Current Research (2000) Newfoundland Department of Mines and Energy
Geological Survey, Report 2000-1, pages 33-47

DEGLACIAL HISTORY OF NORTHERN ST. GEORGE'S BAY, WESTERN NEWFOUNDLAND

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ABSTRACT

Quaternary mapping in the Stephenville area has identified a sequence of late-glacial and Holocene events, which are based upon surficial and paleo ice-flow indicator mapping, and the documenting of features and sediment related to sea-level change. The entire area was glaciated during the late Wisconsinan. The earliest ice-flow direction identified was from the north. This flow was identified in the Harrys River valley and over the entire Port au Port Peninsula. Later flows were generally coastward from ice centres in The Topsails and the southern Long Range Mountains. The latter flow crossed the northern St. George's Bay impinging on the coastal platform west of Stephenville, and extending as far west as Abrahams Cove on the Port au Port Peninsula, but did not cover the north coast of the Peninsula.

Deglaciation commenced about 13 500 BP. Marine limit was up to 65 m asl on the Port au Port Peninsula, decreasing eastward. This suggests eastward-retreating ice in the Stephenville area, and this retreat is suggested by the pattern of eskers observed in the area. Glaciers were calving into a raised postglacial sea, as indicated by sediment sequences exposed in coastal cliffs west of Stephenville, many of which are interpreted to have been deposited in an ice-proximal glaciomarine environment. No evidence was found to support a regional, late-glacial re-advance of ice in the area.

Holocene sea levels fell until a lowstand at -25 m at about 9500 BP. At this time, a series of shallow ponds occupied modern East Bay and West Bay, with the intervening lowland area being a wetland. The remnants of this wetland are found on the Shoal Point spit. The continuous sea-level rise from the lowstand to the present day has resulted in coastal erosion of unconsolidated cliffs.

INTRODUCTION

The focus of Quaternary geological mapping undertaken by the Survey is the systematic identification, delineation and interpretation of unconsolidated deposits that overlie the bedrock. It includes mapping of ice-flow indicators and surficial sediments, coastal change and sea-level history, modern processes, and their environmental impact on the Province. The selection of the project area was determined by its impact at the community or development level, and in consultation with the stakeholders. Thus mapping is conducted, when necessary, in areas, either adjacent to communities that may use the data in land-use planning, or in areas of mineral potential, or both.

Mapping of the Quaternary sediments and features in northern St. George's Bay is a two-phase project, the first being detailed stratigraphy of sediments exposed in coastal cliffs west of Stephenville (Batterson and Janes, 1997). The second phase is surficial mapping that provides continuity between recent mapping to the south (Liverman *et al.*, 1999), and to the north (Batterson and McGrath, 1993; Batterson and Vatcher, 1992). It also provides stratigraphic data for the Stephenville municipal area that could be useful in their ongoing groundwater management issues. Mapping also identifies the depositional environment of sediments suitable for granular aggregate extraction.

LOCATION AND ACCESS

Fieldwork was conducted over a 3500 km^2 area of western Newfoundland between 48°15' and 48°45 N and 58°00 and 58°17 W (Figure 1). It included all, or parts of five 1:50 000 NTS map areas (12B/6, 8, 9, 10, 11), extending

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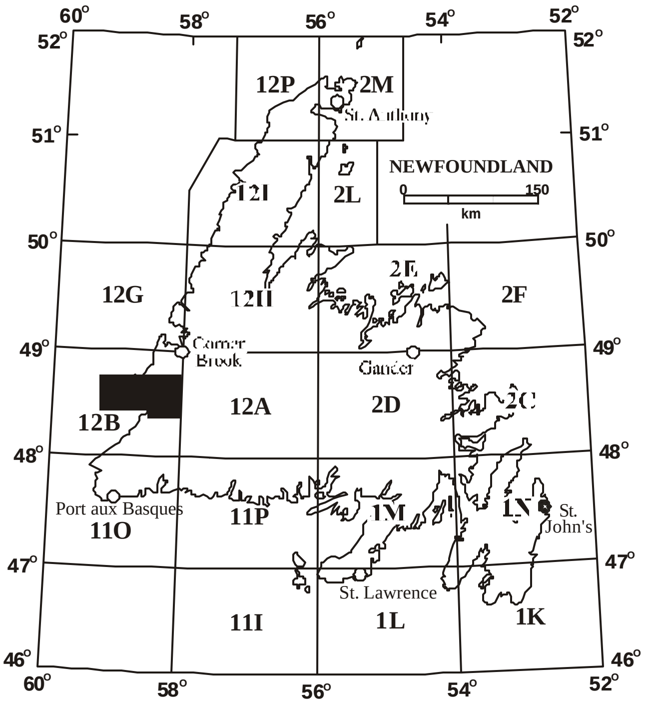


Figure 1. *Location of study area.*

west to east from the Port au Port Peninsula to Grand Lake, and north to south from the southern extent of the Lewis Hills to the Flat Bay Brook valley. Access to much of the area is via a network of paved and gravel roads using a combination of a four-wheel drive vehicle and ATVs. Areas of limited access (mostly the foothills of the Long Range Mountains), were reached by helicopter. Within the study area, the largest community is Stephenville (population 7500), which acts as the regional centre; it also has a harbour at Port Harmon. Smaller communities exist along the coast, both east and west of Stephenville. Within the field area, these include Stephenville Crossing, Barachois Brook and St. George's, east of Stephenville, and Kippens, Port au Port East, Fox Island River and the Port au Port Peninsula communities of Piccadilly, Lourdes, Mainland, and Cape St. George located west of Stephenville (Figure 2).

PHYSIOGRAPHY AND BEDROCK GEOLOGY

The study area includes several physiographic regions. The Port au Port Peninsula is mainly bedrock dominated. Sediment is confined to a narrow (less than 1 km) coastal strip, along the south coast, and wider (1 to 3 km) on much of the west and north shores. Two large promontories extend into Port au Port Bay on the north shore; The Bar northeast of Lourdes, and the Shoal Point peninsula north of Boswarlos. Both are bedrock cored, The Bar by Ordovician limestone and the Shoal Point peninsula by red and green shale of the Humber Arm Allochthon. The Port au Port Peninsula is connected to the mainland by two, 400-m-wide gravelly tombolos, separated by the brackish Gravels Pond (Plate 1). North–south-trending bedrock uplands, separated or dissected by valleys, form much of the study area east of the Port au Port Peninsula. In the west, a series of fault-controlled ridges including Table Mountain (380 m), Whale Back Ridge (350 m), and Indian Head Range (564 m) are separated by southward-flowing streams including Romaines Brook, Gadons Brook and Cold Brook (Figure 2). The westward-flowing Fox Island River forms the northern boundary of the area, north of which are the Lewis Hills (maximum 814 m); the longest river in the area is Harrys River, which flows southward out of Georges Lake, reaching the sea at Stephenville Crossing. The western flank of the Long Range Mountains forms the eastern edge of the study area. The mountains are dissected by a series of wide (up to 1.5 km), largely flat-bottomed valleys containing westward-flowing streams, including Bottom Brook, Southwest Brook, Little Barachois Brook, Flat Bay Brook and Fischells Brook (Figure 2).

Regressive cliffs of unconsolidated sediment dominate the northern and northeastern St. George's Bay coast. A narrow coastal plain west of Romaines Brook has an almost flat surface dipping partly westward having a slope of about 1:210. Numerous active gullies and amphitheatrical depressions resulting from cliff failure, punctuate the cliffs. Cliff recession in this area is up to 1.25 m per year as estimated by digital photogrammetry (Forbes *et al.*, 1995) but is likely episodic. In 1994, a cliff failure about 1 km west of Romaines Brook, resulted in about 60 m of headwall recession of a gully.

