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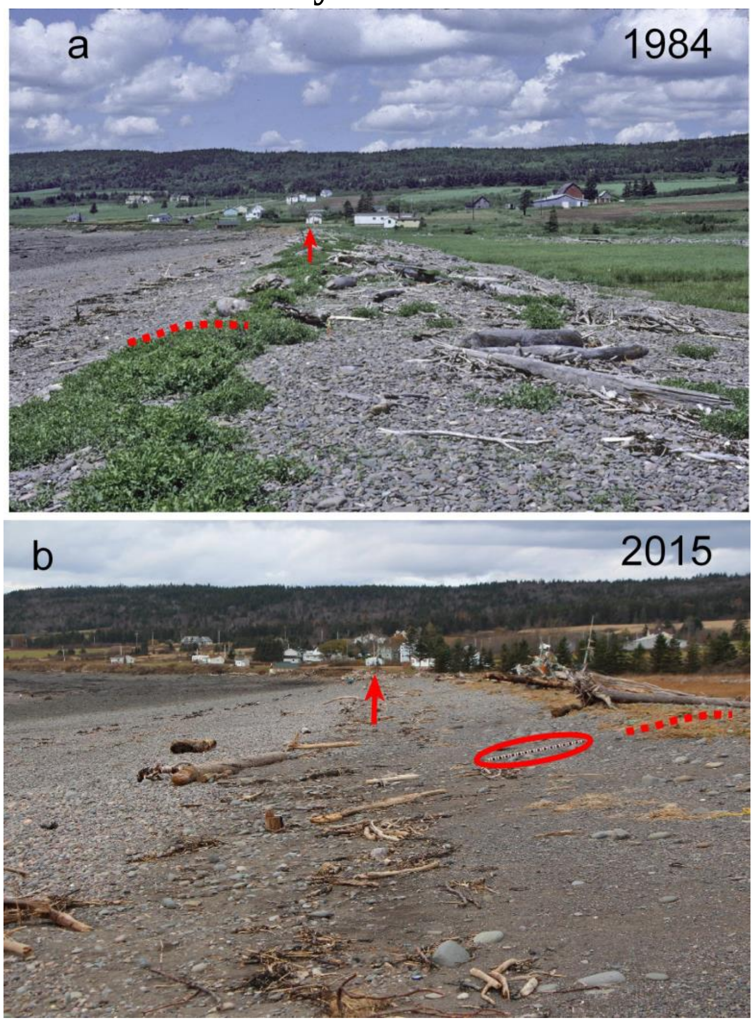
Physical Changes and Evolution of Scots Bay Beach, Nova Scotia

R. B. Taylor and J. Shaw



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Abstract

Scots Bay Beach is one of the largest bay head gravel barrier beaches within the inner Bay of Fundy that are exposed to waves generated along the length of the bay. It is a 60 m wide transgressive barrier with a limited coarse sediment supply. Less than 3 m of coarse sediment overlie buried marsh clay which is often exposed along the mid-lower beach face. The steep sloping beach face is fronted by an 800 m wide, intertidal flat. The beach is backed by wave washover and/or dune deposits and a 100 to 200 m wide salt marsh. The marsh is drained by tidal creeks which enter the sea through an outlet near the centre of the beach.

Terrestial seismic reflection and refraction surveys, vibracoring and marsh boreholes reveal a complex coastal stratigraphy. Landward of the salt marsh about 18 m of lower velocity sediment interpreted as glaciofluvial or raised beach deposits overlie bedrock. Thickest marsh deposits cored were 8.8 m, but core penetration was limited because of abundant driftwood buried in the marsh. The intertidal flats, within 200 m of the beach face, consisted of wave reworked sands, granules and pebbles over a wedge of salt marsh clay and an intermediate velocity deposit interpreted as a diamicton. It extends to bedrock which slopes steeply westward to a depth of 19 m beneath the tidal flat. Barrier beach positions at 1000 years (1ka), 2000 and 3000 years BP (radiocarbon years (^{14}C years) before present where present is 1950) were reconstructed using paleo-marsh elevations, sea level curves and a radiocarbon date of 3160 ± 50 BP from a vibracore sample collected within 150 m of the present beach face. The beach at 1 ka BP was no closer than 115 m from the present beach face and the 3 ka beach was a minimum of 150 m seaward and probably more than 300 m seaward of the present beach face (using a beach migration rate of 0.1 m /a). Scattered boulders and a thin bed of well-rounded polished granules and fine pebbles over truncated marsh deposits observed beneath the intertidal flat may represent a sedimentary facies of a transgressive macro-tidal barrier beach.

The barrier beach can be divided into seven distinct cross-shore zones between the intertidal flats and the back barrier marsh. Driftwood accumulation is an important factor controlling beach crest sedimentation and stability, particularly along the central and northern barrier where backshore dunes are absent. Rates of landward beach migration between 1945 and 1987 were documented by comparing repetitive air photography. The landward edge of the barrier migrated 22 to 47 m during the 42 years; a rate of 0.5 to 1.1 m/a, most along the central part of the barrier and least toward its north and south ends. Since 1984 shore migration was documented using repetitive cross-shore surveys at three locations. The landward edge of the northern barrier migrated 12 m and the beach crest at three sites has migrated 12 to 18 m during the 24 years since 1984, an average rate of 0.5 to 0.8 m/a. Rates of landward beach migration have been similar since the 1940s and higher than the suggested paleo-rates. Accelerated migration may have been triggered by the loss of sediment reserves by beach mining and the loss of wharf structures between the late 1940s and late 1950s. The beach crest can experience short term building phases and remain fairly stable for several years, e.g. 1986-1991. The beach crest is pushed landward episodically, only when westerly storms coincide with higher high tides e.g. Feb. 1976 and Oct. 2015, resulting in sheet wave overwash of the entire barrier. Storm wave run-up can exceed the elevation of the present beach crest of 7.6 m and the maximum flood level

can reach 6.4 m (Geodetic Datum) along the back edge of the marsh. It was observed that flooding of Scots Bay Beach and the access road to the beach occurred after water levels reached 8.5 m or higher (Chart Datum) at Saint John, N. B., e.g. Oct. 30, 2015. Therefore, in the future, during periods of sustained strong westerly winds, water levels recorded at the tide gauge in Saint John, New Brunswick could provide a warning of potential flooding at Scots Bay Beach. Based upon rates of landward beach migration since 1984, much of the marsh, particularly behind the northern barrier, will be squeezed out and disappear by 2100, as the beach migrates and builds against the higher backshore.

Cover photo: Views in a) 1984 and b) 2015 toward the north end of Scots Bay Beach at cross-shore survey line 4 (red dashed line) where the beach has migrated 11 to 17 m landward. Sediment supply is limited and driftwood is an important component of beach dynamics, particularly along the crest and back of Scots Bay Beach. A 1.5 m long staff (circled in b) provides scale. Arrows on each photo mark the same location / building, which provide a visual perspective of beach migration. By 2015 the higher high tide level (HHTL) / beach intersect was at the position of the beach crest in 1984.

Physical Changes and Evolution of Scots Bay Beach, Nova Scotia

Introduction

Scots Bay is one of three large, southwest- and west-facing, beaches in the upper Bay of Fundy that are fully exposed to waves generated along the entire length of the Bay (Fig. 1). The other two are Advocate Harbour N.S. and Salisbury Bay N.B. (Fig. 1a). Both Advocate Harbour and Scots Bay were selected as representative sites for monitoring barrier beach dynamics and cross-shore sedimentation in a macro-tidal environment (Taylor et al., 1995). Each site has a slightly different physical character and wave fetch orientation. Scots Bay is impacted by waves from the west and Advocate Harbour more by waves from the south. Scots Bay Beach is fronted by an extensive tidal flat; Advocate Harbour Beach is not (Forbes and Taylor, 1987). The study builds on previous sedimentological investigations of Scots Bay Beach (Amos et al., 1980) and differences in cross-shore morphology and sedimentology previously described for Scots Bay and Advocate Harbor Beaches (Forbes and Taylor, 1987). The study also provides a useful comparison with the depositional shoreline history recently documented in Salisbury Bay, N.B. (Dashtgard et al. 2007).

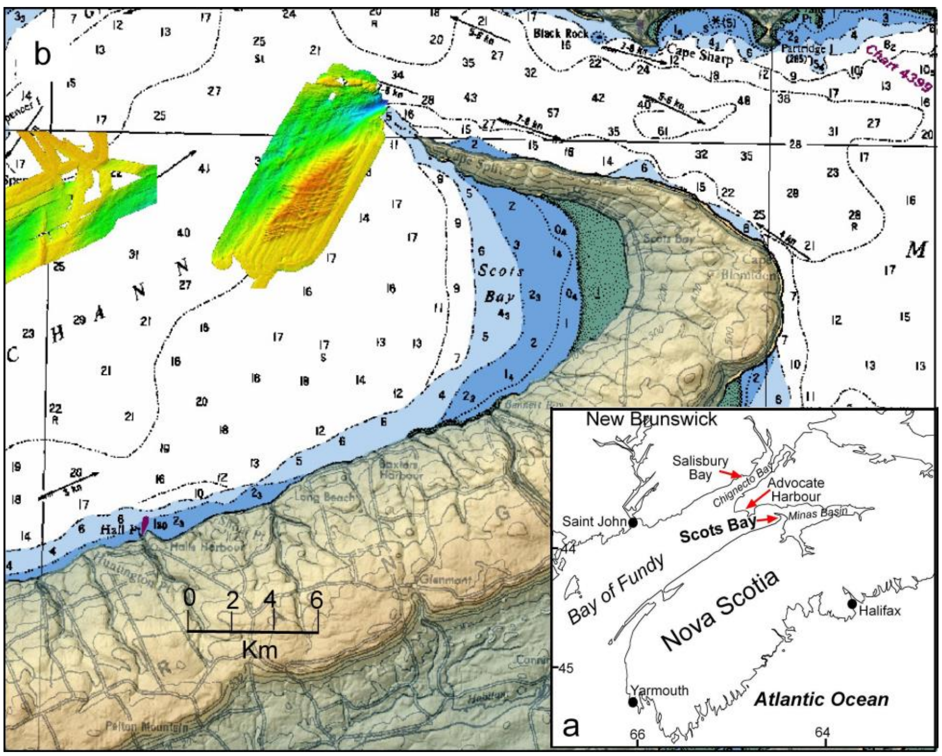

Figure 1. (a) Location map of three large bayhead barrier beach complexes (Salisbury Bay, Advocate Harbour and Scots Bay) along the upper Bay of Fundy and (b) a combined bathymetric and terrain elevation map of Scots Bay environs including a detailed multi-beam bathymetric survey at the mouth of Scots Bay (Miller and Fader 1990). The terrain DEM is courtesy of Chris Beasy, COGS, Lawrencetown, N.S.). The bathymetry is in fathoms (1 fathom =1.828 m) (CHS 1983)

Methodology

In June 1984 four cross-shore survey lines were established using physical line markers at Scots Bay Beach. Unfortunately, the markers at line 3 were lost before the first survey on August 28, 1984 and the line was not re-established. At the three remaining lines (Fig. 2) metal line markers (t-bars) were added in 1986 and Geological Survey of Canada (GSC) benchmarks, numbered 182 to 184, were added in 1996. Repetitive cross-shore surveys were completed on six to nine occasions between 1984 and 2008 (Table 1). In 1984, 1985 and 1987 additional surveys were completed by students at the Nova Scotia Land Survey Institute as part of class requirements. A contour map of the river outlet was also completed by the students. In 1991 a site reference mark was established on a rock at the north eastern base of the footbridge leading to the beach but could not be identified in 2015. In March 1992 shorefast ice conditions were documented at line 4. In 2004, new line markers had to be established at all survey lines because of burial and/or loss of the original markers, as the barrier migrated landward. The new line markers were re-established at the same locations as the original ones using differential GPS technology. The beach was most recently visited in November 2015 when physical conditions at each line were photographed and select tape measurements were completed from line markers remaining from 2004 on lines 1 and 2.

Vertical datum for the beach surveys was transferred from Nova Scotia Survey monuments 8270 and 8269 (Fig. 2, 3) using a total station in 1991 and differential GPS-Real Time Kinematic (RTK) technology in 1996 and 2004. By 2004 monument 8270 was at the edge of the shore cliff and could not be used safely (Fig. 3c) so a RTK base station was established adjacent to the monument and the survey points were adjusted for the offset from the control monument. Elevations in this report are relative to Geodetic Datum, unless stated otherwise. At Scots Bay, Geodetic Datum (zero) is 19.93 m below Ellipsoid Datum and 6.11 m above Chart Datum (Fig. 3a). For the student surveys, a known elevation was established at the top of the foundation of the NW corner of the barn, situated on the SW corner of junction of Hwy 358 and wharf road - elevation was 16.727 m (54.88 ft) above sea level (authors assumed relative to mean sea level since no vertical datum was listed), pers. comm. Dr. David Woolnough, College of Geographic Sciences (COGS).

In 1984 surface sediment samples were collected by hand across line 2, from the dune at line 1 and from sites of potential beach sediment supply, e.g. glacial deposits, at the south end of the beach. Temporal changes in sediment character were documented using photos of surficial sediment taken from selected sites across Lines 1 and 4 during each survey between 1984 and 2004.

To document beach stratigraphy, seismic reflection and refraction survey (Fig. 2b, 4a,b) were completed by colleagues from the Geological Survey of Canada, Ottawa, in June 1991 across line 4 (Taylor et al., 1992). In addition, boreholes were augered between 1987 and 1992 across and near Line 4, to investigate the thickness and composition of the back barrier marsh. On 19 August 1987 one borehole (bh1/1a - Fig. 2b) reached a depth of 8.8 m just landward of the wave washover gravels. The hole was initially drilled with a hand auger which broke at a depth of 5.5 m and was completed using a Hiller borer. Three additional boreholes were completed with a

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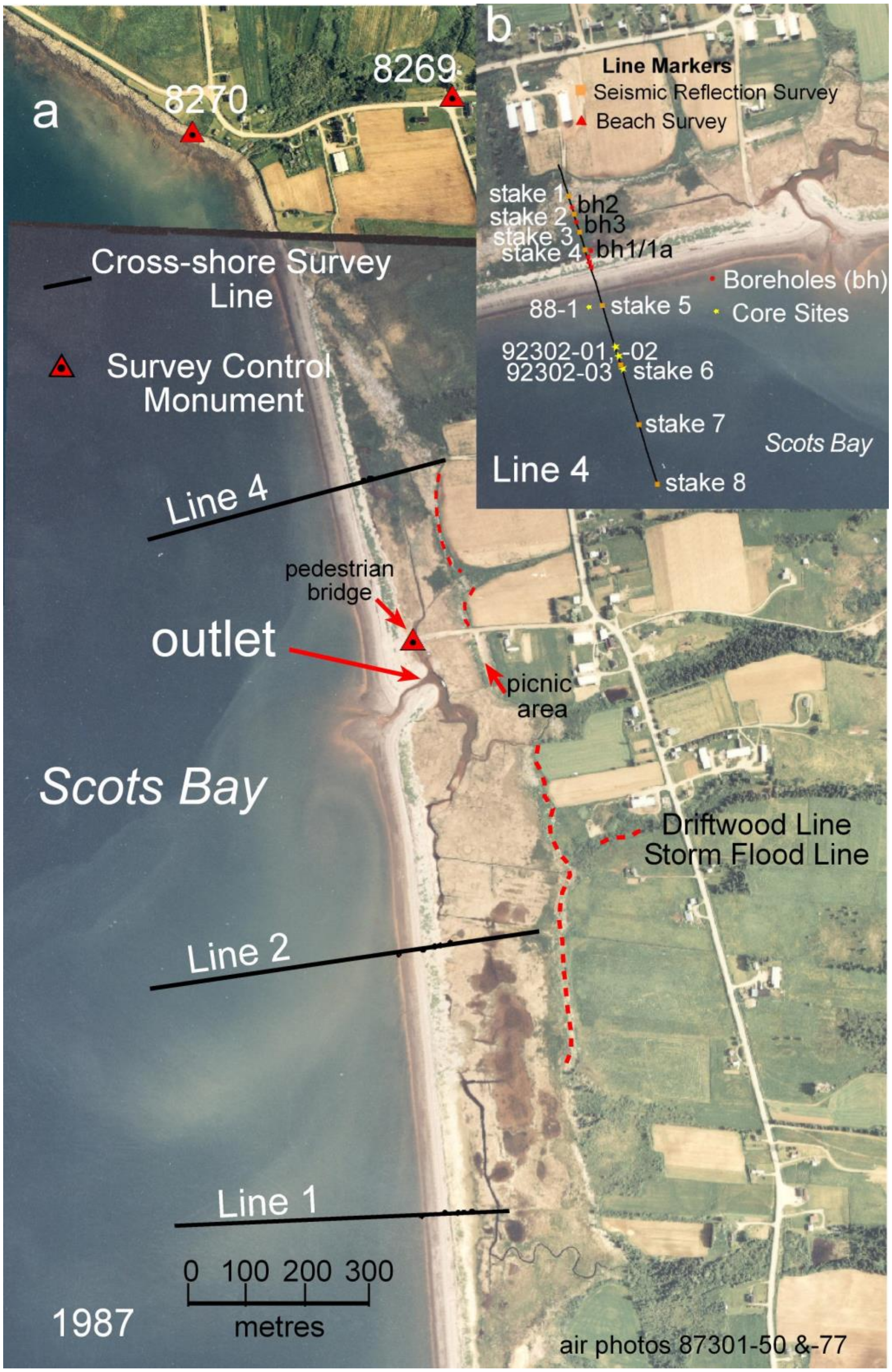


Figure 2. Aerial view of Scots Bay Beach, coastal marsh and farmland taken on June 19, 1987 showing the location of the three cross shore survey lines, the beach outlet and storm flood line (red dash) and primary survey control markers 8269 and 8270. (photo 87301-50 & 77, N.S. Land Information Services). b) detailed map of Line 4 showing the location of line markers, boreholes (BH) and vibracores (Scots 88-1 and 92302-01-02 and -03). Wood stakes1-8 were used for positioning during the seismic reflection survey completed in 1991. Stakes 1 to 4 were 30 m apart and 5 to 8 were 100 m apart.

