delta would likely develop. If that is the case, then a major delta was forming in the Sop's Arm area throughout deglaciation and continued to prograde and incise itself as sea level fell. It began forming prior to 11 200 ± 100 years BP, the time of the 40 m sea-level stand. The delta was building out toward the Corner Brook Pond area at 10 200 years BP, when sea level was 30 m above present, based on a ^{14}C date on marine shells (Blake, 1988). Some time after this, sea level fell to 20 m above present, and the delta had built at least as far south as Corner Brook Valley. The southern part of the delta built out toward what is now Corner Brook Pond, effectively damming this area and creating a glacial lake. The modern pond is a remnant of this lake. A lack of features other than beaches related to the 10 m stand may mean that glaciofluvial deposition had ceased by this time. In Holocene time, much of the Sop's Arm delta must have been eroded away.

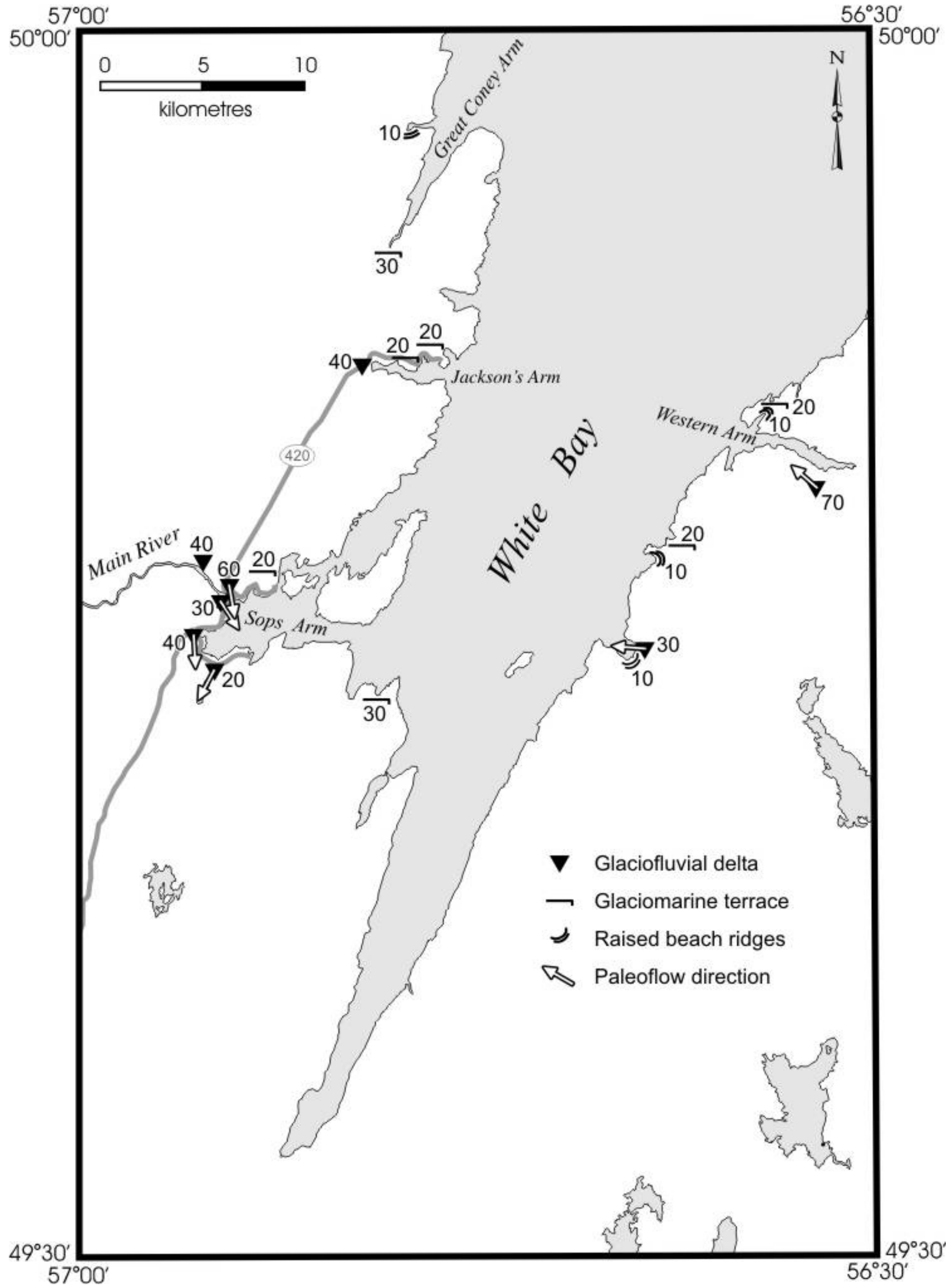

Figure 5. *Landforms marking former sea levels. Number beside feature is elevation above sea level in metres, rounded to the nearest 5 m. Highway 420 is included for reference.*

Two other major deltas are ice-contact features that form major dams. The Jackson's Arm delta dams Jackson's Pond to the west so that the pond drains northeastward to Great Coney Arm (Plate 6). Purbeck's Fiord contains two unnamed lakes that are dammed by the Purbeck's Cove delta. Drainage has cut through the delta, the only possible path to the ocean from this steep-sided valley.

The sea-level history for the area includes sea-level fall, followed by sea-level rise (Liverman, 1994; Quinlan and Beaumont, 1981). No evidence of sea-level rise was documented in this study. Offshore work (e.g., multibeam bathymetry) is needed to determine the extent of late sea-level rise in the White Bay area.

Plate 6. *Jackson's Arm ice-contact delta. Note Jackson's Pond behind it, which has been dammed by the delta. Development has occurred mainly on the delta surface, rather than on the rocky hillsides.*

IMPLICATIONS FOR MINERAL EXPLORATION

There are a number of facts about the region's Quaternary history and geology that would be useful to explorationists planning to use till geochemistry in the area.

1. The area has a complex ice-flow history.
2. The last flow event (ice flow directed toward White Bay from surrounding uplands) moved most of the sediment.
3. Transport distances are variable, from 1 to 20 km.
4. There is only one till unit.
5. Fan or ribbon-shaped dispersal trains are expected.
6. Sampling in marine, fluvial and glaciofluvial settings should be avoided. These include valley bottoms and areas below the 70 m asl marine limit.

SUMMARY AND CONCLUSIONS

Evidence of the last glaciation was found in the White Bay area. During ice build up, ice flowed toward White Bay from the Long Range Mountains, but did not cross the bay. At the height of the last glaciation, ice flowed north-northeastward along White Bay. Later, ice drawdown in the bay and thinning ice resulted in ice caps developing on either side of the bay. As a result, ice flow gradually shifted until ice was flowing into the bay from either side at roughly right angles to it.

Most till deposition occurred in the southern part of the study area, where it is thicker and contains numerous large boulders; ice probably stagnated in this area. Elsewhere, till is thin and discontinuous. Exposed bedrock is common at high elevations and along the coast. Glaciofluvial and glaciomarine sediments are uncommon, occurring only at lower elevations. Several deltas, marine terraces and raised beaches indicate former sea-level stands at 70, 60, 40, 30, 20 and 10 m asl. The 40 m stand happened at 11 200 years BP and the 30 m stand 10 200 years BP. Evidence for sea-level rise was not identified in this study.

Modern deposits include fluvial, beach and tidal flat sediments, mass-wasting and bog deposits. Rockfalls are common along White Bay's steep walls.

Till samples taken during this study are currently being analyzed for geochemistry. This data will be released later in 2003.

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