Flat Island forms a prominent feature off the St. George's Bay coast. Although it only slightly impinges on the study area, Flat Island has produced a shallow bay to the east (St. George's Harbour) and has significantly reduced wave energy to the sand-dominated coastal cliffs between St. George's and Barachois Brook. This has reduced the potential coastal recession in this area to less than 0.25 m per year (Forbes *et al.*, 1995).

The physiography of the region is mainly controlled by the bedrock geology. Precambrian granite and granitic gneiss that form the Long Range Mountains extend along the eastern margin of the study area. Similar rocks are found in the Indian Head Range between Stephenville and Stephenville Crossing. Carbonate platformal rocks of Mid Cambrian to Middle Ordovician age underlie much of the remainder of study area. These include limestone and dolostone (St. George Group, Port au Port Group, Reluctant Head Group) and shale, greywacke and conglomerates (Curling Group, Old Man's Pond Group). Bedrock is rarely exposed on the coastal plain but where found, consists of

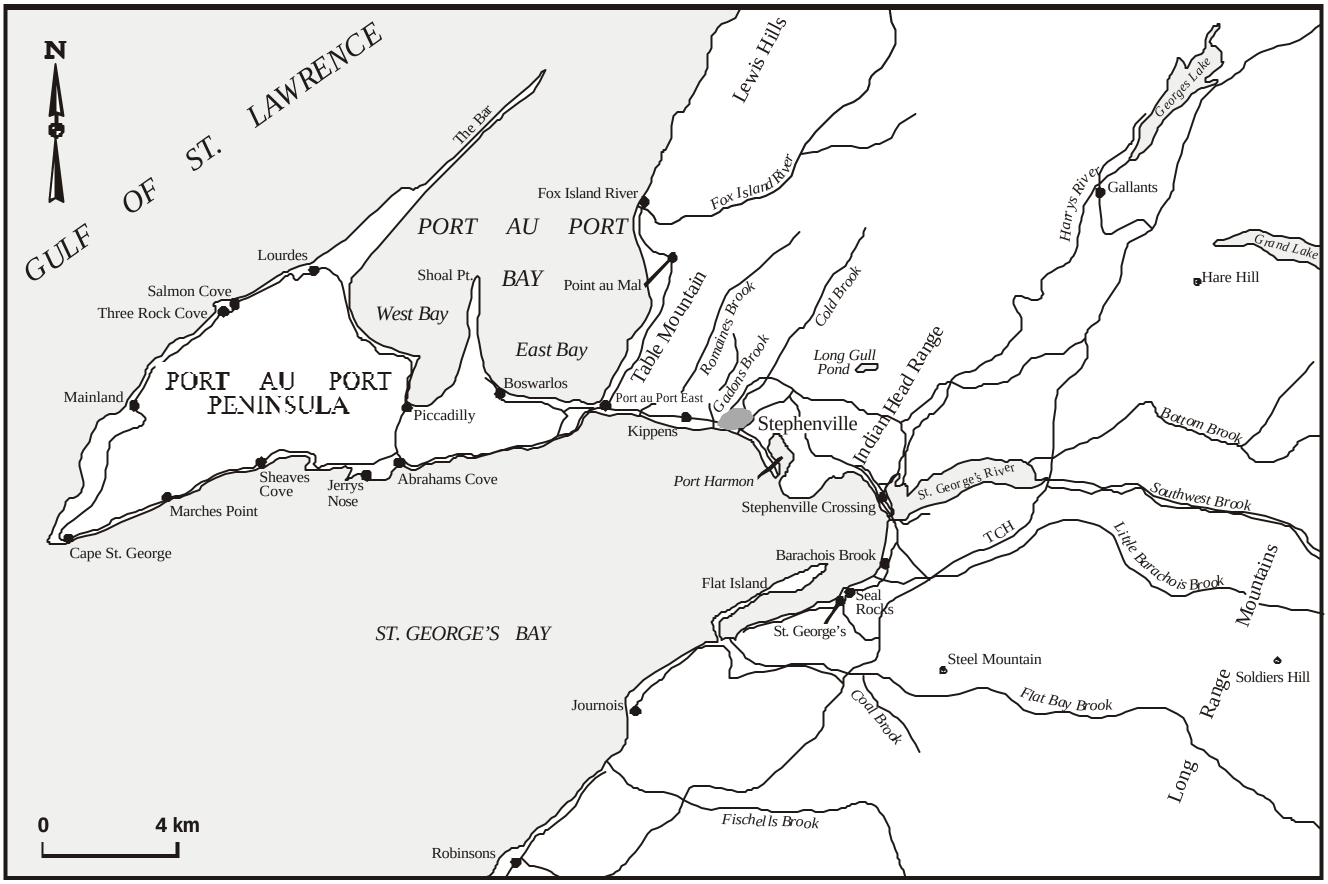


Figure 2. *Map showing place names and features mentioned in text.*

Plate 1. *Raised marine delta at Port au Port East. The delta surface is 45 m asl, and dips toward the foreground. The delta was likely ice contact, remnants of which are found on the east shore of the Port au Port Peninsula. Parts of the two tombolos that connect the Peninsula to the main part of Newfoundland are seen in the middle of the photograph. The tombolos are separated by Gravels Pond.*

Carboniferous fossil plant-bearing sandstone of the Barachois or Codroy groups. Gypsum is exposed at Romaines, and strikes eastward for several hundred metres. The upland along the outer coast that forms the Lewis Hills is part of the Humber Arm Allochthon. These are ophiolitic rocks (mostly harzburgite, peridotite, gabbro and pillow basalt), commonly with a distinctive brown-weathering surface, that were thrust over the carbonate platform about 450 million years ago.

This part of Newfoundland hosted some of the earliest mining activity on the Island, notably asbestos from the Lewis Hills in the late 19th century. Industrial minerals are significant exploration targets in the study area. Atlantic Minerals Limited, operator of the Lower Cove quarry on the Port au Port Peninsula, produces high-purity limestone and dolomite. High-calcium limestone is supplied to the iron ore companies in Labrador and Quebec for making fluxed iron ore pellets and dolomite is exported for use in the steel industry. Galen Gypsum Mines Limited mines gypsum at Coal Brook and supplies about 10 000 tonnes of crushed gypsum annually to North Star Cement in Corner Brook. Granular aggregates are mined at several locations across the area mostly as part of short-term projects (e.g., road upgrades). Recently, sand has become an important commodity for export to the United States. Oil exploration has been a significant contributor to the exploration activity. The Hunt/PanCanadian Port au Port No. 1 well, north of Cape St. George was spudded in September 1994. Follow-up drilling by Hunt and PanCanadian at Long Point and in St. George's Bay during 1996 was disappointing; both wells were plugged and abandoned. Similarly, PanCanadian abandoned an exploration well at Shoal Point in the summer of 1999.