Hiller borer on August 26, 1987, however penetration was limited to 4 m depth or less because of the presence of buried wood. On May 12 and August 03, 1988 several attempts were made to core the upper tidal flat using a vibrocorer. The first three coring attempts did not penetrate more than 1.5 m most likely because of wood and/or a change in sediment composition. At borehole 4, vibracore Scots 88-1 was collected on the upper tidal flat just north of line 4 (Fig. 2b). The corer was stopped at ~ 1 m before reaching a final depth of 1.7 m.

The seismic reflection survey was successful across the tidal flat and terrain landward of the salt marsh. No evidence of bedrock was identified beneath the salt marsh because of the rapid attenuation of seismic energy by a nearly 9 m thick silty peat and stiff grey clay. Refraction surveys across the beach crest failed because of poor coupling between the sound source and the material. Location stakes for the seismic survey were established along line 4, at 30 m intervals in the marsh, and at 100 m intervals across the tidal flat (Fig. 2b). Shot holes were drilled across the tidal flats at 1 m spacing with a Stihl auger (Fig.4b). Each hole was drilled to approximately 1 m depth. An energy source was provided using a "buffalo gun". The barrel of the gun was pushed into the drill holes and the trigger pin dropped onto a shotgun shell. Seismic energy was received by an array of 12 geophones (strings of three accelerometers) set at 1 m intervals across the sandflat. After each shot, the array was shifted 1 m seaward. The seismic data was recorded on a Scintex S-2 Echo portable seismograph.

The photos from 1992 and 2004 (Fig. 3b, c) show the extensive intertidal rock platform and low shore cliff at the north end of Scots Bay Beach. Sod drapes and clumps visible along the shore bank (indicative of erosion) were more pervasive in 2004 and by 2008 it was no longer possible to set up a tripod over the control monument because of cliff retreat.

In April 1992 three vibrocores were collected at two locations across the upper tidal flat on line 4 (vibracores 92302-01, -02 and- 03, Fig. 2b) to investigate the seismic reflectors. Unfortunately, coring was limited to a depth of less than 1.5 m.

Physical Setting

Coastal morphology of the Bay of Fundy has been described in varying detail by Welsted (1974, 1979), Owens (1977), Owens and Bowen (1977), Amos and Long (1980) and captured on videotape and slides during aerial coastal surveys in 1987 and 1990 (Taylor and Frobel, 1993).

The plan form of Scots Bay is defined by resistant Triassic basalts of North Mountain. The north shore of Scots Bay forms part of a large hooked peninsula which extends into the Bay of Fundy at the mouth of the Minas Basin (Fig.1b). Cape Split with its spectacular rock sea stacks and churning seas mark the west end of the peninsula. The outer shores of Scots Bay consist of low rock cliffs, intertidal rock platforms, and numerous coves with pocket gravel beaches (Fig. 5). The intertidal rock platform north of the beach varies from 400 – 500 m wide (Fig.3b). There is little evidence of abundant sediment supply for beach development.

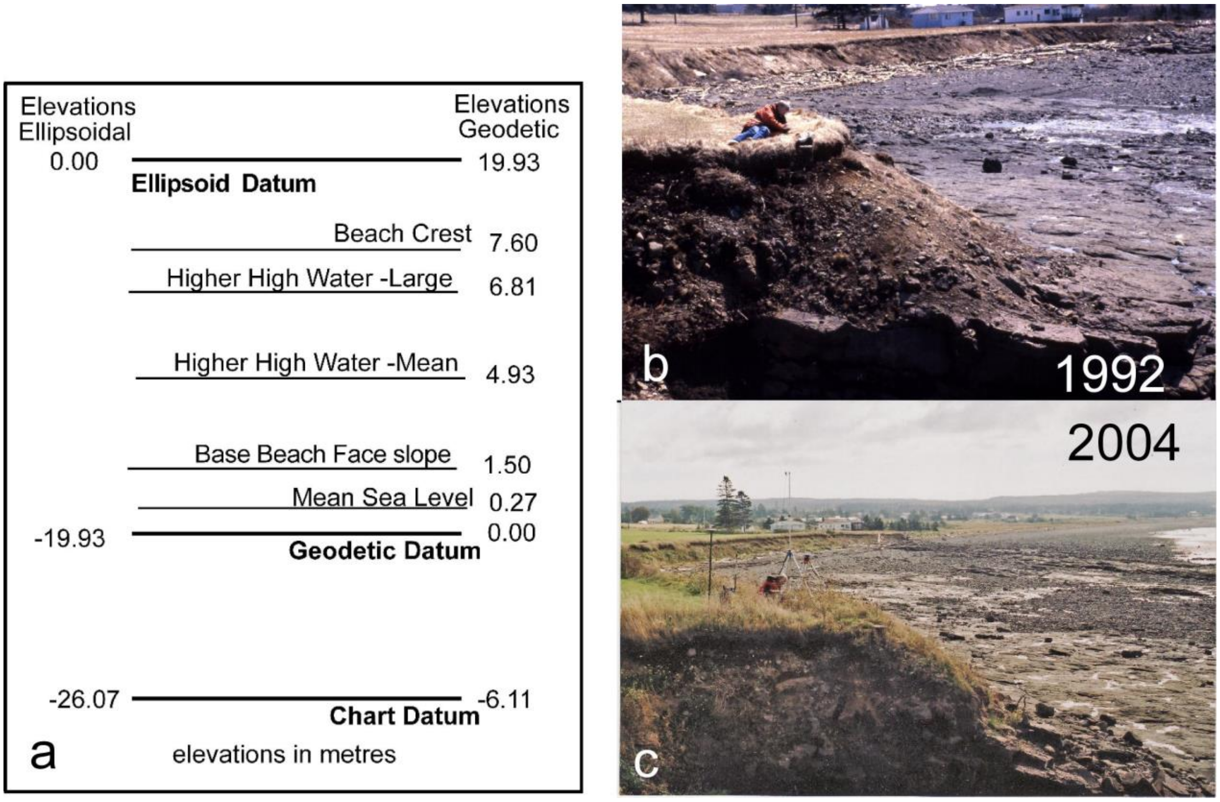


Figure 3. (a) Terrestial and marine elevations can be related to a number of vertical datums including Ellipsoid, Geodetic and Chart. All elevations in this report are relative to Geodetic Datum, unless otherwise stated. (b, c) Elevations were derived from a tie-in survey to NS control monument 8270 (person and tripod) at the north end of the beach (Fig 2a).

Table 1. Field surveys completed between 1984 and 2008 at Scots Bay Beach (Site 2007) by the Geological Survey of Canada, Atlantic. The site was visited in October 7, 2015 by R. Taylor. Photos were taken at three lines and select measurements from markers were taken at two lines.

Date	No. of Lines Surveyed	Type of Surveys: Cross Shore	Type of Surveys: Line Markers	Survey Method*	Photos
28-Aug.-1984	3	✓		1	✓
11-Dec-1986	3	✓		1	✓
26-Aug-1987	1	✓	✓	3	
12-May-1988	1	✓		1	
4 to 7- June-1991	3	✓	✓	3	✓
26-March-1992	1	✓		1, 3	✓
27-May-1996	3	✓	✓	4	✓
7-Oct-2004	3	✓	✓	4	✓
7-Oct-2008	2	✓	✓	3	✓

* Survey Method (1: abney level; 2: level/theodolite; 3: total station; 4: DGPS)

Figure 4. Sediment stratigraphy was obtained by using (a, b) seismic reflection surveys across the marsh, beach and tidal flat at line 4 which were ground truthed by (c) vibrocoring in the tidal flat and soil augering in the marsh (Fig.2b).

Scots Bay Beach is a bay head beach. It fringes a salt marsh which increases in width from less than 50 m at its north and south ends to just over 200 m in width in the middle (Fig. 2a). The salt marsh is drained by three creeks. They flow toward a tidal outlet which cuts through the central part of the beach.   Above high tide, the barrier beach locally known as the “seawall” is 50 – 60 m wide and consists of a single primary crest which rises to a height of 7.6 m (Geodetic) or 13.7 m (Chart) datum (Fig. 3a). North of the tidal outlet the barrier crest is a gravel ridge and to the south, the crest becomes progressively more capped by a sand dune (Fig. 6). Cross-shore survey lines were selected to represent the varying beach crest morphology: line 1 crosses a sand dune, line 2 crosses a low, wave overwash area and line 4 crosses a higher gravel storm ridge (Fig. 2a, 6). Driftwood is a significant component of the barrier beach crest and an important influence on sediment accumulation (Fig. 6b, c).   Exposures of salt marsh along the lower beach face (Fig. 7a) suggest that Scots Bay Beach is in a transgressive phase, migrating landward over top of marsh deposits.

Figure 5. (a) View eastward toward the head of Scots Bay along the north shore which is mainly bedrock with pebble-cobble-boulder pocket beaches. (b) close-up of intertidal rock platform illustrating the weathering and source of large clasts for beach building (Red field book is 17.3 cm long for scale).

Scots Bay Beach is fringed by intertidal flats as much as 800 m wide that extend to -3.9 m elevation. Little is known about the inshore stratigraphy which is masked by gas however farther offshore at the mouth of the Bay in water depths of 30 – 40 m, sand waves 10 – 15 m in height (Fig. 1b) overlie an extensive lag veneer of sand and gravel (Miller and Fader, 1990). Seismic reflection records suggest at least 20 – 30 m of Quaternary deposits consisting of acoustically-stratified glaciomarine sediment and a non-stratified unit, interpreted as ice-contact sediment, overlie bedrock (Taylor et al., 1991). The glaciomarine sediment is separated from the overlying sand layer by an unconformity (Shaw et al. 2012). A large scour trough exists seaward from the subsea dune field at the entrance to Scots Bay (Shaw et al. 2012).

Post-glacial marine limit at Scots Bay is 20 m, based on raised beach features (Stea et al. 1987). Beach sediment is largely derived from late Wisconsinan glacial outwash (Swift and Borns, 1967, Amos et al., 1980), and older beach deposits and marine sediment trapped in the bay. Larger clasts are derived from the bedrock platform. The glacio-fluvial deltas developed at the head of the Bay were built over an older till veneer when sea level was higher than at present (Amos et al., 1980). These deposits were subsequently trimmed by marine action as isostatic recovery occurred. One raised beach terrace extends along the highway in the village (Fig. 2a). Stea et al. (1992) mapped the surficial deposits as ground moraine: a till (gravel, sand and mud) often sandy and stony; with loose inclusions of water-lain material 2 to 25 m thick. A type section was described by Stea et al. (1992) at Bennett Bay just southwest of Scots Bay Beach. In a 13 m section, a red muddy diamicton (east Milton Till) was overlain by red stony sandy diamicton, and a basaltic diamicton (Bennett Bay till) topped by cross bedded sand and red silt and horizontally laminated pebbly gravel. The upper unit was interpreted as a raised beach deposit.

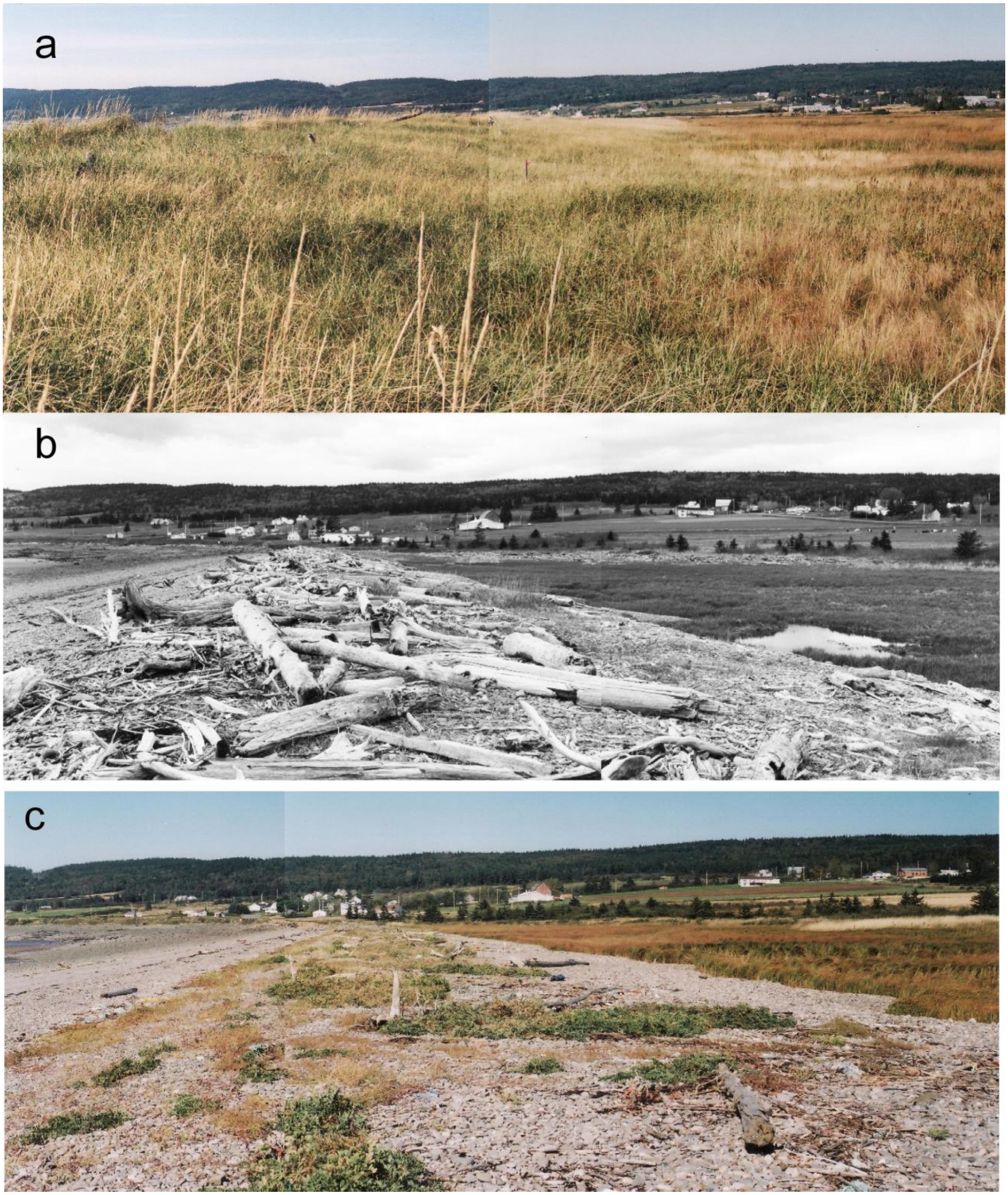
a
b
c


Figure 6. At Scots Bay, beach crest morphology changes from (a) a sand dune with scattered driftwood along the south end (Line 1) to (b) a pebble-cobble storm ridge with accumulations of driftwood along the central to northern section (Line 4). Views of Line 4 in (b) May 1996 and (c) October 2004 illustrate that driftwood can be floated off the beach into the marsh during high water storm events, e.g. in January 1997 (Table 3).

In 1984, backshore deposits to the south and north of Scots Bay Beach were sampled (Table 2). To the north, at the shore cliff where survey monument 8270 existed, 2 to 3 m of poorly sorted sandy-pebble material with a mean size of -2.12 phi (4.34 mm) overlies moderately dipping bedrock. At the south end of the beach, vegetated shore cliffs consisted of a soil overtop of 5 to 6 m of sandy-pebble with well sorted, thin bands of granule near the top. The bands of granule resemble a raised beach or fluvial deposit. The mean size of the material was -1.88 phi (3.68 mm) (Table 2). It consisted of similar proportions of gravel and more sand than the north site which consisted of a larger mud fraction. A two metre high cliff exposure was sampled farther inland. It consisted of nearly equal portions of gravel, sand and mud. The sample was finer and less well sorted than the other two deposits. The coarser clasts were very angular and all the same lithology.

Scots Bay has had a long history of logging, milling and shipbuilding industries (Deal, 2004). A map of 1872 lists five sawmills and a shipyard (Church, 1872). One sawmill was located at the north side of the outlet where the George Jess and Huntley Brooks converge in the marsh. All that remains of the structure are three vertical posts. Two wharves were built on either side of the stream (referred to as the outlet). Since the wharfs do not appear on the map of 1872, Deal (2004) suggested they were probably built in during the 1870s or late 1860s, after Church's mapping. The platform south of the outlet was used for unloading scows (Stan Huntley, pers. comm., 1991). The wharfs remained in use until the late 1940s, when the accumulation of mud prevented cargo vessels from docking (Deal, 2004). Between 1850 and 1918 at least 26 vessels were built in Scots Bay (Deal, 2004). Three of the shipyards were located between the north end of the beach and the outlet. A postcard from 1917 shows a vessel being built at the Lockhart shipyard (Deal, 2004). A local resident (Stan Huntley, pers. comm., 1991) reported that four-masted schooners used to frequent the harbour at Scots Bay in 1918 and ships used it in 1935.

Gravel was reported extracted from the beach area for use in highway construction in the 1940s to 1960s and some locals suggested the mining led to a beach retreat of 75 to 100 feet (22 to 30 m). Vehicles could reach the beach via a bridge until at least 1967. By 1977 a pedestrian bridge provided access to the beach (Fig. 2, 7c).

Processes

Although Scots Bay Beach is exposed to prevailing winds and a large wave fetch, wave energy is dissipated across a wide littoral zone because of the large tidal range. At Scots Bay the semi-diurnal tides have a large range of up to 13.5 m (CHS, 1999). Mean sea level (MSL) is at 0.27 m and higher high water large tidal range is 6.81 m (Fig. 3a). Ice may be present for up to 4 months, but the Bay of Fundy is never completely ice-covered (Owens and Bowen, 1977).

Storms

Waves have most frequently over washed the low, central portion of the Scots Bay Beach near the tidal outlet and less frequently to the north and south where the beach crest is higher reaching 7.6 m elevation (Fig. 3a, 6, 7). For high water events to occur in the Bay of Fundy the phasing of a storm surge (> 60 cm) with a rising tide is required and the window of concern is when events coincide with perigean spring tides (Parkes et al. 1997).

Table 2. Sediment samples collected from the vicinity of Scots Bay Beach. Samples 2434 and 2435 were from a site south of the beach and sample 2436 was from a site north of the beach. Both sites represent potential sediment sources for beach building. Samples 2438 to 2442 were collected from Line 2 and sample 2437 was from Line 1 (from Forbes and Taylor, 1987).

Sample No.	Cross-Shore Zone	Mean (phi) (mm)	Sorting* (phi)	Skewness	Composition (%) Gravel	Sand	Mud
2434	glacial-fluvial	-1.88 (3.68)	2.05	0.86	68.6	30.6	0.8
2435	till	1.47 (0.36)	4.59	0.66	38.3	33.6	28.1
2436	till	-2.12 (4.34)	3.33	1.27	74.1	18.9	7.0
2440	2 tidal flat-upper	1.15 (0.45)	1.41	0.01	8.5	90.1	1.4
2439	4 beach face –upper	-0.83 (1.77)	1.99	-0.26	41.8	57.7	0.5
2438	4 beach face -upper	-1.55 (2.92)	2.16	0.22	59.3	40.5	0.2
2441	5 beach face-swash ridge	-2.96 (7.78)	0.94	-1.11	99.8	0.2	0.0
2442	5 beach crest	-4.22 (18.63)	0.67	2.04	99.6	0.4	0.0
2437	6 dune	0.65 (0.63)	0.70	7.13	0.1	98.9	1.0

* sediment sorting worsens as the phi number increases eg. < 0.35 very well sorted, 0.5 -0.71 mod. well sorted; 0.71-1.0 mod. sorted;1.0 – 2.0 poorly sorted (Folk, 1974).

For Saint John, New Brunswick, the reference tidal station for the Bay of Fundy, the average annual frequency of storm surges (i.e. > 0.6 m) was 7.2 (data 1947–1975, Galbraith, 1979) to 8.1 events (data 1985–1995, Parkes et al. 1997). Storm surge frequency increases in October and November and peaks in December (Parkes et al. 1997). The "Storm of the Century" on March 14, 1993, produced the only one metre surge recorded between 1985 and 1995 but it did not coincide with either a high tide or a spring tide so it is not remembered as a high water event. Storms associated with extreme high water in the Bay of Fundy that are known to have impacted Scots Bay are listed in Table 3. Historical storms of note include: Nov. 3–4, 1759, October 4–5, 1869 (Saxby Gale), possibly Aug. 24–27, 1873 (August Gale), (Ruffman 1999, 2004), Sept. 14–20, 1953 (Hurricane Edna); and Feb. 2, 1976, (Groundhog Day Storm). Hurricane Edna pushed the beach and drift logs to the back of the marsh and a boat was carried to where the small picnic park and washroom facilities now exist (Fig. 2a, S. Huntley, pers comm. 1991).

In the early hours of January 12, 1997, huge waves, driven by strong winds coinciding with an unusually high tide, severely damaged the harbour infrastructure at nearby Halls Harbour (Advertiser Weekend News, Jan 17, 1997). The storm was reported as one of the worst in 20 years. Waves generated by hurricanes Bob in August 1991 and Arthur in July 2014 were responsible for severe damage to the wharf at Scots Bay; however, most hurricanes have coincided closer to low tide, resulting in minimal impacts to the upper beach and marsh.

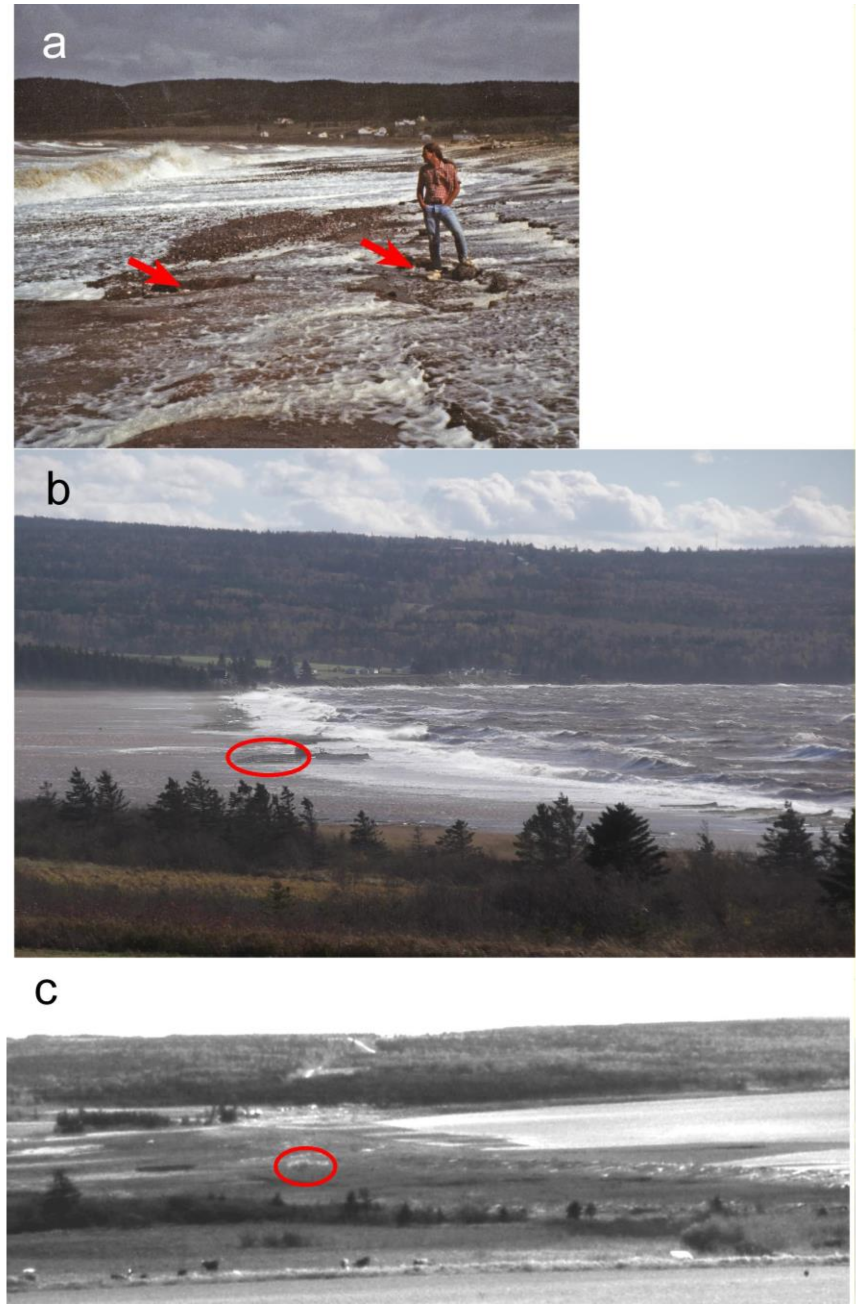


Figure 7. (a) Waves generated during storms, e.g. Hurricane Bob in August 1991, scour the overlying beach face material and cut terraces into the underlying salt marsh clay (arrows, where person standing) which contributes to the landward migration of this beach. (b) When large waves coincide with a high tide such as on Oct. 30, 2015 Scots Bay Beach is extensively overwashed, sweeping driftwood into the marsh. (c) contrasting view of Scots Bay beach from north in June 1991 during non-storm conditions near low tide. (Pedestrian bridge to the beach is circled on photos b, c), photo b courtesy of J. Huntley, Scots Bay).

On February 10, 2001, a small storm surge coincided with a higher high tide resulting in higher sea levels and waves. At Advocate Harbour seas reached 6.6 to 7.3 m and wave run-up reached 8.0 m which equates to 0.4 m higher than much of the beach crest at Scots Bay. However no physical impacts to Scots Bay Beach were documented.

On January 21–22, 2011 the spring high tide coincided with westerly winds. Waves overwashed and flattened the beach crest and pushed driftwood into the marsh. A rare August storm occurred on August 29, 2011. It was not as large as the storm in January but most driftwood was swept off the beach into the marsh (J. Huntley, pers comm. 2011). The most recent storm which coincided with high tide was on October 30, 2015 when waves extensively washed over the northern two thirds of the beach removing the driftwood and producing large washover fans along the backshore (Fig. 7b, J. Huntley, pers comm., 2015). The access road to the beach, where most people park when visiting, was flooded as far inland as the picnic area (Fig. 2a). Water levels recorded at the tide gauge in Saint John N.B. could be used as a warning of potential flooding at Scots Bay and other locations in the upper

Bay of Fundy. For example, on February 10, 2001 (Table 3) water levels reached 8.9 m (Chart datum) at Saint John, N.B. prior to flooding at Advocate Harbour, N.S. (Fig1). On October 30, 2015 water levels at Saint John reached 8.5 m (Chart Datum) 1.5 hours before flooding was recorded at Scots Bay, N.S. (Fig 7b).

Shore Ice

In winter, a shorefast barrier of ice often protects the upper portion of Scots Bay Beach from wave attack. On March 26, 1992 shorefast ice conditions were surveyed at line 4. The icefoot was composed of broken blocks of dirty sea ice, (Fig. 8a). It extended 1.7 m across the upper beach slope from an elevation of 4.3 m to 6.0 m. The seaward face of the icefoot was 1.5 m high and varied in width from 15 m to a maximum of 25 m. Snow covered the beach crest. By late March the icefoot was breaking down and a small ridge of brash ice had accumulated along high tide (Fig. 8a). Large blocks of sea ice had accumulated within the mouth of the outlet and rafted over top of the nearby marsh surface (Fig. 8b). The main tidal creeks and the upper reaches of the saltmarsh remained frozen and covered by snow. Frozen sand existed across the upper exposed tidal flat but was unfrozen farther offshore.

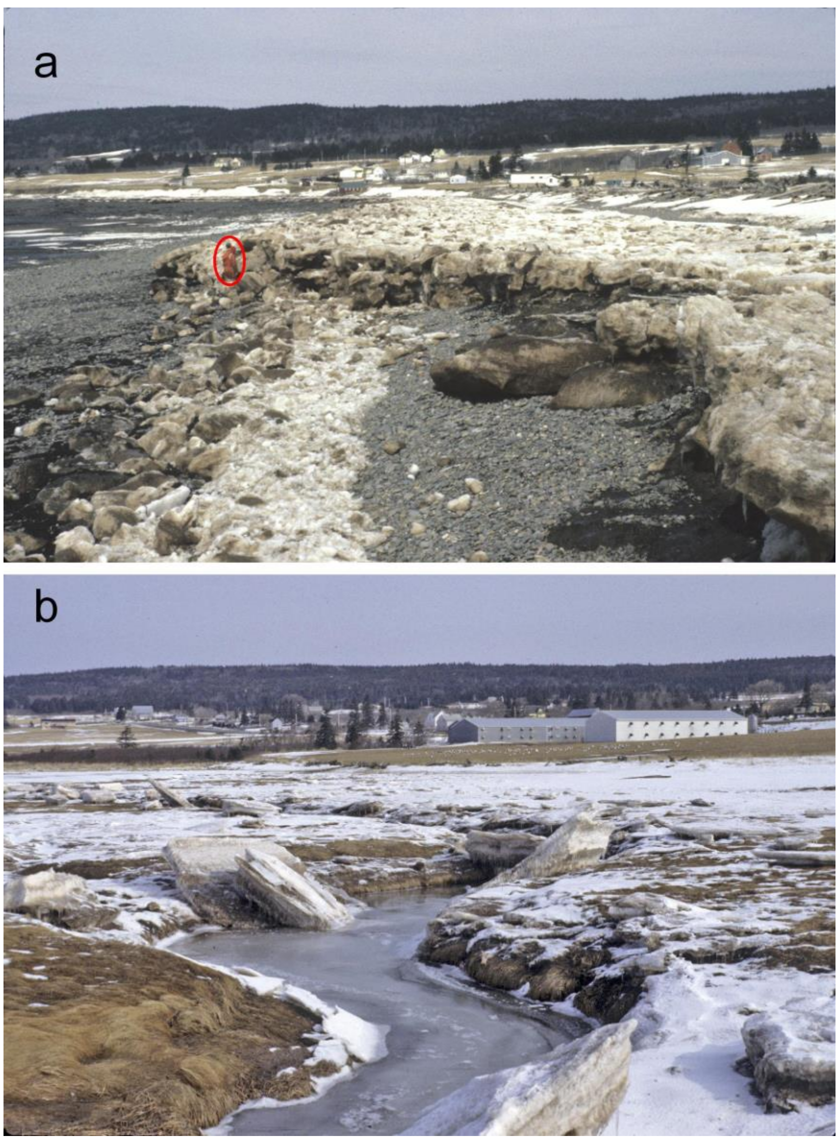


Figure 8. During the winter the beach and marsh can become snow covered and frozen for variable lengths of time. These photos taken March 26, 1992 show (a) the extent of shorefast ice, i.e. icefoot, which protects the upper beach from direct wave attack (person circled for scale) and (b) ice cakes riding-up onto the marsh surface along a tidal channel near the outlet. The ice cakes can break off pieces of frozen peat and transport them around the marsh.

Sea Level History

Maximum submergence of the Bay of Fundy occurred immediately after local deglaciation, circa 13,500 years BP (Fig. 9a; Amos and Zaitlin, 1984-1985). Highest high water (HHW), at the time, was 48 m higher than present mean sea level (MSL). MSL dropped 80 m to its lowest level, circa 7000 years BP and rose steadily thereafter. Oscillations in the position of marine limit are observed along the Bay of Fundy because of local changes in glacial conditions. For example, a raised beach was reported at 42 m near Advocate Harbour (Fig. 1a) and one was mapped at 20 m above mean sea level at the head of Scots Bay (Stea et al., 1987).

Sedimentological evidence suggested that the extreme tidal range occurring at present in the Bay of Fundy is fairly recent, dating at about 6000–7000 years BP (Amos, 1977, 1978). Although there remains a debate about the initial timing of the tidal amplification (Grant 1970; Scott and Greenburg, 1983; Amos and Zaitlin, 1984-1985; Bleakney and Davis, 1983), most agree it has increased during the past 4000 years. Shaw et al. (2010) invoked the presence of a barrier beach across Minas Passage for the differences in tidal expansion in Chignecto and Minas Basins (Fig. 1a). The barrier delayed tidal expansion in Minas Basin until ca. 3400 years BP (radiocarbon years (^{14}C years) before present where present is 1950). It is now believed mesotidal (2– 4 m) conditions existed at the low stand ca. 7000 yrs BP and macrotidal (> 4m) conditions began just before 4000 BP in the Bay of Fundy (Amos and Zaitlin, 1984-1985, Shaw et al. 2010).

Since the early 1900s mean sea level recorded on tide gauges at Saint John and Charlottetown has risen at rates of 30.1 and 35.5 cm/ century respectively (Carrera et al. 1990). Shaw and Ceman (1999), working at Amherst Point at the head of the Bay of Fundy, observed a stepped pattern of marsh aggradation varying from 10.4 cm to 53.3 cm per century with a mean rate of 25.9 cm per century since 900 BC. They concluded the stepped pattern resulted from eustatic fluctuations superimposed on signals of crustal subsidence and tidal range expansion. The eustatic fluctuations appeared to have a range of 0.8 m.

Physical Beach Changes

Repetitive vertical aerial photographs taken in 1945, 1954, 1967, 1977 and 1987 were compared to determine decadal changes in beach morphology and shoreline infrastructure (Fig. 10, 11). The photos were also examined for evidence of storms impacting Scots Bay Beach. Intermittent field observations and repetitive cross-shore surveys provided more detailed measurements of beach changes at three sites after 1984 (Fig. 12; Tables 1, 4 to 7).

1945 to 1987

Between 1945 and 1987 there was little major change in the plan form of the beach, tidal flats or the position of the tidal outlet (Fig. 10). The largest changes observed included: the loss of wharf structures on both sides of the tidal outlet, and landward beach migration into the saltmarsh, particularly just south of the outlet. Most of the large wave washover features formed between the 1967 and 1977 (Fig. 11b, c) are attributed to the Groundhog Day storm of 1976. Wedler (1984) estimated that the northern part of Scots Bay Beach had migrated 25 m landward since the 1940s and the southern half had remained stable.

Figure 9. (a) Post-glacial sea level curve for the Bay of Fundy (Amos and Zaitlin,1984-1985). Sea level fell from a high of + 48 m ca. 13,500 BP to a low of -25 m ca. 7,000 BP and rose thereafter. At Scots Bay the highest raised beach is at 20 m elevation (Stea et. al. 1987). Present sea level is roughly the same as it was at 10,500 BP and the present large tidal range developed after ca. 4000 BP. (b) Rise of mean higher high water in Chignecto Bay since 4000 BP based on paleo-indicator data shown (from Shaw et al. 2010). The curve in (b) was used to reconstruct higher high water level and beach evolution in Scots Bay since ca 3000 BP (Fig. 26).