PREVIOUS WORK

Coastal exposures around St. George's Bay were examined by MacClintock and Twenhofel (1940), who distinguished a three-fold stratigraphy for the area consisting of a basal till (St. George's River Drift), a delta complex (St. George's Bay Delta), and surface ice-contact sediments (Robinsons Head Drift). Brookes (1969, 1970, 1974, 1977) expanded on this stratigraphy and provided further details on the areal extent, character and relation to postglacial sea-level changes. The St. George's River Drift overlies bedrock and outcrops in many places around St. George's Bay. It is described as a compact greyish pink to grey till, and generally is overlain by delta bottomsets and foresets of the St. George's Bay delta that was deposited in the sea up to about 45 m asl. The area between Stephenville and just west of Romaines Brook was an exception, where there was a delay in raised marine sedimentation until the sea level had fallen to near 30 m. This delay was the result of a re-advance or stillstand of the ice front termed the Robinsons Head re-advance. Brookes (1970) mapped this re-advance as extending from near Romaines Brook in the north of St. George's Bay, to near Highlands in southern St. George's Bay. The re-advance took the form of several lobes of ice that advanced from the Long Range Mountains and Table Mountain. The Robinsons Head re-advance was dated by Brookes (1977) at about 12 600 BP, based on a single radiocarbon date from marine shells found within a sand bed sandwiched between kame gravels at Kippens. However, a section at Romaines, located at the western end of the Robinsons Head moraine, contains organic material, the dating of which has provided a conflicting view of the local glacial chronology (Grant, 1987; Proudfoot *et al,* 1988; Liverman and Batterson, 1995). Whale bone and marine shells found in sediments overlying those interpreted as Robinsons Head Drift are dated at around 13 000 BP. Liverman and Bell (1996) described coastal cliff exposures in southern St. George's Bay, and suggested that sediment sequences could be explained by sedimentation along the grounding line of a tidewater glacier. Batterson and Janes (1997) found similar sediment sequences, without the ridge/non-ridge topography observed to the south. The extent, timing and existence of the Robinsons Head event in western Newfoundland remains the subject of debate.

Taylor (1994) recorded a complex ice-flow history in the Stephenville area through striation mapping. An early southwestward (220°) flow is observed on the Port au Port Peninsula, followed by a westward flow from The Topsails ice centre that changed to northwestward during the late stages.

Research in the offshore and nearshore St. George's Bay by the Geological Survey of Canada (Forbes *et al.,* 1993; Shaw and Forbes, 1995; Shaw *et al.,* 1997; Shaw and Courtney, 1997) described late glacial and Holocene events. In particular, a sea-level lowstand at about –25 m was identified based on submerged deltas, and dated at about 9.5 ± 1 ka. This lowstand would have produced two shallow, brackish (?) ponds in modern Port au Port Bay connected to the ocean by tidal currents.

ICE-FLOW HISTORY

Ice-flow indicators, mostly striations, were identified at 24 sites across the study area. These data supplemented the 153 sites contained within the Newfoundland Striation Database (Taylor *et al.,* 1994). Elongate diamicton ridges are common around St. George's River and provide additional ice-flow data. Well-oriented clast fabrics (S1>0.6) also are interpreted to represent paleo ice flow (*cf.* Batterson, 1998).

In the study area, three distinctive ice-flows are indicated (Figure 3). The earliest is a southward flow and can be traced across the entire Port au Port Peninsula and also between Stephenville and the Harrys River valley. Rare southward-oriented striations are also found on the Lewis Hills and on Table Mountain where the striations are fresh and unweathered. The next is a west to southwestward ice flow recorded in the area north of Barachois Brook and west to Fox Island River. These striations commonly crosscut those of the earliest southward ice flow. The third and most recent flow was a westward to west-northwestward flow recorded on the south coast of the Port au Port Peninsula, and across the Stephenville lowlands and Harrys River valley. A westward ice flow is the only flow recorded in the Long Range Mountains between Grand Lake and Fischells River.

The source of the southward ice flow is uncertain. Batterson (1998) reported early southward striations in the Humber River valley and several clast fabrics having a preferred southward orientation in the Humber Arm near Corner Brook. This flow overtopped the highlands near Corner Brook. Southward striations are found at the North Star quarry site near Corner Brook. Other indicators of southward flow have been reported along the Great Northern Peninsula (Mihychuk, 1986; Grant, 1994), south of Corner Brook (Taylor, 1994), and in southern St. George's Bay (Liverman *et al.,* 1999). In each case, indicators represented the earliest recorded ice flow with no evidence for an ice-