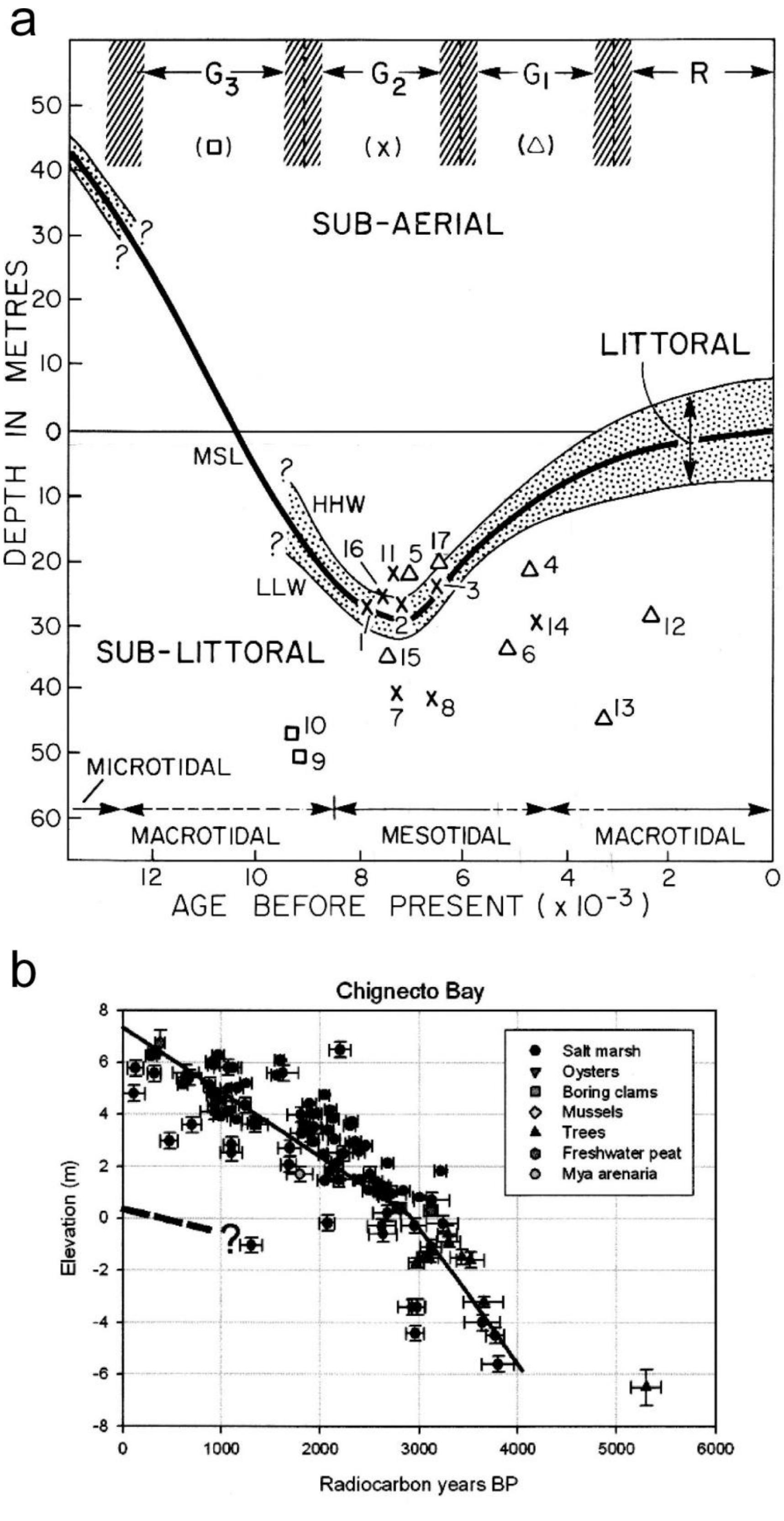


Table 3. List of storms and high water events that significantly impacted shores along the Bay of Fundy (derived from Galbraith, 1979, Parkes et al. 1997, # Ruffman, 1999, 2004, field observations and accounts from local residents, e.g. J.Huntley, Scots Bay N.S.).

Date	Water Levels		
	Saint John	Yarmouth	Surge and notes
Nov. 3–4, 1759#			
Oct. 4, 1869#			1.7 to 2.1
Aug. 24–27, 1873			
Sept. 14–20, 1953			Hurricane Edna
Feb. 2, 1976	9.1	5.9*	1.2 to 1.5 *(record Water level for 1966– 96)
Mar. 14, 1993			"Storm of the Century" Did not coincide with high tide
Jan. 10–12, 1997			
Feb. 10, 2001			
Feb. 2, 2008			
Jan 29, 2010			
Jan 21–22, 2011	8.9	5.3	Worst since 1997 (Huntley)
August 29, 2011			Hurricane Irene driftwood swept off Scots Bay Beach (Huntley)
Feb. 11, 2014			
Feb. 22, 2014			
July 3, 2014			Hurricane Arthur
Oct. 30, 2015	8.5	4.9	Scots Bay Beach and access road Flooded (Huntley)

A re-measurement of positional changes along the barrier beach and cliffed shore to the north between 1945 and 1987 was completed by comparing rectified vertical air photos in ARCGIS. The landward edge of the beach migrated 22 to 47 m (0.5 - 1.1 m/a) landward; least at the north and south sections and most toward the middle. Largest landward beach migration was just south of the outlet.

Cliff top retreat north of the beach, decreased northward from 16 to 18 m at the south end to 6 to 8 m close to the bend in the shoreline, west of the river outlet (Figs. 3, 10b). Therefore, the rate of cliff top retreat decreased northward from 0.4 m/a to less than 0.1 m/a. In 1984 much of the cliff face was vegetated whereas by 2015 an erosional free face existed along most of the shore. Photos taken in 1992 and 2004 (Fig. 3b, c) confirm that cliff erosion was increasing as the beach migrated landward. By 2015 one property owner had added armour rock to the cliff base closest to the beach. Little or no sediment accumulation was observed across the intertidal platform but there was a variable accumulation of driftwood along the cliff base.

Wedler (1984) comparing land use activities on air photos from 1945 and 1977 found that much of the land changed from pasture to forage crops and hay and more cottages and non-farming residences appeared by 1977.

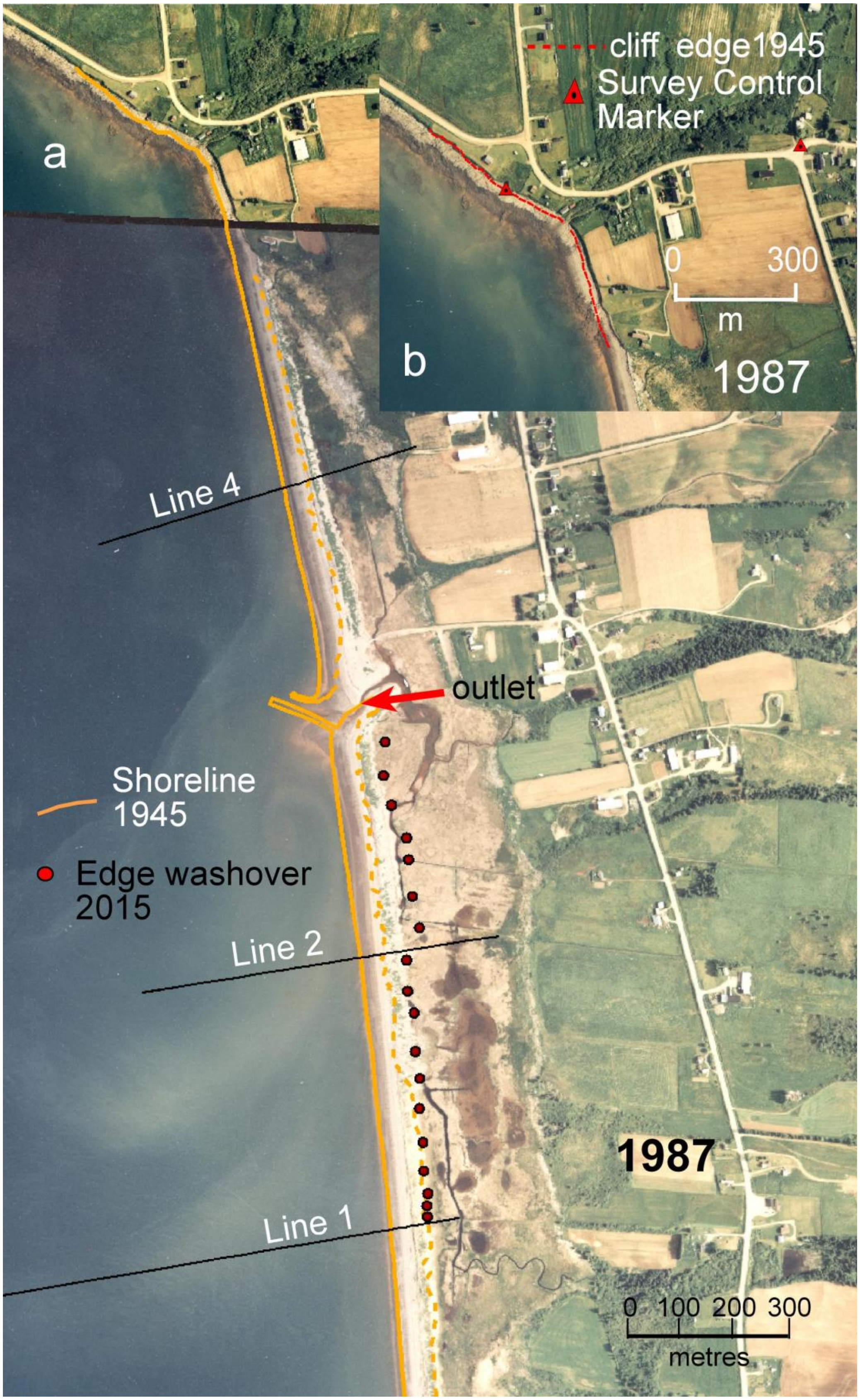


Figure 10. Shoreline positions of Scots Bay Beach in 1945 (orange lines) and 1987 (photo base) were plotted using georectified vertical air photos in ARCGIS. (a) For 1945, the solid orange line represents the base of the beach face (approx. mean sea level) and the landward dashed line marks the the landward edge of washover deposits. The dots in the backshore show the landward edge of wave washover deposits resulting from the storm in October 2015 (Fig. 7b). (b) Cliff top retreat at the north end of Scots Bay Beach. Between 1945 (redline) and 1987 (air photo base) cliff top retreat increased from 6 to 18 m from the bend in the shoreline to the south end of the cliff.

Physical shoreline changes observed in this study by comparing vertical air photos between 1945 and 1987 are listed below.

By 1954 (Fig 11a) the wharves had fallen apart in the mid sections and they appeared no longer in service. There was a significant cut into the gravel barrier just landward of the north wharf which may have been the result of a sediment extraction operation. There was evidence of significant wave overwash along the barrier north of the outlet (possibly the consequence of waves from hurricane Edna in 1953). South of the outlet there was a more continuous vegetated backshore, less so close to the outlet. The tidal channel appears to have been dredged and the dredged material added on the marsh surface along the edge of the channel. There were older washover fans observed along the edge of the marsh signifying that wave washover was not new.

By 1967 (Fig. 11b) little remained of the wharf structures and natural "spit -like" lobes were developing along the shores of the outlet. Relict crib work (Fig 11b- dashed lines) from the wharves controlled sediment movement around the seaward side of the outlet, e.g. the ebb delta. A consistent wave washover line along the northern barrier and just south of the outlet provided evidence of sheet overwash during a recent major storm. Only intermittent cuts were observed across the higher dunes farther south. An artificial squared flat located within the inner north side of the outlet was well pronounced in 1967 (Fig. 11b, red circle). It could be the remains of sediment excavation or ship building activities.

By 1977 (Fig. 11c) the artificial flat at the inner outlet had formed the foundation for a washover lobe along the south edge of the outlet. The south end of the beach consisted of a continuous vegetated backshore dune. Closer to the outlet there were three massive (up to 55 m inland and 27 to 46 m wide) wave overwash fans (Fig. 11c. red circles) across the barrier and the lobes on both sides of the outlet had been extended inland. These changes are attributed to the Groundhog Day storm of 1976. The ebb delta at the outlet was well defined in 1977, partly because of the water level at the time of photography. Marsh deposits were exposed in the beach just south of the outlet in the lee of the ebb shield (Fig. 11c, red arrow). Only a pedestrian bridge provided access to the beach. North of the outlet the barrier crest was vegetated and covered by driftwood.

By 1987 (Fig. 10a) there was evidence of increased wave overwash landward to the bridge just north of the outlet. Along the south beach the largest washover fans from 1977 were augmented by newer washover deposits which increasingly blocked the salt marsh tidal channel. The backshore dune was less continuous. Supports for the former wharves at the outlet were more buried and exerted less impact on wave processes at the outlet.

1984 to 2008

When cross-shore surveys began in August 1984, there was a well-defined swash ridge built at or near higher high tide level (Fig. 12a, 13a). This ridge and swale morphology represented a beach building phase. By December 1986 the beach crest and back barrier had been reworked by waves. The large swash ridge from 1984 was erased and the upper beach was built higher (Fig.12a, Table 4). At lines 1 and 4 there was minor beach crest retreat, whereas at line 2, the beach crest was built seaward (Table 4). There was also sediment accretion across the backshore at line 2 where 0.1 to 0.2 m of sediment accumulated at the line markers. There was very little physical change across the beach face and intertidal flats. Changes observed were attributed to the intermittent formation and disappearance of sand bars just below mean sea level.

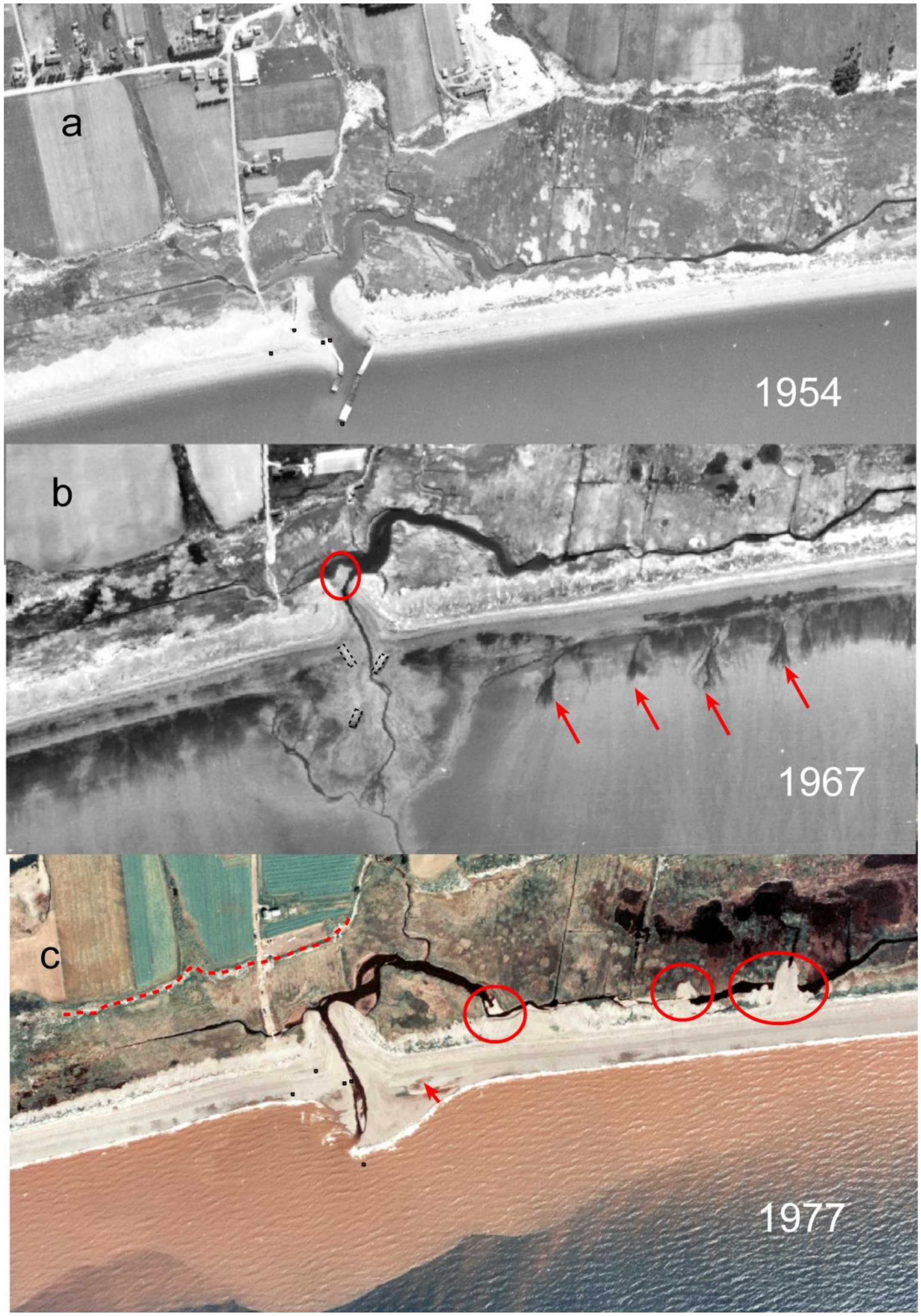


Figure 11. Close-up of the Scots Bay Beach in (a) 1954, (b) 1967 and (c) 1977 showing the deterioration in the wharves at the tidal outlet. The dots shown on the 1954 and 1977 photos mark the location of the remaining wharf support posts exposed in 1991. The dashed lines on the 1967 photo (b) highlight the remaining wharf structures. The increased number of wave washover lobes (red circles) along the back beach and a well-defined flood line (red dash) in 1977 (c) are attributed to the Groundhog Day storm of 1976. In 1967 (b) photos taken at low tide also show drainage features (arrows) at the seaward base of the barrier beach. The scale of the photos is 1:5000.

Although there was some evidence of waves moving driftwood farther landward at line 2, no significant changes were recorded across the upper beach from December 1986 to June 1991. The largest physical change recorded was across the lower beach face and upper tidal flats (Fig. 12a, Tables 4, 5). At lines 1 and 4, the lower beach face retreated 6 m and 7.2 m and the tidal flats were scoured by as much as 0.7 m (Table 6). During Hurricane Bob in August 1991, the thin cover of beach face gravel was rapidly combed downslope, exposing underlying back-barrier clay. Breaking waves cut small terraces in the clay (Fig. 7a) which were quickly reburied by beach gravel during post- storm waves.

Between June 1991 and May 1996 net changes across Scots Bay Beach were small (Fig. 12b; Tables 4 to 6). The greatest morphological changes were recorded across the upper beach and dune along the southern barrier (Fig. 12b). The dune at line 1 retreated 1.2 m exposing a line marker buried since 1986 and a relic dune surface (Fig.13b, c). The upper beach face had retreated by 4.4 m (Table 4), but there was evidence of renewed upper beach building just prior to the 1996 survey. Surface fluctuations across the lower beach face and tidal flat were similar to changes during earlier time periods (Table 5, 6, Fig. 12). By 1996 more than one metre of gravel washover covered the old marsh surface and wood support structures exposed at the back of the outlet in 1991. Elsewhere along the backshore, washover lobes extended several metres landward into the marsh creek.