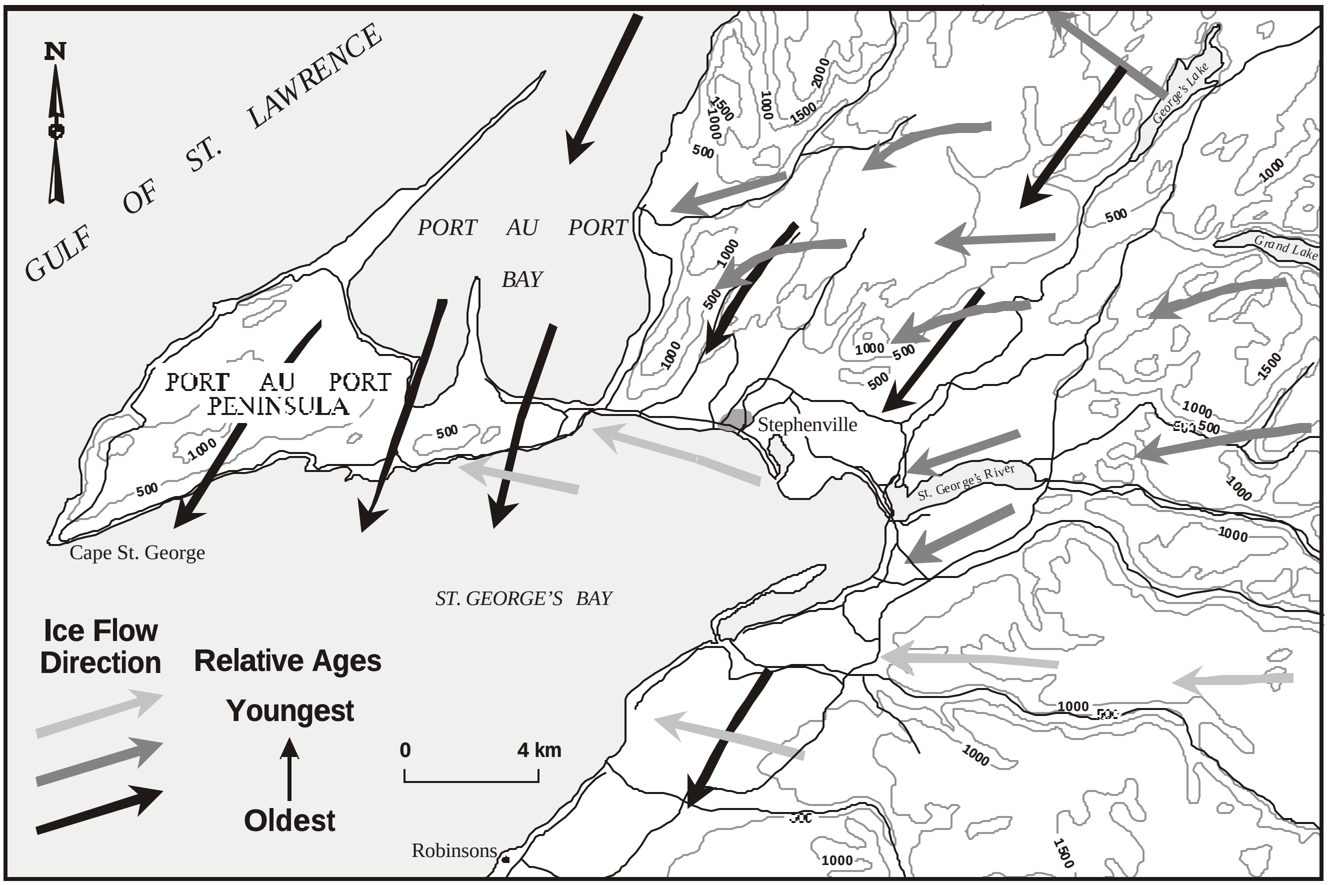


Figure 3. *Map showing regional trends of paleo ice flow.*

free period between them and those showing the most recent flow. Batterson (1998) speculated that either Newfoundland ice was directed southward by ice occupying the Gulf of St. Lawrence, or that the southward flow represents Laurentide ice that impinged on the coastal fringe of Newfoundland. Whether or not ice crossed the coastal highlands is difficult to determine due to the lack of ice-flow indicators. Ice crossed parts of the Lewis Hills as evidenced by the presence of peridotite clasts in diamictons at Abrahams Cove on the Port au Port Peninsula, although peridotite bedrock is found adjacent to the modern coast in the Deadman's Brook area. The origin of the southward flow remains unclear.

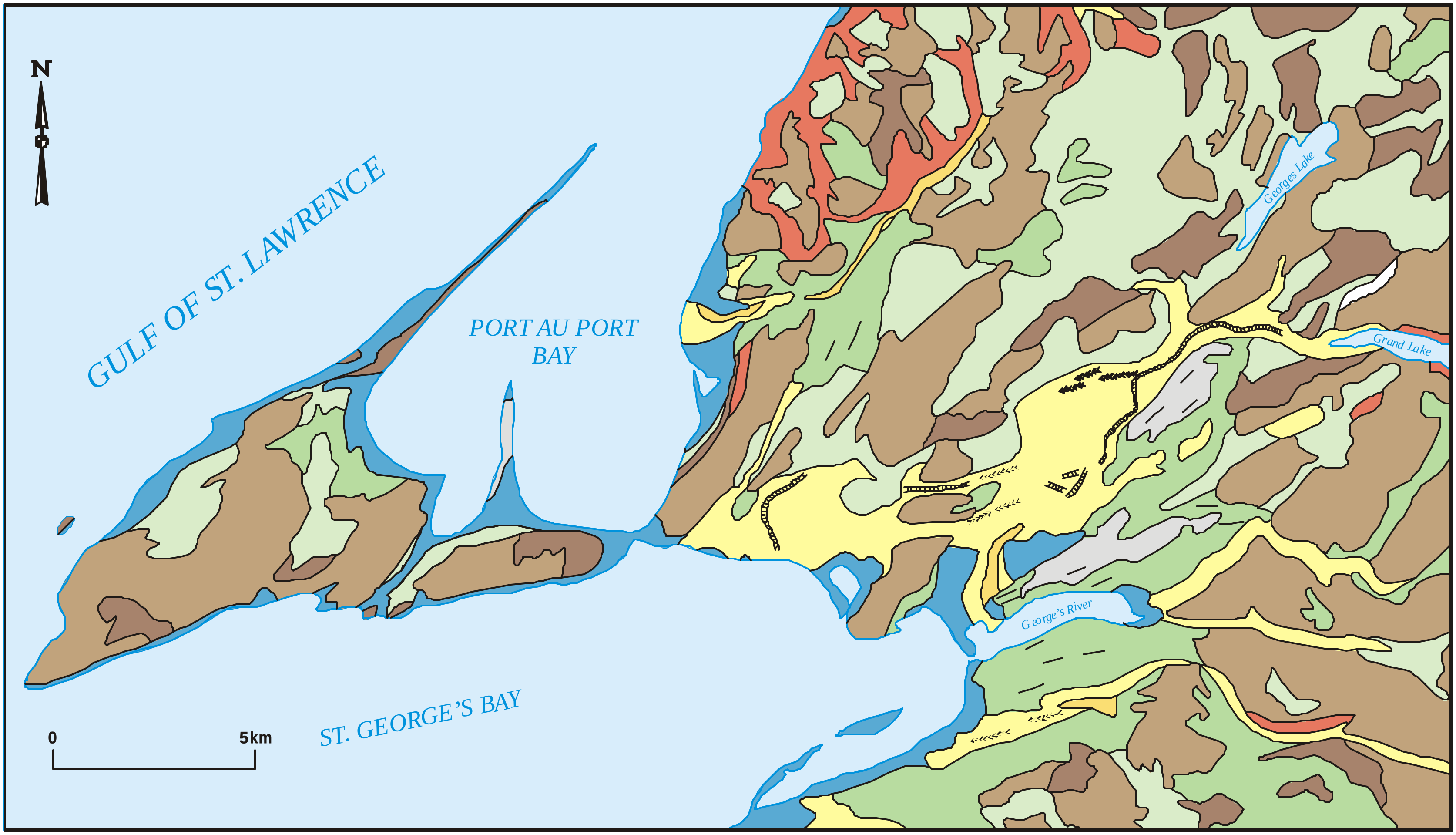
The west to northwestward flow in northern St. George's Bay originated from an ice centre in the southern Long Range Mountains. Ice flow and clast data support this interpretation. This flow crossed the northern part of St. George's Bay covering the coastal plain west of Stephenville and extended to the southern part of the Port au Port Peninsula. There is no evidence that this ice flow covered the Peninsula's northern coast suggesting that the Port au Port Peninsula was either at the western extent of the westward flow or that it was covered by ice from the north. There is no evidence that this flow affected the St. George's River area. This Long Range Mountain flow was blocked by ice from The Topsails. Ice from The Topsails flowed through the Grand Lake valley toward the coast. This flow was northwestward through the Serpentine Lake valley, southward through Harrys River and westward along the Fox Island River valley. The Lewis Hills deflected ice southward suggesting that The Topsails ice was relatively thin. Some Topsails ice may have been directed through the Romaines Brook valley, somewhat protected from westward-flowing ice by the Indian Head Range. The presence of Topsails granite clasts in diamicton in Romaines Brook shows some influence from Topsails-centred ice.

SURFICIAL GEOLOGY

The surficial geology was mapped using 1:40 000 black and white aerial photographs and extensive ground-verification mapping. Five main surficial units were identified (Figure 4).

BEDROCK

Areas of exposed bedrock and bedrock concealed by a thin veneer of vegetation or sediment are found throughout the region (Figure 4). The Port au Port Peninsula contains



- ▨ Bog : **Accumulations of degraded organic matter deposited in poorly drained low lying areas**
- 🟥 Colluvium : **Accumulations of poorly sorted detritus around the base of steep hills derived from the slopes above**
- 🟨 Fluvial : **Low relief plains with channeled surfaces close to modern rivers, consisting of moderate to well sorted gravel, sand, silt, and clay, deposited in modern river systems**
- 🟦 Marine sediment : **Moderately to well sorted gravel and sand, and mud. Mostly exposed in marine terraces, or within glaciomarine deltas**
- 🟨 Glaciofluvial sand and gravel : **Poorly to well sorted sand and gravel, 1.5 to 50 m thick, with a diverse surface topography. Mostly found within valleys across the area**
- 🟩 Diamicton Veneer : **Thin (less than 1.5 m) discontinuous sheet of diamicton (poorly sorted sediment containing a mixture of grain sizes from clay to boulders) overlying bedrock. Patches of exposed bedrock and thicker sediment cover common. Relief and topography variable, and bedrock controlled**
- 🟩 Diamicton : **Continuous diamicton cover thicker than 1.5 m. Includes areas with a channeled surface topography, ridged topography or hummocks. Diamicton of similar composition to diamicton veneer. Sand and gravel are common at the surface within channels**
- 🟫 Concealed bedrock : **Mainly bedrock concealed by vegetation with patches of till, sand and gravel, bog, and exposed bedrock**
- 🟫 Exposed bedrock : **Areas of bedrock with little or no surface sediment. Includes areas of bedrock concealed by a thin mat of sediment and vegetation**
- **Esker**
- **Large proglacial channel**
- **Flutes**

Figure 4. *Generalized surficial geology map of the Stephenville area (modified from Grant, 1991).*

large areas of exposed rock, mostly limestone. Other areas of bedrock are upland areas, including Table Mountain, Indian Head Range and the Long Range Mountains south of Grand Lake. Bedrock is exposed rarely on the coastal lowlands, except at the base of coastal cliffs.

DIAMICTON

Diamicton is found on the interfluves between the major valleys and along the foothills of the bedrock-controlled upland areas where it is thin and discontinuous, but forms a continuous blanket in large parts of the study area (Figure 4). The thickest diamictons are associated with flutes found north and south of St. George's River. These flutes are commonly 15 to 20 m high, 100 to 400 m wide and up to 5000 m long. No bedrock core was noted. The diamicton is a grey (Munsell colour 10YR 6/1), moderately compact sediment with weak to moderate fissility, and a silty-sand matrix. Clasts commonly are subangular to subrounded and have a median size of 4 cm; they are mostly granites, granitic gneiss and other rock types with a Long Range Mountains provenance. Finer grained rock types are commonly faceted and striated. This sediment characterizes most of the observed diamictons between the southern margin of the field area and the Southwest Brook valley; median thickness is about 4 m. The diamicton is interpreted to represent primary subglacial sediment. This interpretation is supported by its stratigraphic position above bedrock, strong unimodal fabrics having a preferred clast orientation similar to adjacent striations, and striated clasts (Ashley *et al.*, 1985; Dowdeswell and Sharp, 1986; Dreimanis, 1988; Hicock *et al.*, 1996).

Diamicton found elsewhere across the area is more variable and commonly reflects local bedrock geology. Diamictons in the Long Range Mountains are commonly thin (less than 1.5 m), discontinuous, and are matrix- to clast-supported and have a silty-sand to sand matrix. The diamicton is poorly to moderately consolidated having a variable clast content (30 to 60 percent), dominated by local rock types; the colour is variable and is controlled by the underlying bedrock. Over the limestone terrane, north of Stephenville, the diamicton is thin and discontinuous. Rare peridotite clasts within diamictons indicate a southward ice flow consistent with ice-flow directions determined from striations.

A single diamicton sheet is common over much of the area. The exception is in coastal exposures west of Stephenville, where two diamictons are exposed overlying bedrock at Kippens (Batterson and Janes, 1997). Several thin diamicton units are common in coastal exposures west of Romaines Brook and on the Port au Port Peninsula. They are commonly separated by sand, gravel or mud. Diamicton interbedded with waterlain sediments suggest the glacier terminus was in standing water. Diamictons located on inclined surfaces above basal tills, and interbedded with sand, silt and/or gravel are interpreted as sediment gravity flow deposits, possibly formed in an ice-contact glaciomarine environment (Powell, 1981, 1984; Lawson, 1988; Lønne, 1995).

GLACIOFLUVIAL

Deposits of glaciofluvial sediment are common over much the study area east of the Port au Port Peninsula (Figure 4). They are generally confined to modern valleys, including Harrys River, Little Barachois Brook, Flat Bay Brook and Bottom Brook. The exception is the area north and west of Stephenville, where a thick mantle of sand and gravel covers much of the coastal plain.

Glaciofluvial sediment ranges from coarse-grained pebble to boulder gravels and sandy gravels deposited in an ice-proximal environment, to planar-bedded, finer grained gravelly sands to sandy gravels deposited as distal glaciofluvial outwash. The ice-contact sediments are commonly found in association with well-defined esker ridges. These ridges are interpreted to show the pattern of glacial retreat across the area. This pattern, shown in Figure 4, indicates a westward retreat of ice across the Stephenville area toward the Harrys River valley through Noels Pond and into the Long Gull Pond valley. Ice subsequently retreated northeast along the Harrys River valley into the Grand Lake basin. Esker ridges are also found in the Little Barachois Brook and Flat Bay Brook valleys, and show glacial retreat toward the southern Long Range Mountains. Ice-contact sediments are commonly coarse-grained pebble to boulder gravels. They contain a wide range of clast sizes and rock types and are commonly subrounded to rounded having numerous percussion marks. The sediment structure is complex containing truncated and discontinuous beds and high-angle crossbeds.

Sediment characteristic of a distal glaciofluvial environment is found in Harrys River, Flat Bay Brook and Little Barachois Brook. Distal sediments are commonly found adjacent to the modern valley floor, in contrast to the ice-contact sediments found at higher elevations along the valley sides. The sediment is pebble to cobble sandy gravel to gravelly sand. Exposures commonly show planar bedding, numerous cut-and-fill structures and trough crossbedding, all of which are typical of a braided stream environment (Miall, 1977; Maizels, 1995).

GLACIOMARINE/MARINE

Sediments deposited either in a raised postglacial sea or by modern coastal processes are common on the north coast of St. George's Bay (Figure 4). Littoral, sublittoral and delta sediments are found in various locations around the modern coast.

Deltas are common in northern St. George's Bay where they are commonly flat-topped features comprising inclined beds of sand and gravel (foreset bedding). These features have been identified at Three Rock Cove, Piccadilly and Abrahams Cove on the Port au Port Peninsula; and at Port au Port East, Kippens, Stephenville, St. George's River and Seal Rocks on the mainland (Plate 2). Grant (1991) also identified a glaciomarine delta in the Harrys River valley, near Stephenville Crossing at ~45 m, although the lack of exposed internal structure makes interpretation difficult, except on geomorphological grounds.

Plate 2. *A raised marine delta at Seal Rocks, near St. George's. The delta surface is 26 m asl, and is part of a graded fluvial system from the Little Barachois Brook valley.*

Deltas are important in reconstructing sea-level history because they provide a minimum sea-level estimate at that point. The highest of these features is at Port au Port East (45 m). Others are at lower elevations, commonly 25 to 30 m. This part of St. George's Bay contrasts with the southern part where no deltas have been identified (Liverman *et al.*, 1999), suggesting that the area was ice covered until sea level had fallen to below modern levels. In northern St. George's Bay, ice had retreated sufficiently to allow the development of fluvial systems feeding deltas. The contrast between the southern and northern parts may be explained by differences in the timing of deglaciation, relation of the two areas to isobases, or both.

Sublittoral sediments, mostly muds, are found in several sites. Most are rhythmically bedded silt, very fine sand and clay. Sites at Bellmans Cove (Port au Port Peninsula), Port au Port East, in coastal exposures west of Stephenville (Batterson and Janes, 1997) and at Seal Rocks near St. George's all contain muds interpreted as marine. Most contain marine shells, of which only the Port au Port East site is dated (13 400 ± 290 BP; GSC-1187). These sediments all indicate deep-water conditions.