By the next cross-shore surveys in 2004, large changes had occurred along Scots Bay Beach. The greatest change was observed across the upper beach and crest (Fig. 12c). Driftwood accumulations were broken up and either buried or floated into the back barrier marsh (Fig. 6b, c). The beach crest was lowered and migrated up to 17 m landward (Tables 4, Fig. 12c) and the upper beach face retreated by as much as 10.5 m exposing salt marsh clay and older driftwood (Fig. 14a). Backshore deposition was 0.4 – 0.5 m at lines 4 and 2 and at Line 4 a marker in the marsh was buried by 1.1 m (Fig. 14b). Along the southern beach driftwood accumulated at the base of the eroded dune, trapping sand and enhancing vegetation growth. At Line 1 the dune had been scoured and eroded back by 11.3 m and subsequently infilled by at least 0.6 m of sand seaward of the dune scarp (Fig.13d). Although the period spans 8 years, the changes are attributed to only a couple of storms, January 12, 1997 and possibly February 10, 2001 (Table 3).

In 2008 repetitive surveys were only completed at lines 1 and 2 (Fig. 2, 12c) and photos were taken at Line 4. The beach crest had built slightly seaward as more driftwood accumulated; the upper beach face had retreated slightly and fluctuations across the lower beach face were similar to the past (Tables 4, 5). In November 2015, no cross-shore surveys were completed but there was evidence of extensive wave overwash across Scots Bay Beach during a major storm at the end of October 2015 (Figs. 7b, 10a). Along the northern barrier there was a uniform washover edge and a transfer of driftwood into the marsh. Along the southern beach the lower crest, i.e. near Line 2, contained numerous scour pits caused by water flowing over the beach crest and driftwood (Fig.15b). Backshore deposition between 2004 and 2015 at the line marker on Line 2 was 0.4 m and greater where new washover lobes extended into the marsh channel. The landward penetration and extent of wave overwash across the backshore in 2015 decreased southward alongshore as the crest increased in elevation (Fig.10).

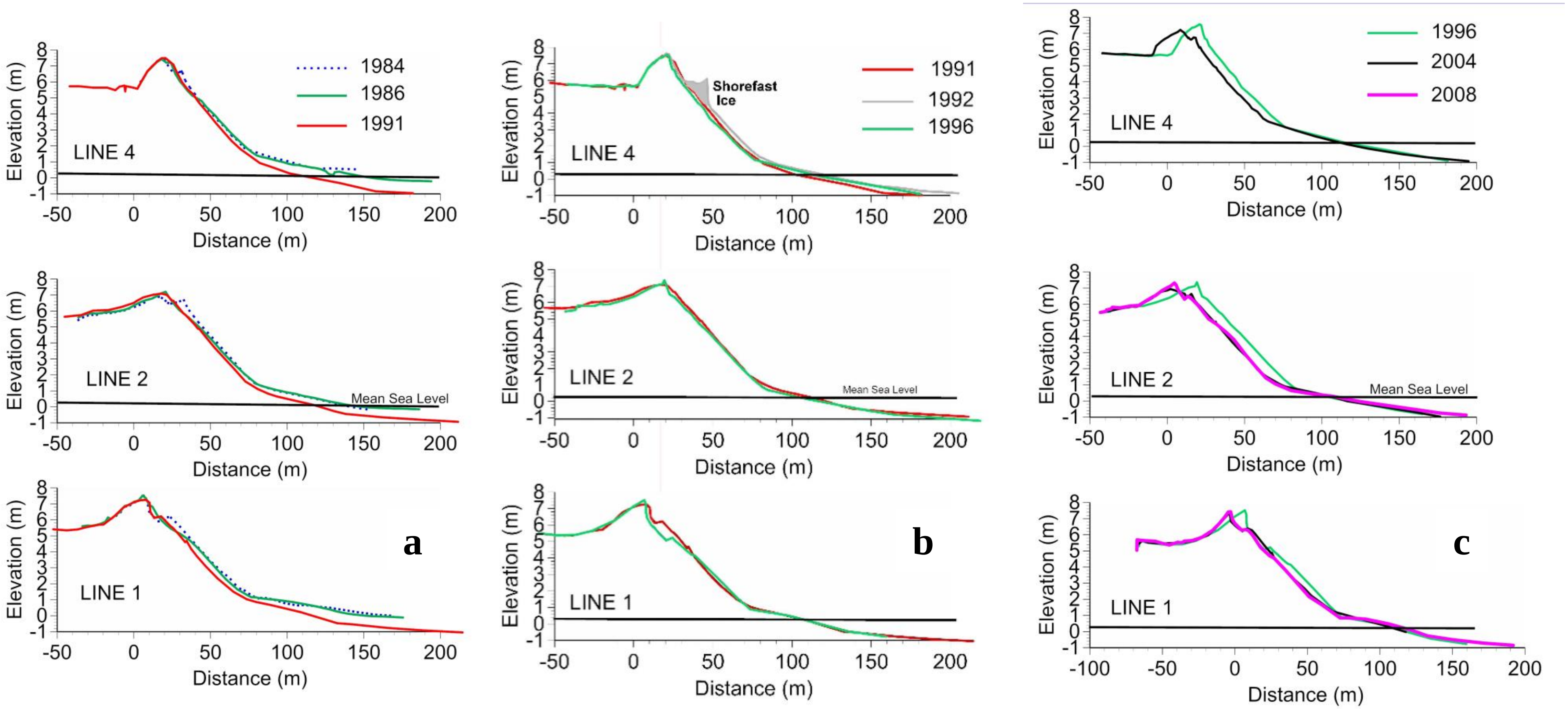


Figure 12. Repetitive cross-shore surveys from1984 to 2008 at three lines on Scots Bay Beach: (a) 1984–1991 (b) 1991–1996 and (c) 1996–2008. Scots Bay Beach experienced minor changes between 1984 and 1996 and significant landward migration between 1996 and 2004. Markers at line 4 could not be found in 2008 which prevented its survey. Physical changes at the other two lines between 2004 and 2008 were minor. Locations of the survey lines are shown on figure 2.

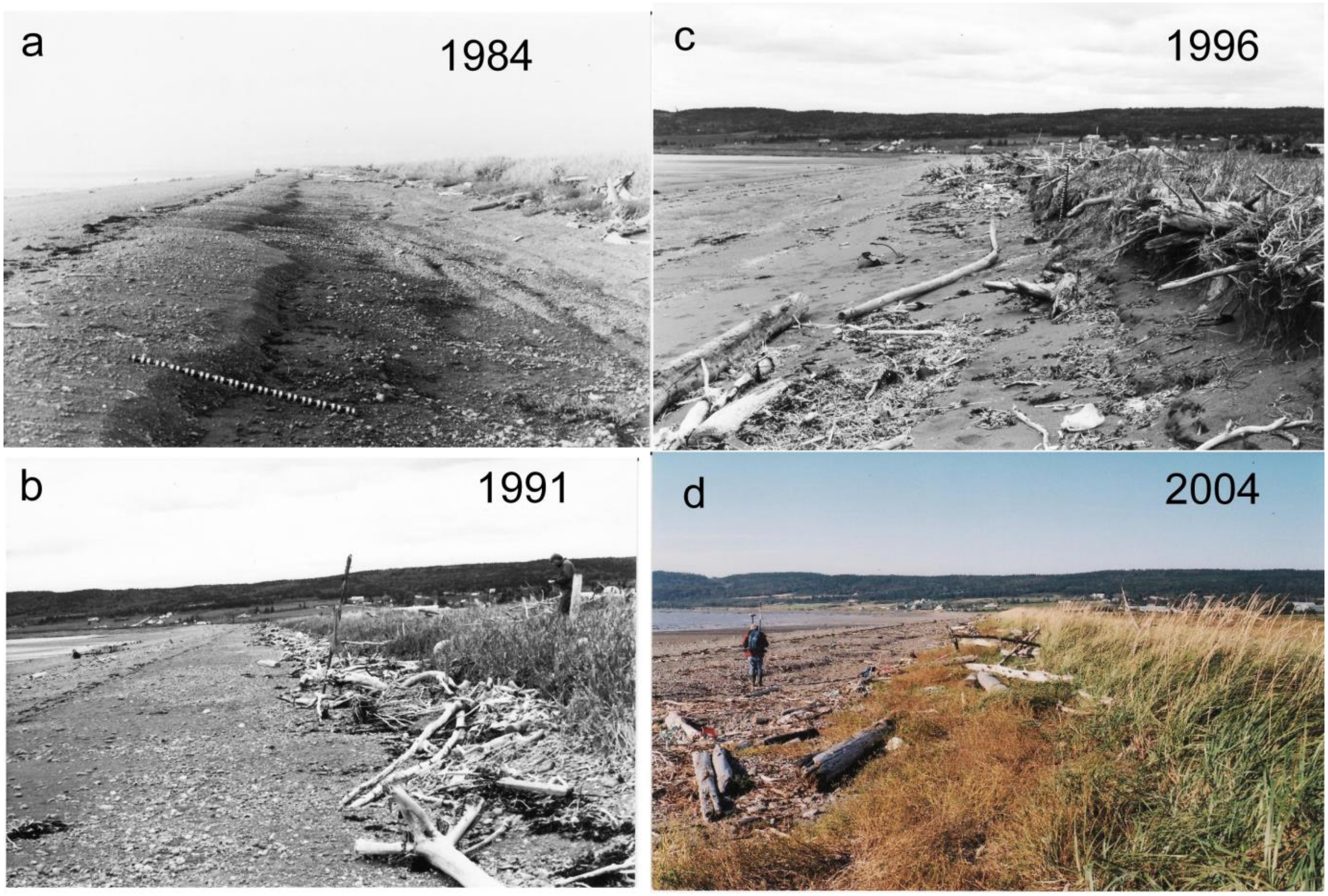


Figure 13. Repetitive photos from 1984 to 2004 of changes in dune and beach crest morphology at Line 1, Scots Bay. (a) In 1984 and (d) 2004 upper beach building is characterized by a well-defined swash ridge outlining a swale seaward of the dune; (b) 1991 illustrates the next stage in building as the swash ridge and driftwood accumulate against the dune; (c) 1996 illustrates intermittent dune erosion and (d) 2004 illustrates regrowth and recovery of dune vegetation and trapping of sediment by driftwood following a period of dune scouring. Figures 12a-c provide graphs of the beach changes.

Between 1984 and 2004 the net change in beach sediment volume, above mean sea level (0.3 m elevation) across three survey lines, varied from a loss of 65 m^3 to 100 m^3 (Fig.16). The greatest sediment losses were recorded across the tidal flats between 1986 and 1991, across the upper beach face between 1996 and 2004 (Tables 4 to 6). Sediment accretion was most across the backshore and salt marsh. A net loss of 23 m^3 to 36 m^3 was recorded across the beach crest and backshore which is roughly one third of the total net beach change. Although there are no repetitive surveys near the outlet, recent aerial photos of Scots Bay beach suggest that sediment is moving south extending the northern beach southward. Gravel clasts were also accumulating across the ebb shield at the outlet.

Photos taken in 1984 and 2015 (cover) looking northward alongshore at Line 4 illustrate the physical changes that occurred over the 31 years, including changes in the character and height of the beach crest and accumulation of driftwood across the backshore. Landward beach migration is better perceived when aligning the beach crest with the same buildings (arrows on cover photo) at the north end of the beach. The photos also illustrate increased wave attack at the shore cliff north of the beach where some armour rock was added by 2015.

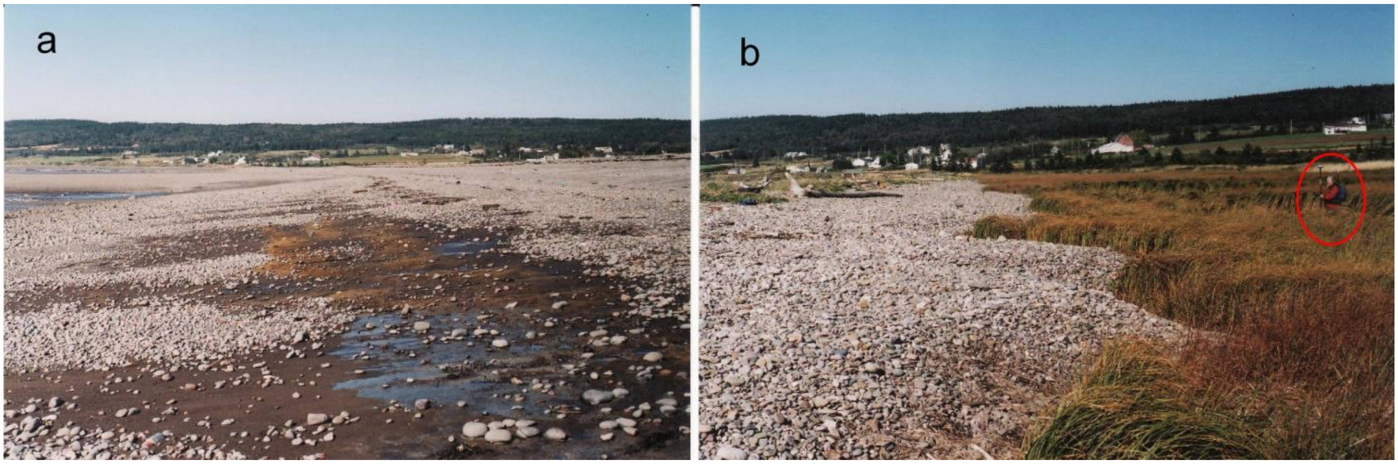


Figure 14. Natural recycling of beach sediment: Beach gravel eroded from the beach face is transported landward and deposited as washover lobes in the marsh or trapped in the ebb shield at the tidal outlet. (a) beach face scouring in 2004 and exposure of marsh between Line 2 (foreground) and the tidal outlet (background) and (b) marsh infilling at Line 4 where a line marker established in 1986 was buried by 1.1 m of sediment by 2004 (person circled for scale).

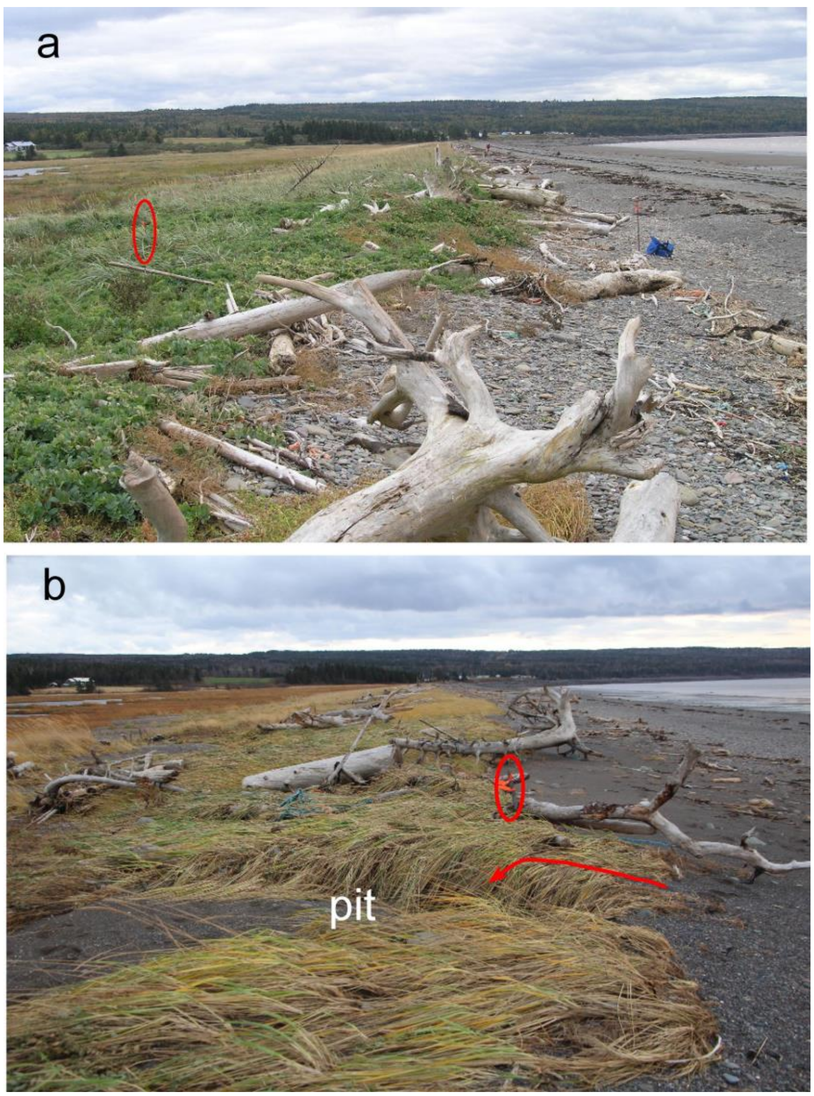


Figure 15. Between (a) 2008 and (b) 2015, the beach crest at Line 2 was cut back to the line marker (circled) a total distance of 4.5 m over the seven years. Much of the change is attributed to a storm on October 30, 2015, when waves overwashed (arrow) Scots Bay Beach scouring pits landward of driftwood deposited on the beach crest (b).

Table 4. Net positional changes at select points across three cross-shore survey lines (Fig. 2) at Scots Bay Beach, Nova Scotia. ("-"is landward retreat and "+" is seaward building in metres). The beach crest represents the highest point across a beach and the landward edge of washover is at the beach sediment / saltmarsh interface. Changes on the lower and upper beach face were measured at an elevation of 1.5 m and 5 m, respectively. The edge of washover shifted significantly seaward at Line 1 when backshore water levels increased and flooded the marsh vegetation.

Survey Period (years)	Beach Survey Line	Lower Beach Face (m)	Upper Beach Face (m)	Beach Crest (m)	Landward Edge Washover (m)
1984–86	1	-2.3	-2.5	-0.3	-0.6
	2	1.0	-3.1	5.2	0.6
	4	-6.3	-1.3	0.0	-0.1
1986–91	1	-5.7	-3.2	2.3	-1.1
	2	-7.3	-1.7	-2.8	-1.0
	4	-3.1	-0.2	2.5	0.5
1991–96	1	0.6	-1.0	-1.2	--
	2	1.3	0.0	1.2	-0.8
	4	1.0	-4.1	0.3	-0.6
1996–04	1	-3.6	-4.2	-11.0	-8.7*
	2	-9.9	-8.7	**-17.1**	-0.4
	4	-9.0	-7.1	-12.5	-6.0
Net Change 1984-2004 (m)	**1**	**-11.0**	**-10.9**	**-10.2**	**-10.4**
	2	**-14.9**	**-13.5**	**-13.5**	**-1.6**
	4	**-17.4**	**-12.7**	**-9.7**	**-6.2**
2004–08	1	-0.3	-7.2	-0.3	5.9
	2	-0.5	-4.5	2.5	-1.2
2008–15	1	----	----	-2.0	---
	2	----	---	-4.6	---
	4	----	---	-4.5	---

* landward overwash at L1 is from 1991 to 2004

Table 5. Temporal changes in the accumulation of tidal flat sand against the beach face. Oscillations in the distance sand extends upslope are relative to its 1984 position (- seaward , + landward). For example, at lines 1 and 4 sand built the farthest landward in 2004 but was not built as high upslope at Line 4 in 2004 compared with 1984. The most consistent sand build up recorded during the six surveys was observed at Line 1 where the maximum fluctuation was only ± 0.4 m.