Sediments on the Shoal Point peninsula are interpreted to have been deposited in a tidal environment (Plate 3). The sediment is a crudely stratified, clast-supported, grit to pebble mud having a silt matrix. It is overlain across a gradational contact by 5 cm of structureless, organic-rich mud containing numerous root fragments. The underlying sediment contains numerous, regularly spaced (~45 cm) vertical cracks (Plate 3). The central part of the crack is filled with organic-rich mud, and pebble-sized clasts on the crack margins are oriented into the crack. The origin of these features is uncertain, but are likely desiccation cracks (*cf.* Leeder, 1982). The Shoal Point tidal sediments are overlain by terrestrial peat and the sequence exposed in section should pro-

Plate 3. *Exposure of sediment on the Shoal Point peninsula. The photograph shows tidal muds overlain by terrestrial peat. The muds show evidence of cracking (to left of trowel) possibly formed by dessication.*

vide valuable data on relative sea-level change on this part of the coast, providing a date on the marine–freshwater transition.

Other areas of importance are salt marsh deposits (Plate 4). Several of these occur on the north coast of the Port au Port Peninsula and are under investigation by a research team from Holland.

Plate 4. *Coastal salt marsh near Tea Cove, Port au Port Peninsula. These marshes are important areas for reconstructing paleo sea-level history, and were the subject of a research team from Holland in 1999.*

Raised littoral sediments are common on the Port au Port Peninsula and are rarely exposed elsewhere. The southern coast of the Peninsula contains an almost continuous sequence of (fossiliferous) beach sediments that are characteristically crudely stratified moderately sorted, open-work pebble gravels. The clasts are commonly flat lying to slightly imbricate. The matrix component is small (less than 15 percent) and mostly coarse sand; marine shell fragments are common. Raised beaches provide useful data for determining the position of paleo sea levels, as well as providing a minimum date for regional deglaciation. Raised beaches at Marches Point and Campbells Cove have already been dated at 12 500 ± 160 BP (GSC-2496; 3 m) and 13 300 ± 120 BP (GSC-4346; 12 m) respectively. Additional samples have been submitted for radiocarbon dating.

SEA-LEVEL FLUCTUATION HISTORY

The evidence from late-glacial marine–glaciomarine sediments shows that marine limit decreased in elevation from west to east across the study area. On the Port au Port Peninsula, marine limit may have reached 65 m in the Cape St. George area and at least 50 m near Three Rock Cove. At Port au Port East, a (ice-contact?) delta with a surface elevation of 45 m has been dated at 13 400 BP based on marine shells within marine muds at the base of the delta. Deltaic sediments are truncated in coastal exposures by ice-proximal glaciomarine sediments (Batterson and Janes, 1997). A series of fossil limestone cliffs were also identified along the southern coast of the Port au Port Peninsula (Plate 5). These cliffs had a maximum elevation of about 45 m and were identified at Jerrys Nose, Pigeon Head, and Sheaves Cove. Along the coast west of Stephenville, surface fluvial or glaciofluvial gravels obscure evidence for higher sea level. However, a 45 m delta was identified at Port au Port East (Figure 2). This surface dips west and southwestward and is interpreted as an ice-contact delta (*cf*. Batterson and Janes, 1997). Sediments interpreted as delta foresets found on the east side of Romaines Brook and at Kippens indicate that the sea level was at least 20 m higher than present. Fluvial gravels truncate both these features. The top of delta sediments found in a pit opposite the Abitibi Price paper mill is at 25 m where they are truncated by 5 m of fluvial sand and gravel. At Seal Rocks, northeast of St. George's, is a raised marine delta having a surface elevation of 27 m. This feature is part of a graded fluvial system that extends into the Little Barachois Brook valley. The timing of late-glacial sea-level change remains unresolved. Data are presented in Table 1 that generally indicates progressively younger dates from west to east consistent with the elevation of raised marine features. Organic material submitted for radiocarbon dating is also indicated. These data should help define a sea-level curve for this part of St. George's Bay.

Plate 5. *A fossil limestone cliff near Lower Cove, Port au Port Peninsula. The cliff was formed along a paleo coastline during a period of higher relative sea level about 13 ka. Fossil cliffs such as these are common on the Peninsula.*

Terrace surfaces noted along the coast are fluvial and therefore provide little information on paleo sea level. The terraces are presumably part of graded fluvial systems, but the rapid regression of the cliffs means that the position of the paleo shoreline cannot readily be determined.

Table 1. Radiocarbon dates used for construction of relative sea-level curves presented in Figure 5

Location	Date BP	±	Lab Number	δC13	Elevation m	Material
1. Flat Island	1350	70	Beta 19583		0.4	Freshwater peat
2. Flat Island	760	60	Beta 19585		0.65	Saltmarsh peat
3. Flat Island	640	60	Beta 19584		0.2	Saltmarsh peat
4. Flat Island	470	60	Beta 19571		0.15	Saltmarsh peat
5. Flat Island	300	50	Beta 19586		1.5	Freshwater peat
6. Turf Point	7340	220	GSC-1145		0	Plant detritus
7. Turf Point	9350	120	WAT-883		0	Peat
8. Stephenville Crossing	1850	40	GSC-3269		16.8	Peat
9. Stephenville Crossing	4450	110	GSC-3345		22.1	Peat
10. Stephenville Crossing	7120	80	TO-4954	25	2	Peat
11. Stephenville Crossing	2040	80	GSC-3253		22.1	Peat
12. Stephenville Crossing	3130	110	GSC-3291		22.1	Peat
13. Stephenville Crossing	6210	130	GSC-3342		22.1	Peat
14. St. George's Bay	3695	95	Beta 30001		42	Polychaete worm tubes
15. Stephenville	13300	810	GSC-2063		5-6	Shells
16. Kippens	12600	140	GSC-2295	2.2	10	Shells
17. Kippens	12600	120	GSC-5942		17	Hiatella arctica
18. Kippens	12610	90	TO-6138	25	8	Hiatella arctica, Macoma calcarea & Mesodesma deauratum
19. Romaines	13345	230	S-3074		6-8	Whalebone
20. Romaines River	12800	130	GSC-4858	1.9	6-8	Hiatella arctica & others
21. Romaines	13100	180	GSC-4095	1.2	3	Mya truncata
22. Romains River	12800	100	GSC-5030	1	2-4	Hiatella arctica
23. Romaines	12700	110	GSC-4017	34.6	1.0	Plant debris
24. Romaines	11500	100	GSC-4291		1	Peat
25. Romaines Brook	13680	100	TO-6137	25	37	Mya truncata
26. Romaines Brook	13540	100	TO-7027	25	18	Hiatella (sp) fragments
27. Port au Port	13400	290	GSC-1187		2	Balanus sp.
28. Campbells Cove	13300	120	GSC-4346	1	11	Hiatella arctica
29. Abraham's Cove	13600	180	GSC-968		7.5	Hiatella arctica
30. Abraham's Cove	13700	230	GSC-1074		45	Hiatella arctica
31. Abraham's Cove	13600	110	GSC-2015		40	Hiatella arctica
32. Marches Point	12500	160	GSC-2496	0.2	2-3	Mytilus edulis
33. Piccadilly	13000	110	GSC-4584	0.7	14	Mya truncata
34. Hynes Brook	2365	175	GX-9527		1.8	Peat
35. Hynes Brook	2770	300	UQ-646		2.8	Peat
36. Victor's Brook	2840	80	GSC-4243		3.2	Wood
37. Rocky Point	13200	220	GSC-937	1.9	3.7	Mya arenaria
38. Two Guts Pond	2110	80	GSC-4292		0.1	Saltmarsh peat
39. Port au Port Bay	9570	150	GSC-4724		34	Spisula polynyma
40. Port au Port Bay	11165	95	Beta 30003		34	Shells
41. Port au Port Bay	11300	100	Beta 30005		34	Astarte undata
42. Port au Port Bay	11740	100	Beta 30004		41	Astarte undata
43. Port au Port Bay	13710	115	Beta 30002		41	Portlandia arctica
44. Port au Port Bay	5800	210	GSC-1203	2.5	24	Hiatella arctica

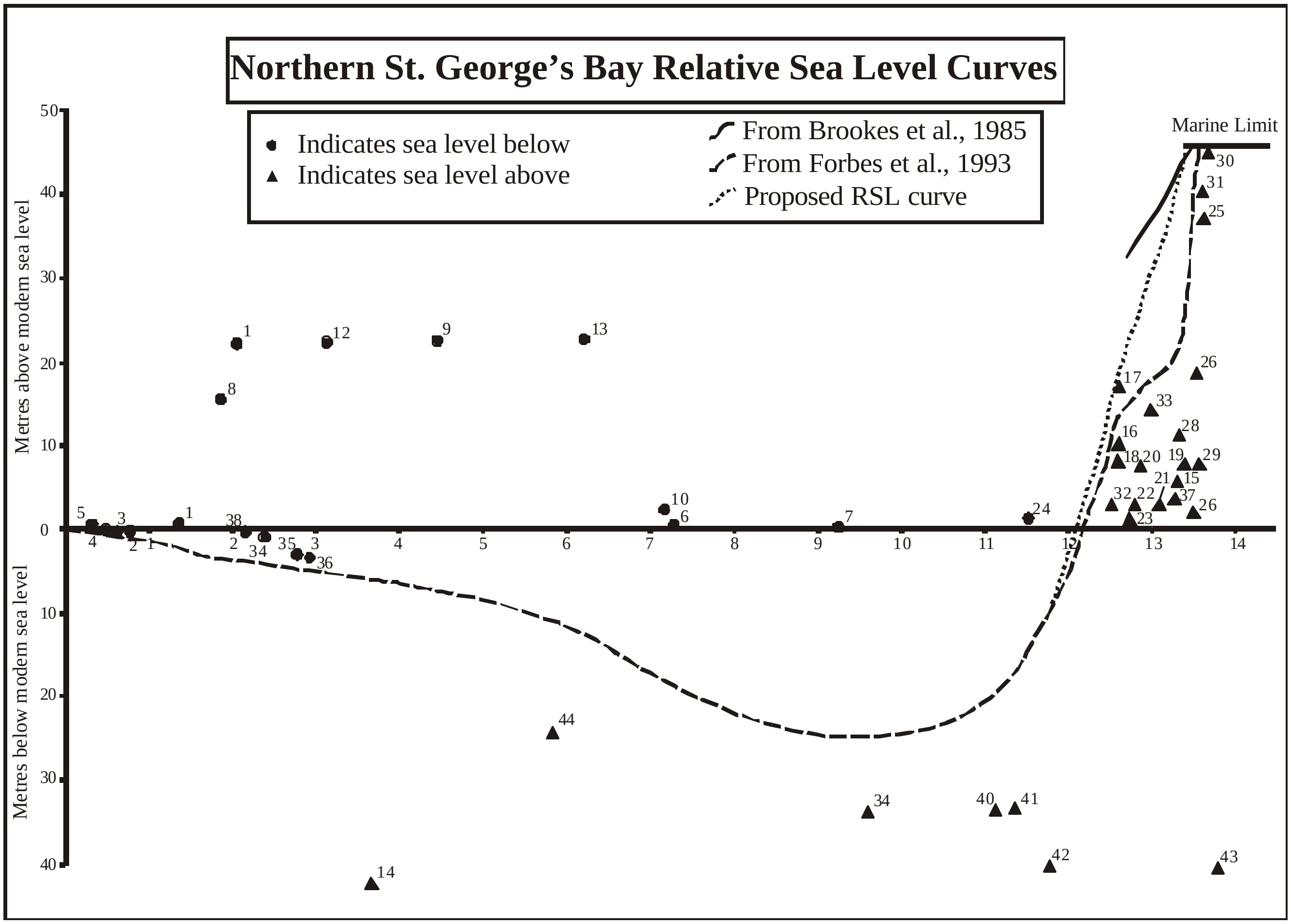


Figure 5. *Relative sea-level curve for northern St. George's Bay. Data from various sources.*

Discussion of sea-level history is thus largely constrained by radiocarbon dating of marine or freshwater organisms, and not by geomorphology. Postglacial relative sea-level change was controlled by isostatic adjustment of the crust following deglaciation. Isobases are generally perpendicular to the coast, increasing northward (Quinlan and Beaumont, 1982; Grant, 1989). Northward migration of a collapsing forebulge has been a major controlling influence on RSL (relative sea level) changes on the west coast. Two relative sea-level curves have been produced for the St. George's Bay area (Figure 5). The curve by Brookes *et al.* (1985) is based on 9 radiocarbon dates, including one from Robinsons, 30 km south of Stephenville. Marine limit is from a date of 13 600 BP at 44 m at Abrahams Cove on the Port au Port Peninsula, from which sea level fell gradually to below modern sea level at about 9700 BP, based on a date of 9400 BP ka on terrestrial peat near modern sea level at St. George's (Figure 5). The curve presented by Forbes *et al.* (1993) is based on 43 radiocarbon dates, including the 9 considered by Brookes *et al.* (1985). The curve includes dates between Highlands in the south and Rope Cove in the north, a distance of 85 km. The curve shows a rapid RSL fall from marine limit, falling below modern sea level at about 12 000 BP, with a sea-level lowstand occurring at about 9500 BP at a depth of 25 m (Figure 5). Shells collected in 1996 dated at 12 610 ± 90 (TO-6138) from the lowland west of Kippens at 6 m provide further support for the RSL curve of Forbes *et al.* (1993).

Both curves may be criticized for the use of dates that cross isobases up the coast. Exclusion of dates from southern St. George's Bay does not significantly alter the shape of the curve produced by Forbes *et al*. (1993), although it does suggest that the RSL history of southern St. George's Bay may be explained by a rapidly falling RSL since deglaciation, falling below modern sea level at about 13 000 BP, as suggested by Liverman (1994).

The Forbes *et al*. (1993) curve is preferred here over that derived by Brookes *et al.* (1985) because the Forbes *et al.* (1993) curve is better constrained, arguing for a rapid RSL fall following deglaciation, in accord with other curves derived for western Newfoundland (*cf*. Grant, 1989).

DISCUSSION

A sequence of late Quaternary events has been established for the Stephenville area supported by detailed surficial and ice-flow mapping, and recognition of raised marine features and sediments. There was no evidence for any ice-flow direction predating the last, late Wisconsinan stage. Initial ice flow during the late Wisconsinan was southward from an undetermined source and on much of the Port au Port Peninsula this is the only recorded flow. It is uncertain whether this flow crossed the Lewis Hills or whether it maintained its own independent ice cap during the late Wisconsinan. The early southward flow was directed down the Harrys River valley, and may have flowed across the coastal plain west of the southern Long Range Mountains (Liverman *et al.*, 1999). The second flow had a westward component from a source in The Topsails. It affected the area north of St. George's River and is shown by numerous large, southwest-oriented flutes. In the north of the study area, this flow was northwestward toward Serpentine Lake and westward toward Fox Island River, or was deflected southwestward along the footslope of the Lewis Hills. The area between the Indian Brook Range and Table Mountain contains evidence for a dominant south flow; whether from the early south flow or westward flow deflected southward is uncertain. The southern part of the field area was covered by a westward to northwestward flow from a source in the southern Long Range Mountains. This flow failed to overtop the large flutes surrounding St. George's River, but crossed the northern part of modern St. George's Bay to impinge on the coastline between Stephenville and Abrahams Cove on the Port au Port Peninsula. There is no evidence that this flow crossed into Port au Port Bay, suggesting it may have been occupied by ice derived from the north at the time.