Year	L1		L2		L4	
	Dist. (m)	Elev. (m).	Dist. (m)	Elev. (m).	Dist. (m)	Elev.(m)
Aug. 1984	0	1.06	0	1.47	0	1.90
Dec. 1986	+ 4	1.16	- 7	1.23	- 6	1.59
June 1991	- 9	0.86	- 14	0.65	- 8	1.28
May 1996	+ 5	0.85	- 3	0.85	- 5	1.17
Oct. 2004	+13	1.25	+ 10	1.20	+ 9	1.72
Oct. 2008	+ 8	0.85	+ 10	1.05	nd	nd
Range 1984-2008		**±0.40**		**±0.82**		**±0.73**

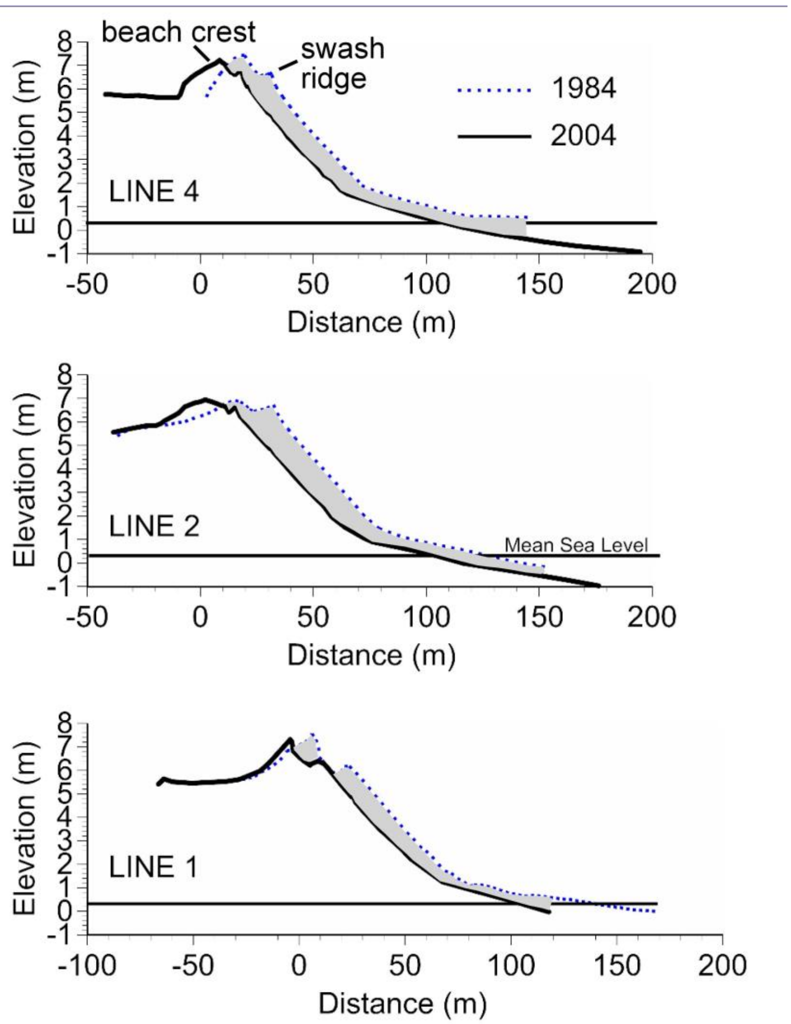


Figure 16. Net beach retreat (grey areas) surveyed across the three beach survey lines between 1984 and 2004. The intertidal flat was scoured by 0.3 to 0.7 m; the beach face migrated landward 17 to 18 m; the beach crest at Line 2 migrated nearly11 m and washover lobes were extended landward nearly 12 m into the back barrier marsh at Line 4. Despite the backshore extension, there was a minor net loss in sediment volume across the beach crest and backshore during the twenty years.

Table 6. Surface elevations (geodetic) at select locations across the intertidal flats of three cross-shore survey lines at Scots Bay, N.S.

Line	**Year**	**Distance across the intertidal flat (m)**									
1		**103**	**108**	**119**	**132**	**139**	**159**	**164**			
	1984	0.70				0.32					
	1986	0.86	0.79	0.57	0.29	0.13	-0.04	-0.05			
	1991		0.23		-0.46			-0.76			
	1996	0.52			-0.44	-0.44	-0.77				
	2004	0.37		-0.03							
	2008		0.47	0.08	-0.26						
	1986–04	**-0.49**	**-0.56#**	**-0.60**	**-0.75#**		**-0.73#**	**-0.71#**			
	1986–08		**- 0.32**	**-0.49**	**-0.55**	**# 1986 –1991**					
Line	**year**	**Distance across the intertidal flat (m)**									
2		**118**	**138**	**142**	**165**	**175**	**211**	**263**	**318**	**394**	**415**
	1986	0.55	0.14	0.08	-0.09	-0.11					
	1991	0.12	-0.44		-0.66		-0.93	-1.22	-1.51	-1.88	-1.98
	1996				-0.81		-1.18	-1.39	-1.65	-2.01	-2.14
	2004	-0.01	-0.4	-0.4	-0.73	-0.96					
	2008			-0.34		-0.74					
	1986–04	**-0.56**	**-0.54**	**-0.48**	**-0.64**	**-0.85**	**-0.25***	**-0.17***	**-0.14***	**-0.13***	**-0.16***
	1986–08			**-0.42**		**-0.63**	***1991–1996**				
Line	**Year**	**Distance across the intertidal flat (m)**									
		82	**101**	**134**	**167**	**180**	**182**	**194**	**214**	**281**	
4	1986	1.32	0.82	0.39	-0.13	-0.18	-0.19	-0.22			
	1991	0.93	0.27	-0.32	-0.51	-0.70	-0.96	-0.79	-1.14	-1.46	
	1996	1.17	0.20		-0.67	-0.89	-0.90	-0.92			
	2004	0.97		-0.14	-0.67			-0.92	-1.04	-1.47	
	1986–04	**-0.35**	**-0.62****	**-0.53**	**-0.54**	**-0.71****	**-0.71****	**-0.70**	**0.10***	**-0.01**	
**** 1986 –1996 * 1991–2004**											

Table 7. Crest elevation (geodetic) along Scots Bay Beach based on surveys at three lines (L1, L2, L4) between 1984 and 2004. Figure 2 shows the location of survey lines.

Year	Crest Elevation (m)		
	L1	L2	L4
1984	7.6	6.9	7.4
1986	7.5	7.2	7.4
1991	7.3	7.1	7.5
1996	7.5	7.4	7.6
2004	7.3	6.9	7.2
2008	7.4	7.3	----
(net change 1984–2008)	-0.2	0.4	- 0.2*

*Net change at L4 only between 1984 and 2004

Scots Bay Shore Dynamics and Sedimentology

Forbes and Taylor (1987) described seven distinct sedimentary facies across Scots Bay Beach. Each facies or zone was defined by changes in beach slope and texture (Figs. 17, 18). In this study the seven zones are used but their names and descriptions have been updated. The facies include: (Z1) lower tidal flat - sandy mud, isolated boulders; (Z2) upper tidal flat-sand over cobble boulder; (Z3) middle beach face -cobble-boulder lag over clay; (Z4) upper beach face -sandy gravel (Z5) barrier crest / terrace-sandy gravel, driftwood; (Z6) backbarrier dune-sand, driftwood / washover-gravel; (Z7) salt-marsh- clay, peat, driftwood. Between facies 2 and 3 a distinct break in slope exists which lies at or near mean sea level (Fig. 17; Tables 4, 8). Forbes and Taylor (1987) speculated that the extensive tidal flat may reflect the near absence of an estuarine sediment sink, fine sediment remains on the lower shoreface while the coarser material is transported onto the upper beach. The latter forms a veneer over backbarrier salt marsh peat and mud which are exposed at the base of zones 3 and 4.

Each of the beach zones are described below and are used as a framework for discussing the cross-shore changes observed at Scots Bay from1984 to 2008. The primary cross-beach framework includes: tidal flat, beach face, beach crest, back barrier slope and salt marsh.

Z1) Tidal Flat -Lower: extends from low tide to within 150 to 200 m of the steeper beach face. This zone has a low gradient (Fig.17, Table 8), featureless, wet surface which consists of a soupy mud, 3–4 cm thick, over firm sand. The surface firmness varies with tidal stage and exposure of the sand substrate (Fig. 18a). Repetitive surveys of the lower tidal flat, across two lines, indicate that vertical surface fluctuations can be ± 0.05 to 0.18 m with the largest change occurring closer inshore. The largest net loss in sediment thickness was 0.70–0.85 m within a swath stretching from 175–195 m from the beach at line 2 and 4 (Table 6). Vertical air photos (Fig. 19a) show a fine, closely-spaced network of drainage channels crossing the flats as well as 5 to 6 larger more incised drainage channels extending seaward from stream outlets to at least low tide level. The fine parallel pattern of channels is not easily identified on the ground whereas the larger channels are more visible (Fig. 19b).

Table 8. Cross-shore Zones and Sedimentary structure at Scots Bay Beach, Nova Scotia. Cross-shore zones are illustrated in Figure 17 and typical surface features in different zones are shown in Figs. 19 – 22.

Cross-shore Zone (Facies)	Slope*	#Width (m)	Structure / Texture
Z1 Tidal flat -Lower	- 0.01	28–129	Sandy mud with isolated boulders
Z2 Tidal flat- Upper	-0.02 / - 0.03	34–150	Rillwash, ripple cross-bedded sand over cobble, boulder gravel, over stiff grey clay
Z3 Beach face-lower to mid	-0.07 / - 0.10	14–22	Weakly imbricated cobble-boulder and /or sand over stiff grey clay and peat
Z4 Beach face –mid to upper	-0.10 / - 0.12	15–26	Crudely stratified sand-pebble over grey clay, peat and driftwood
Z5 Beach Crest	-0.05 / 0.06	2–8	Crude parallel stratified pebble gravel over sand-pebble gravel, driftwood
Z6 Backbarrier -washover	0.05 / 0.26	8–14	Landward dipping sand-pebble gravel over clay, woody peat
Z7 Saltmarsh	0.00 / 0.02	16–34	Woody peat, grey clay, driftwood

*****From 2004 survey, expressed as tangent of slope angle, positive landward, negative seaward; minimum and maximum values. #Width of shore included in slope measurements.

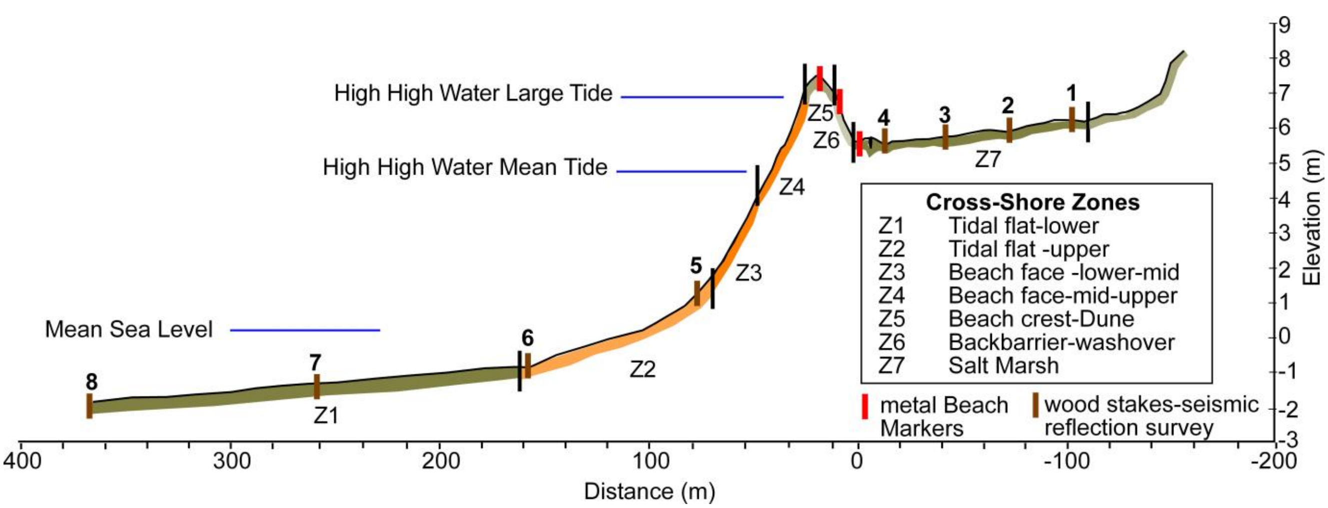


Figure 17. Sedimentary facies and cross-shore zones identified across Scots Bay Beach (Forbes and Taylor, 1987). Each facies or zone was defined by changes in beach slope and texture. The zones include: (Z1) lower tidal flat; (Z2) upper tidal flat; (Z3) mid to lower beach face; (Z4) mid to upper beach face (Z5) barrier crest/ terrace ; (Z6) backbarrier dune/ washover and (Z7) salt-marsh. The location of reference stakes mentioned in the text are plotted here and on figure 2b. Sample photos from each zone are illustrated in figures 18 to 22.

Water was observed bubbling up from the substrate at a few places, e.g. at wood stake 7 (Fig. 2b, 17). Suspended sediment is commonly observed within the water column above this zone as it becomes flooded and reworked by waves.

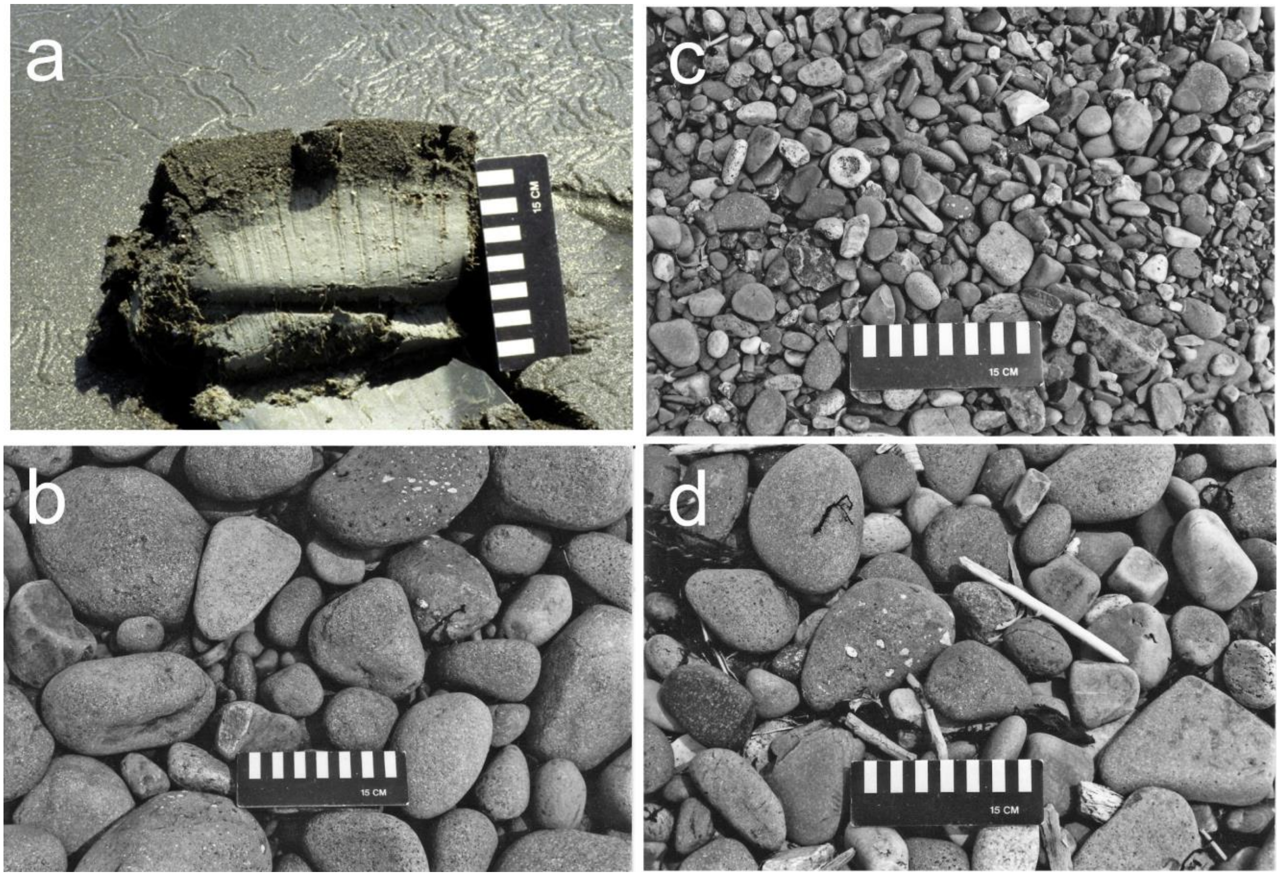


Figure 18. Scots Bay Beach sediment composition varies from: (a) a variable thickness of reduced sand (dark) with animal tracks on surface over grey clay across the tidal flat –zone 1 and 2. (b) moderately well rounded cobble in zone 3 ; (c) well sorted, fine to medium pebbles in the swash ridges - zone 4 and (d) moderately rounded medium pebble clasts at the beach crest- zone 5. The sediment photos are from Line 4, June 1991.