The Port au Port Peninsula was the first area to be deglaciated. Radiocarbon dates from Abrahams Cove provide a minimum date for deglaciation at about 13 600 BP. Ice retreated eastward, shown by the pattern of eskers across the coastal plain west of Stephenville. The ice contact delta at Port au Port East was constructed sometime after 13 400 BP, the date of shells at the base of the delta, when ice was pinned against the southern flanks of Table Mountain. Retreat of ice was toward the Harrys River valley and subsequently into Grand Lake. A large proglacial channel feeding from Grand Lake into Harrys River is indicative of drainage from glacial Lake Howley that occupied the Grand Lake basin during deglaciation (Batterson *et al.*, 1993; Batterson, 1999). South of St. George's River, retreat was generally eastward toward the Long Range Mountains. Meltwater from waning ice was channelled through the major valleys, feeding deltas at the coast. These deltas range in modern elevation from 26 to 45 m, and were formed during a period of rapid relative sea-level fall. Existing data supports a relative sea-level curve that falls from a marine limit recorded at about 13 500 to 14 000 BP, to below modern sea level at about 12 000 BP. Marine limit decreases in elevation from west to east. Coupled with the sedimentological evidence from coastal exposures this indicates that waning glaciers were calving. Numerous sediment sequences on the Port au Port Peninsula, particularly at Salmon Cove and west of Stephenville, are interpreted to represent deposition in an ice-proximal, glaciomarine environment (*cf.* Batterson and Janes, 1997).

MacClintock and Twenhofel (1940) and Brookes (1970, 1974, 1977) described St. George's River Drift, St. George's Bay delta (in restricted areas) and Robinsons Head Drift sediments that show the initial glacial advance, marine incursion and re-advance (or at least late-glacial ice) in the northern St. George's Bay lowlands. The Robinsons Head re-advance sediments were dated at 12 600 BP based on marine shells found interbedded with sediments interpreted as ice-contact (Brookes, 1977). In southern St. George's Bay, Liverman and Bell (1996) argued that the sediment sequences exposed there might represent deposition on grounding-line fans in an ice-proximal glaciomarine environment. This shows progressive deglaciation of a coastline undergoing isostatic adjustment, and does not require glacial readvance. Sea level on this part of the coast is interpreted as dropping rapidly, falling below present about 13 000 BP (Forbes *et al.*, 1993; Liverman, 1994).

Data from northern St. George's Bay leads to a similar conclusion to that of Liverman and Bell (1996). Sediment between Romaines Brook and the Port au Port Peninsula are interpreted to have been deposited on a grounding-line fan in a glaciomarine setting. They show gravity-flow diamictons, interbedded with disturbed muds, and faulted sands, and sand and gravel deposited rapidly through a combination of underflow and channel flow. This area is beyond the limit of the Robinsons Head moraine mapped by Brookes (1970). Sediments to the east of Romaines Brook were deposited farther from the ice-front, and may be explained by a relatively simple deglacial sequence in a shallowing postglacial sea. The section at Kippens, previously interpreted as containing mostly ice-contact sediments, has been reinterpreted by Batterson and James (1997) as showing only initial ice-contact sedimentation overlain by deltaic, then fluvial gravels. Marine shells found in foreset beds near the top of the sequence support this conclusion. Surface geomorphology in the Kippens area that shows numerous near-coast depressions interpreted as kettle holes, supporting an ice-contact environment, may be explained through an origin as gypsum karst sinkholes (Batterson and Janes, 1997).

The development of raised beach sediments and fossil cliffs on the southern coastline of the Port au Port Peninsula were in an ice distal environment. These features dated at 12 500 to 13 300 BP and show ice was gone from the Peninsula at this time. Sea-level fall during the Holocene is recorded by submarine deltas in St. George's Bay and Port au Port Bay, with a postglacial lowstand recorded at 25 m below modern sea level at about 9500 BP (Shaw and Forbes, 1995). This lowstand produced two large brackish (?) ponds in Port au Port Bay (Figure 6). The low-lying area between the ponds produced large wetlands straddling modern East Bay and West Bay, which were subsequently eroded by sea-level rise following 9500 BP. Remnants of these bogs are found on the spit north of Boswarlos. Relative sea level continues to rise today, indicated by the progressive drowning of raised beaches at Port Harmon (Plate 6). This sea-level rise has resulted in active cliff erosion, particularly west of Stephenville. Sandy coastal cliffs along Flat Bay, traditionally protected by Flat Island, have recently undergone recession, likely due to several breaches of the island by storm waves. These areas may require monitoring or protection in the future.

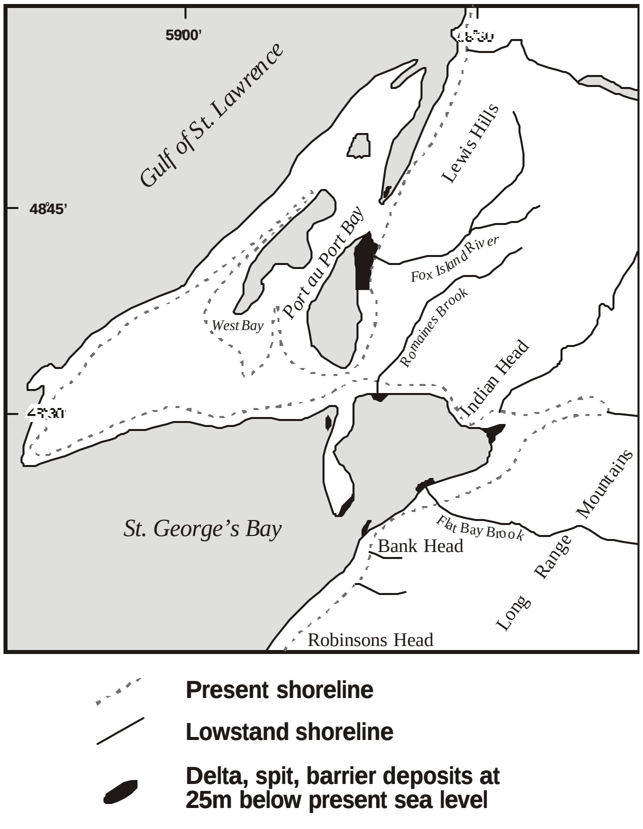


Figure 6. *Map showing reconstruction of coastline during the sea level lowstand (after Shaw and Forbes, 1995).*

Plate 6. *View of Port Harmon looking west. The raised beaches on either side of the harbour show falling relative sea levels during deglaciation. The progressively drowned beaches on the inland side are evidence for rising sea levels during the late Holocene.*

ACKNOWLEDGMENTS

The authors would like to thank the following for their contributions to the project. Sid Parsons and Jerry Hickey provided valuable logistical support. The manuscript was reviewed by Dave Liverman. Cartographic support was provided by Terry Sears and Tony Paltanavange.

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