Z2) Tidal Flat –upper: marks an increase in slope (Table 8), a coarser composition, the presence of better defined bedforms and a thicker mobile bed. The landward edge of the zone is marked by a sharp increase in slope at the beach face and the presence of a cobble boulder frame (Fig. 17, 19c, 20a). The surface is criss-crossed by a network of drainage channels with a parallel to dendritic pattern formed by water flowing seaward during low tide from the beach, the tidal outlets and a few streams (Fig. 19a). The drainage channels are better defined south of the outlet where the salt marsh is wider and the tidal creeks within the marsh are larger. In 1967 there was a nesting of drainage channels within 50–80 m of the beach face (Fig. 19a). The larger drainage networks were spaced 77–108 m alongshore (Fig. 19b). Channel incision increased as the sand aggraded against the beach face. Channels extending parallel to shore were also observed. One such channel located off line 4 in 1986 was 6 m across and 0.2 m deep. Low relief sandbars often developed alongshore between the shore normal drainage channels (Fig. 19c). Bars surveyed off lines 1 and 2 were 28–41 m wide and had a relief of 0.7 to 1.0 m. The landward edge of sand reached a maximum elevation of 1.9 m at line 4 and in most years was least along the southern beach at line 1 (Table 5). However, sand accumulation was most consistent at line 1 and least at lines 2 and 4 where it oscillated by as much as 0.82 m in elevation (Table 5). The tidal flat surface at Line 1 was scoured by as much as 0.73 m between 1986 and 1991 (Table 6, Fig.16). The highest sand accumulated against the beach face was observed in August 1984 and October 2004; the lowest in May 1996 (Table 5, Fig. 12a, c). It is not known to what extent these variations reflect seasonal change versus specific wave conditions. The sand sampled in the upper 0.2 m of the upper sandflat at Line 2 was a poorly sorted, medium sand (Table 2- Sample 2440). Reworking by waves produces a firm, rippled sand surface which in some cases is only a few centimetres thick overlying mud. In winter during cold periods the exposed sand becomes frozen at low tide, e.g. March 1992.

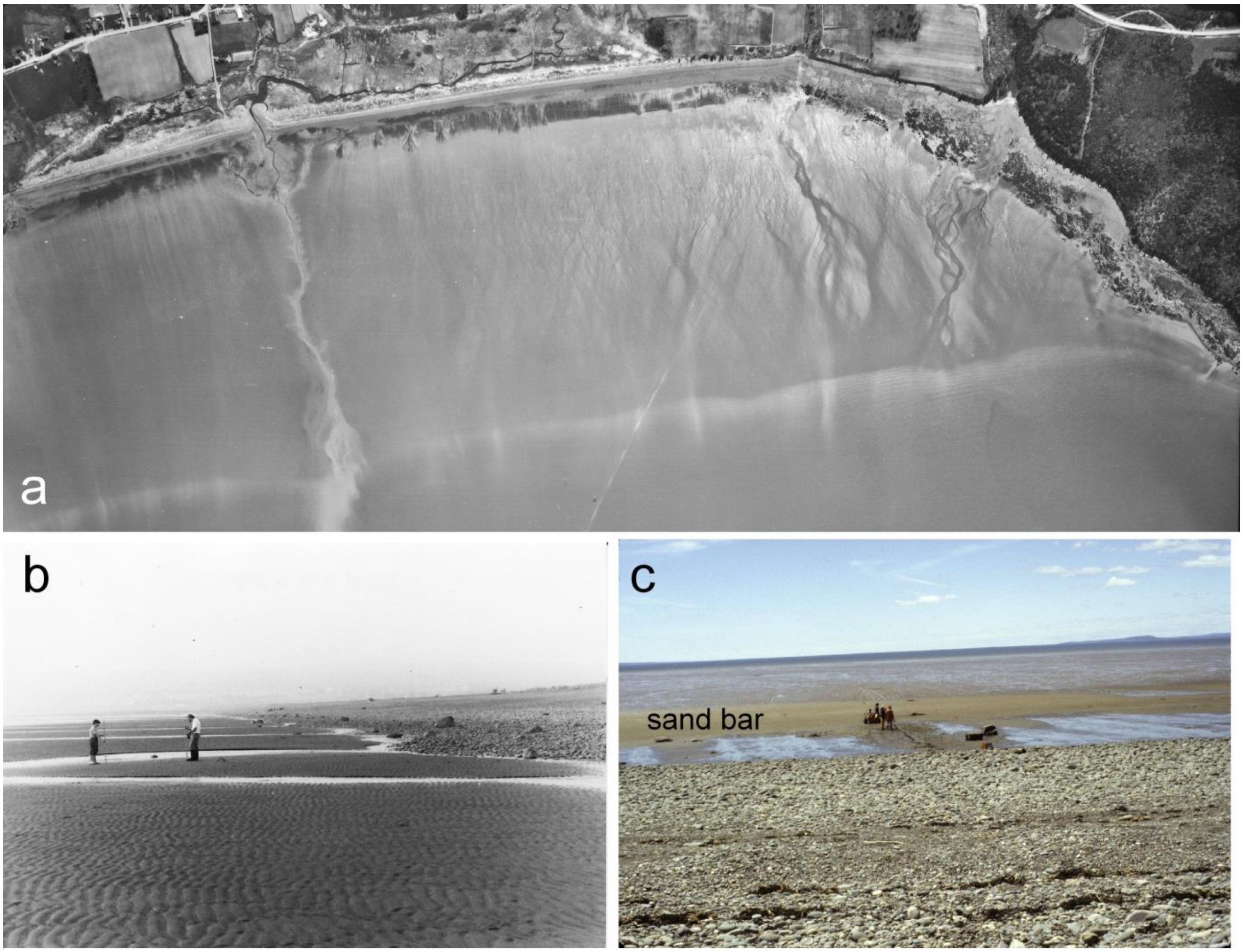


Figure 19 (a) Aerial view of the network of drainage channels crossing the tidal flats at Scots Bay Beach, 14 June 1967. b) In August 1984 when more sand accumulated across the upper tidal flat the drainage channels were better defined; c) view of the tidal flat and sand bar developed at line 4 in June 1991 at the time of the seismic reflection survey.

Z3) Beach Face-mid to lower: has a sharp increase in slope (Table 8) and consists of a poorly consolidated cobble-boulder frame, one to two clasts thick (less than 0.3 m thick) overlying stiff, organic rich, grey, saltmarsh clay. The zone was less than 20 m wide at line 4 and 21 to 34 m at lines 1 and 2. The concentration of cobble clasts across the mid to lower beach face and boundaries of this zone were variable from year to year as a function of wave conditions. The smooth slippery surface of the clay substrate facilitates the movement of the larger surface clasts and enhances wave backwash velocity. The zone marks the location of water seepage from the beach. The seaward edge of cobbles can become buried by sand as the sandflat aggrades and the landward edge merges with sand and gravel moving up and down slope in zone 4 (Fig. 19b). Scattered large boulders are observed along this zone and the upper tidal flat. Despite the coarseness of the sediment, the lower beach face retreated landward 11 to 17.4 m between 1984 and 2004 (Table 4, Fig.16).

Z4) Beach Face-mid to upper: is a transition zone with a slightly steeper slope than the lower beach face (Fig. 17, Table 8). This zone is only reworked for short periods during each tidal cycle. Small swash ridges are initiated in this zone and transferred upslope to the upper tidal limit and barrier crest where they become stranded as the tide recedes. This zone is characterized by a rhythmic shore normal "ribbed "(washboard) morphology developed by the motion of swash and backwash (Fig. 20b). The extent of the ribbed morphology varies with wave conditions. It can be a multiple series of short ribs one above the other or a single more elongated set. The ribs become less well defined downslope toward zone 3. The thickness of the mobile sand and gravel is limited by the underlying clay which becomes increasing buried (> 0.4 m) upslope. The salt marsh is more exposed at the beach surface along lines 4 and 2 than at line 1 (Fig. 14a). Larger waves generated during storms removed the surface sand and gravel and cut terraces into the clay substrate (Fig. 7a). The zone is also an area of water seepage through the barrier. Sediment is a very poorly sorted, sand to granule mean size (Table 2, samples 2438, 2439). The sediment coarsens upslope to the beach crest and becomes better sorted by wave action.

During very cold times of the year the upper portion of this zone is covered by shorefast ice which protects it from wave reworking (Figs. 8a, 12b). Between 1984 and 2004 beach retreat at HHTL varied from 10.9 to 13.5 m, most at Line 2 and least at line 1 (Table 4, Fig.16).

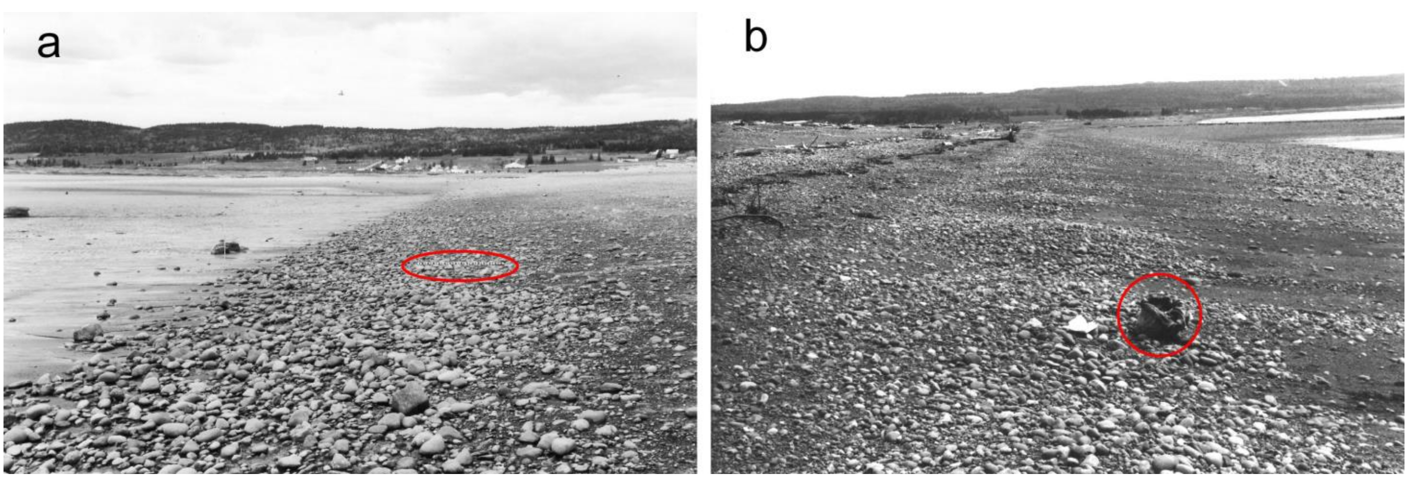


Figure 20. Beach face composition and morphology at Scots Bay Beach: a) cobble-boulder clasts overlie a clay substrate along the lower beach face (1.5m – long staff circled for scale) and b) a rhythmic shore normal washboard morphology often develops across the mid to upper beach face (field pack circled for scale).

Beach Face - at and just above high tide level: is a zone of swash ridge development which could be included in either zone 4 or 5. Swash ridges are initiated in zone 4 but develop into longer lasting physical features closer to high tide level. Waves rework this zone for longer periods than the lower part of zone 4. Multiple swash ridges develop as the tides decrease and larger single ridges develop as the tide increases during each tidal cycle. During storm events, waves can either truncate the larger swash ridges and comb sediment downslope or push the ridge farther upslope and weld it against the beach crest. Three types of upper beach face morphology are observed at Scots Bay: a ridge and swale, convex (i.e. building) and concave (i.e. erosional) slope. Swash ridges have a sedimentary facies which resembles the barrier crest with near horizontal stratified to landward dipping laminae on their backslope. Sample 2441 (Table 2) collected from a swash ridge on line 2 consisted of a moderately sorted open work pebble with a mean size of 7.78 mm.

Repetitive photos from line 1 (Fig. 13) illustrate the different morphologies resulting from changing wave dynamics. Where sand is abundant, a sand ramp may build against the barrier crest. A larger swash ridge and swale can protect the barrier crest from direct wave attack and allow the crest to revegetate and begin to rebuild by aeolian processes (Fig.13d).

Z5) Beach Crest-gravel ridge: is the highest part of a beach which can slope gradually landward or seaward (Fig. 17, Table 8). It is a zone of sediment and driftwood deposition and is only reworked by waves during larger storms or times of extreme high water levels. The crest may be partially to well vegetated depending upon the cover of sand or granule versus pebble cobble clasts. Sample 2442 (Table 2) from the crest at line 2 was a moderately well sorted pebble with a mean size of 18.63 mm. If stable or in a building phase, such as the early 1980s and 1990s, the barrier crest is wider and more symmetrical (Fig. 6b, c, 12). During an erosional phase, such as the late 1990s, the crest has a more assymetrical shape. Tables 4 and 7 document the horizontal and vertical fluctuations in the barrier crest at the three survey lines. In 1996 an undulating beach crest was surveyed between Lines 4 and 1 (Fig. 21). The highest crest varied from 6.9 to 7.7 m in elevation at a longshore spacing of 310 to 320 m. Additional longshore crest surveys would be required to determine the permanency of this rhythmic crest morphology. The lowest crest was between line 2 and line 1 (Fig. 21b) whereas a higher and similar crest elevation existed at lines 1 (with a sand dune) and 4 (without a dune). The lower crest elevation at line 2 explains the higher frequency of wave overwash at that location. Despite the similar elevation at the other two lines, wave overwash was least at Line 1 because of a thicker vegetation cover. Thickness of beach deposits over the marsh ranged from 2.1 to 3.2 m.

Z5) Beach Crest-Sand Dune: a low, single crested sand dune caps the southern end the beach (Fig. 6a). Repetitive surveys illustrate how the dune may alternatively grow and retreat. The magnitude of retreat and growth is less than along the gravel crest (Figs. 12, 16, Tables 4, 7). Driftwood played an important role in the trapping of sand and the growth of dunes during 1986 to 1991. The driftwood becomes recycled as the dune retreats and driftwood accumulation can facilitate sedimentation and repair along the seaward face of the dune (Fig.13d). For example, between 2004 and 2015 dune sedimentation landward was less by 0.3 m to 0.2 m from where driftwood existed on the dune. During periods of higher energy waves, the wood can become an agent of scouring. Longer term cycles of dune growth and decay are visible on decadal aerial photography. The dunes were more continuous, wider and more stable in 1945, 1977 and 1980s than in 1954, 1967 and late 1990s to 2004. Potential sources of sand are at both ends of the beach, the tidal flat and the beach itself. Dunes exist along the southern beach yet, based on line surveys, sand builds to its highest elevation against the northern beach. However sand reaches a more consistent elevation from year to year at the base of the southern barrier which may promote sand transport upslope.

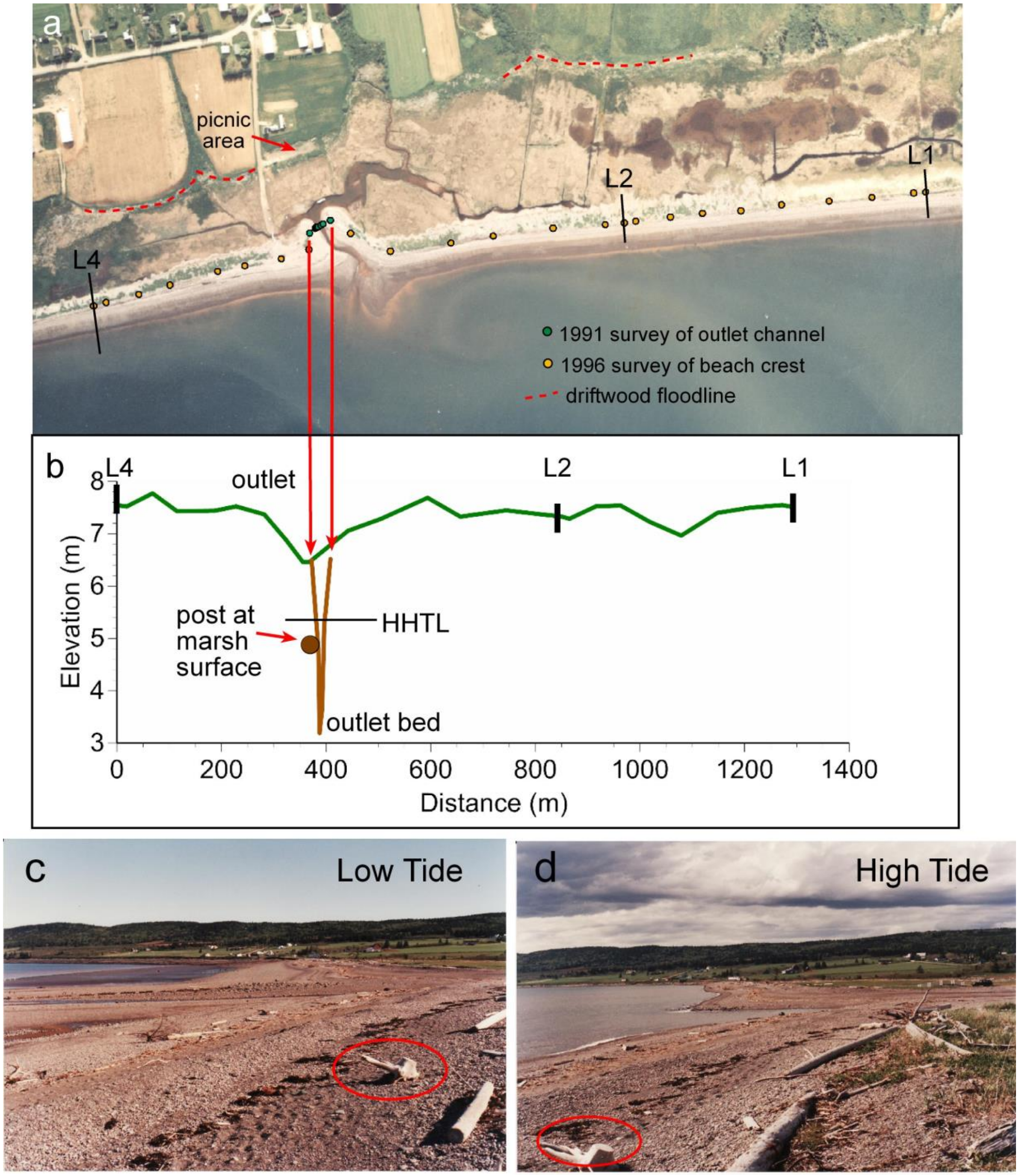
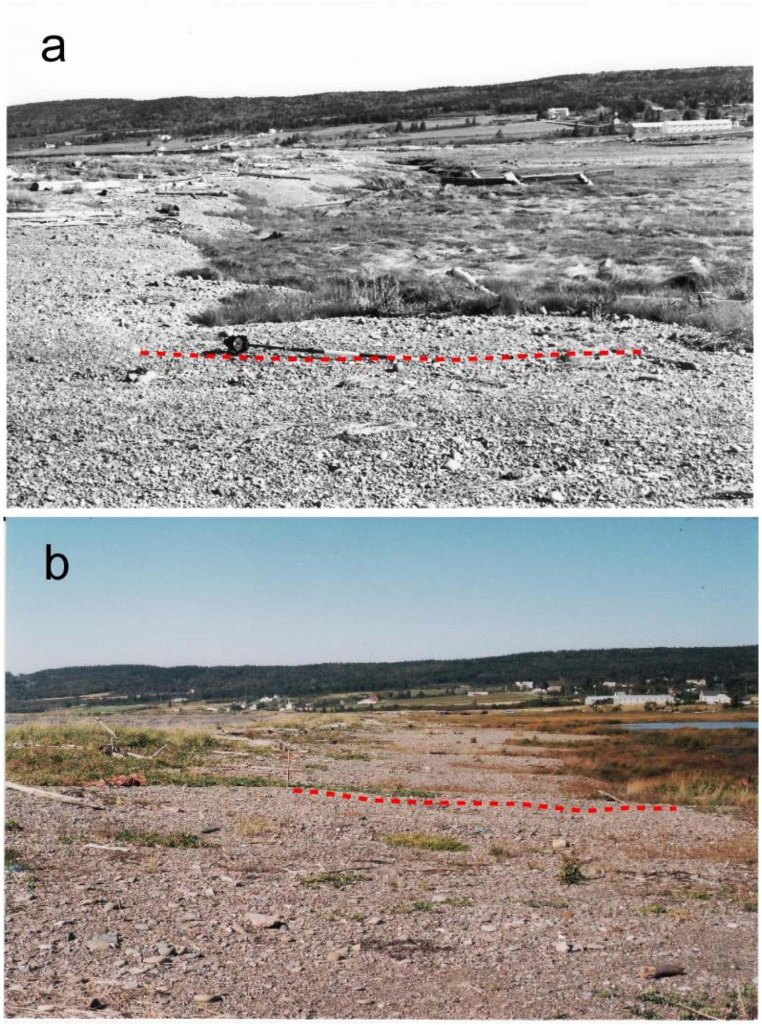


Figure 21. (a) Aerial view in 1987 of the marsh, outlet and beach at Scots Bay showing the location of survey points (dots) and (b) longshore profile of a rhythmic beach crest surveyed from Line 4 to Line 1 and a profile of the outlet channel. The outlet has infilled with sediment since the breakdown of the wharves that existed on either side of it. The outlet bed lies nearly 3 m above mean sea level. Views on 6 June 1991 of the outlet at low tide (c) and high tide (d), The southern barrier is only accessible from north beach at low tide.



Z6) Backbarrier- washover deposits; have a slightly landward slope and often a steep slip face where they flow into the marsh or marsh channel (Fig. 17, Table 8). The backbarrier can have a sharp landward boundary against the salt marsh such as at Line 4 where a high, steep slipface is observed (Fig.14b) or a more gradual slope such as at line 2 where washover deposits slope more gradually over the saltmarsh (Fig. 22b). The extent of washover deposits is a function of barrier crest elevation and stage of its evolution. For example, the barrier crest at line 4 is higher and more narrow than at line 2. At line 1 the back barrier slope aggrades and steepens as the dune is cut back and sand is released and blown onto the backshore and trapped by vegetation. Washover deposits form the foundation for additional landward transfers of sediment during large storm events. These deposits consist of fairly homogeneous clasts, with decreasing sediment size at depth.

Figure 22. Landward beach migration over top of the marsh. Wave overwash occurs as episodic thrusts along different sections of the barrier beach causing localised infill of the marsh. For example, prior to 1991 (a) washover lobes had already extended the backshore at line 2 (dashed line); therefore by 2004 subsequent infilling of the marsh was concentrated north of (i.e. above) line 2 where the backbeach was narrower (b).

Z7) Salt Marsh: the marsh surface at Line 4 varied in elevation from 5.6 m at the beach /marsh interface to 6.2 m at its landward edge. The marsh at Scots Bay is 100 to 200 m wide narrowing toward the ends of the barrier beach (Fig. 2). The marsh is drained by channels from the north and south which join at the tidal outlet which flows seaward through the barrier beach. South of the outlet, the drainage channel has been buried by wave overwash deposits as the beach migrated landward (Fig. 11b, c). In a comparison of air photos taken in 1945 and 1977 Wedler (pers. com. 1984) noted a decline of the high marsh species *Spartina patens* and its replacement by *Spartina alterniflora*. He suggested salt marsh aggradation is not keeping pace with rising sea level which implied little or no sedimentation which differs from our observations. Minor marsh building by aeolian deposits was observed at Line 1. Less sediment aggradation was observed at lines 2 and 4 where the surface was wetter and more hummocky. There is an abundance of driftwood fragments and logs within and particularly along the landward edge of the saltmarsh (Fig. 2, 21a). In winter the salt marsh surface is frozen and snow covered with increasing abundance of rafted ice floes along the main channels closer to the tidal outlet (Fig. 8b).

Tidal Outlet
In the past, the location of the "stream", as it was locally known, was controlled by a set of wharves on each side of the channel and by other infrastructure related to a shipyard. At present only a few support posts of the wharves remain buried in the beach. In 1991 the opening cut through Scots Bay Beach was only 35 m wide (Fig. 21a, b). The tidal channel tapered from 10 m wide at HHTL to 5 m near its base which lies nearly 3 m above mean sea level. At low tide, it is possible to walk across the narrow flow of water to the south barrier beach but at high tide the outlet is filled with water (Fig. 21c, d) prohibiting access to the southern barrier beach.

Stratigraphy

A complex coastal stratigraphy is revealed beneath Scots Bay Beach by high resolution seismic reflection and refraction surveys and coring of the upper sedimentary sequences. In 1991 a seismic reflection survey was completed at Line 4 landward of the marsh to 200 m seaward of the beach face (Figs. 2b, 23). Two parallel, high amplitude reflectors, interpreted as bedrock (red line), dipped westward to at least a depth of 19 m beneath the sandflat surface. A shallower reflector existed below the sandflat. The reflector began 40 m from the base of the beach face (stake 5 -Figs. 2b, and Fig. 17) and extended at least 70 m seaward and possibly farther. The reflector marked the top of an intermediate velocity (1700-2000 m/s) deposit, possibly glacial outwash or diamicton. Results from the seismic refraction surveys landward of the salt marsh, indicated that about 18 m of lower velocity (p-wave velocity of 2700 m/s) material interpreted as glaciofluvial or raised beach deposits overlie higher velocity (6750 m/s) bedrock (Fig. 24). The difference in velocity between the upper (glacialfluvial) unit onshore and the upper unit beneath the sandflat, suggests that they are composed of different material. No bedrock was identified beneath the salt marsh because of the rapid attenuation of seismic energy by the silty peat and stiff clay.

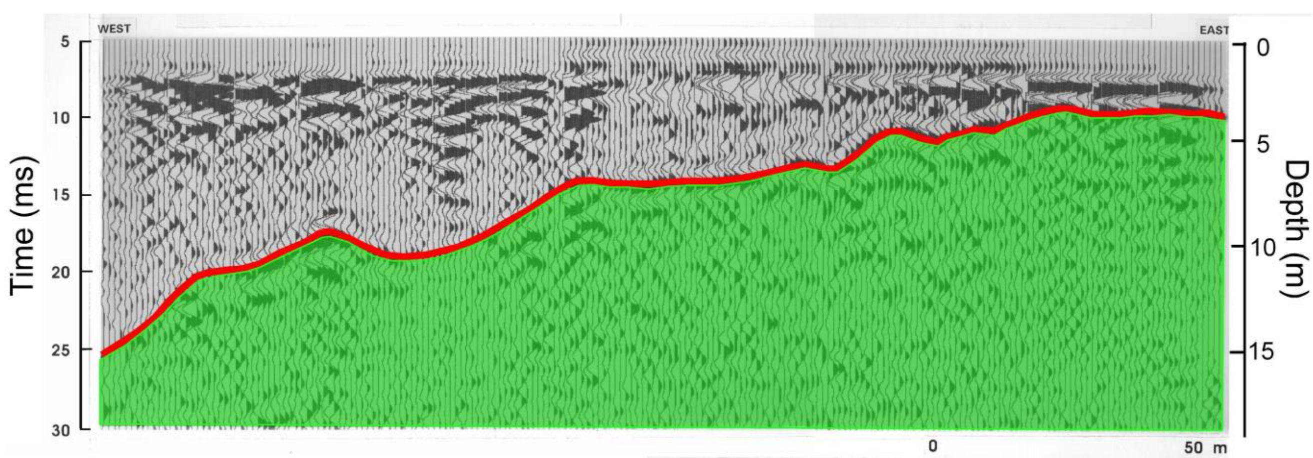


Figure 23. Single channel seismic reflection profile across the intertidal sandflat at survey line 4, Scots Bay. Material with a P-wave velocity of 1700-2000 m/s (grey) overlies a layer with a velocity of 5600 m/s (green). The former velocity is typical of unconsolidated material. The latter velocity is consistent with the basalt bedrock underlying Scots Bay. The interface between the two units (red line) has an apparent dip of 3° west. Depth (m) was calculated assuming a travel time of 1500 m/s.

Saltmarsh stratigraphy is drawn from 3 boreholes 5, 6, 7 (Fig. 24) obtained using a soil auger and Hiller borer. Cores show an inter-fingering muddy and woody peat with a grey clay. At least 4.5 m of silty peat overlies the grey clay which is also exposed at the base of the beach face. Maximum coring penetration was 8.8 m (-3.2 m geodetic) landward of the barrier beach. Farther landward coring was limited to less than 4 m by the presence of driftwood. At Amherst Point, at the head of the Bay of Fundy, Shaw and Ceman (1999) observed a similar salt marsh aggradation of 7.5 m since 900 BC (2.9 ka) which had a mean growth rate of 25.9 cm per 100 years.

In August 1988, a 1.9 m long vibracore88-1 (borehole 4- Fig. 24, 25) was collected at the upper tidal flat. It consisted of 0.4 m of a well sorted medium-coarse sand, granules and shell debris over a truncated deposit of stiff, fibrous olive, grey clay. The clay with woody material extended to a depth of 1.7 m. Granules and subrounded pebble clasts increased in abundance toward the base of this unit. Also, a thin bed (2 cm) of angular granules with a couple of pebble clasts were incorporated in the clay at 0.4 m depth. The base of the core consisted of a darker gravelly sand in a matrix of clay with pebble clasts up to 36 mm A-axis. The basal unit resembled a glacial diamicton. Organic carbon content of a subsample from the basal unit was 1.73% . (W. Leblanc, 1991, pers. comm.).

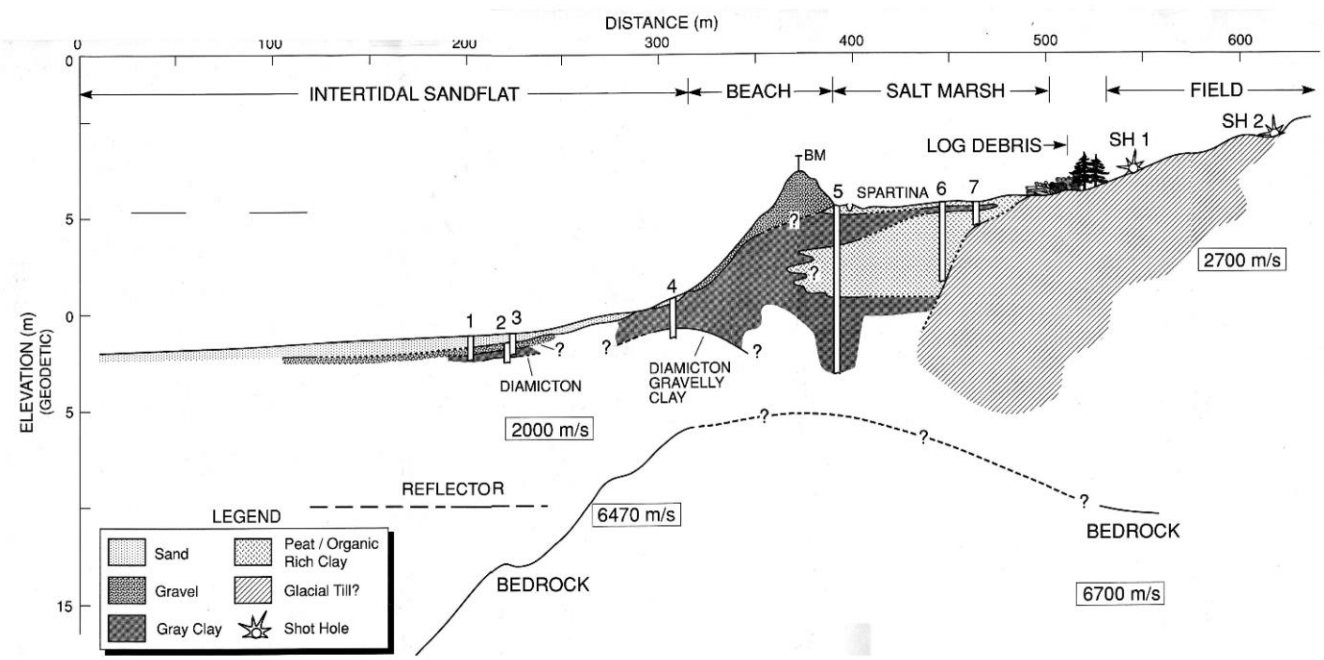


Figure 24. Stratigraphy of Scots Bay beach based on seismic reflection surveys and cores 5, 6, 7 obtained with a Hiller corer in the marsh and cores 1 to 4 (Scots 88-1 and 92302-01 to -03) from the intertidal flat using a vibrocorer. Cores collected from the upper intertidal zone are are shown in Figure 25. The beach presently exists along a bedrock high. The reflector below the sandflat marked the top of an intermediate velocity (1700-2000 m/s) deposit, possibly glacial outwash or diamicton.

Farther seaward across the upper tidal flat, a brown sand layer with scattered boulders over a stiff, grey clay was encountered during drilling with a 1 m long Stihl auger. Within a distance of 32 m from the beach face, a layer of reduced sand with pieces of wood and organics existed below the brown sand. The clay bed was very resistant to initial penetration by the auger but after a short time the clay liquefied allowing deeper penetration. At a distance of 35 to 50 m from the beach face there was considerable upwelling of water across the exposed tidal flat.

In a second attempt to core the tidal flat, the vibracorer was stopped within 1.4 m below the surface. Cores 92302-01 to 92302-03 were collected at 85 and 107 m seaward of stake 5 at the base of the beach face, line 4 (boreholes 1-3, fig 24, 25). Cores 92302-01 and -02 were drilled at the same hole and were combined to illustrate the stratigraphy (Figs. 2b, 24, 25d). The cores consisted of an upper layer (0.6 to 0.9 m) of well sorted, wave reworked sand, which became interlaminated with silty clay beds farther seaward. The sand overlay a bed of well-rounded polished granules, pebbles and coarse sand which lay unconformably on a truncated surface of stiff, fibrous, grey clay. The remaining clay was only 0.5 m thick and was thinning seaward between the two cores. The base of clay decreased in elevation from -2.1 to -2.2 m in cores 92302-02 and 92302-03 respectively. Toward the base of the clay scattered pebble clasts appeared as well as thin seams of grey silt and fine sand. The clay overlay an olive grey coloured, poorly sorted, pebbly sandy clay, with angular clasts which resembled a glacial diamict at 1.2-1.3 m depth (Fig. 25d). The upper seismic reflector may represent the glacial diamicton.

A sample of wood at 0.85 m depth within the stiff clay in core 92-302 (Fig. 25d) was submitted to Beta Analytic, Florida USA for radiocarbon dating (Beta 112052- Table 9)). The conventional C14 age was 3160 +/- 50 years BP. Geodetic elevation of the sample was -1.69 m. Five sediment subsamples were collected from the three cores: 9230201, 9230202 and Scots 88-1 for grain size analysis. From 9230201 samples of the sand (13-17cm), the well, rounded polished pebbles (45-52cm) and the grey fibrous clay (67-70 cm). Samples were taken from the basal unit (pebbly-clay) of each core: Scots 88-1 and 92302-02.

Shoreline Evolution

Maximum submergence of the Bay of Fundy occurred immediately after local deglaciation circa 13.5 ka BP (Amos and Zaitlin 1984-1985). The marine limit identified in Scots Bay at that time was a raised beach at 20 m (Stea et al., 1987). Mean sea level dropped to its lowest level, of -25 m, circa 7 ka BP (Fig. 9a) as a consequence of post-glacial crustal emergence. High tide level has risen 15.2 m since 5 ka BP at an average rate of about 30 cm/century (Grant 1980, 1985). Modelling suggested that the tidal range changed during the period of rising sea level. Mesotidal (2– 4 m) conditions existed at the low stand ca. 7 ka BP and macrotidal (> 4m) conditions began just before 4 ka BP (Amos and Zaitlin, 1984-1985). Tidal modelling also suggested that the M_2 tidal amplitude in the Gulf of Maine /Bay of Fundy had reached 85% of its present range by 3 ka BP, 94% at 2 ka BP and 98% at 1 ka BP (Gehrels et al. 1995).

A debate arose about the initial timing of the tidal amplification (Grant 1970; Scott and Greenburg, 1983; Amos and Zaitlin, 1984-1985; Bleakney and Davis, 1983) but most agreed it has increased during the past 4000 years. To explain the differences in tidal expansion in Chignecto and Minas Basins, Shaw et al. (2010) invoked the presence of a barrier beach across Minas Passage. The barrier delayed tidal expansion in Minas Basin until ca. 3400 BP. Shaw et al. 2012 speculated that as tidal

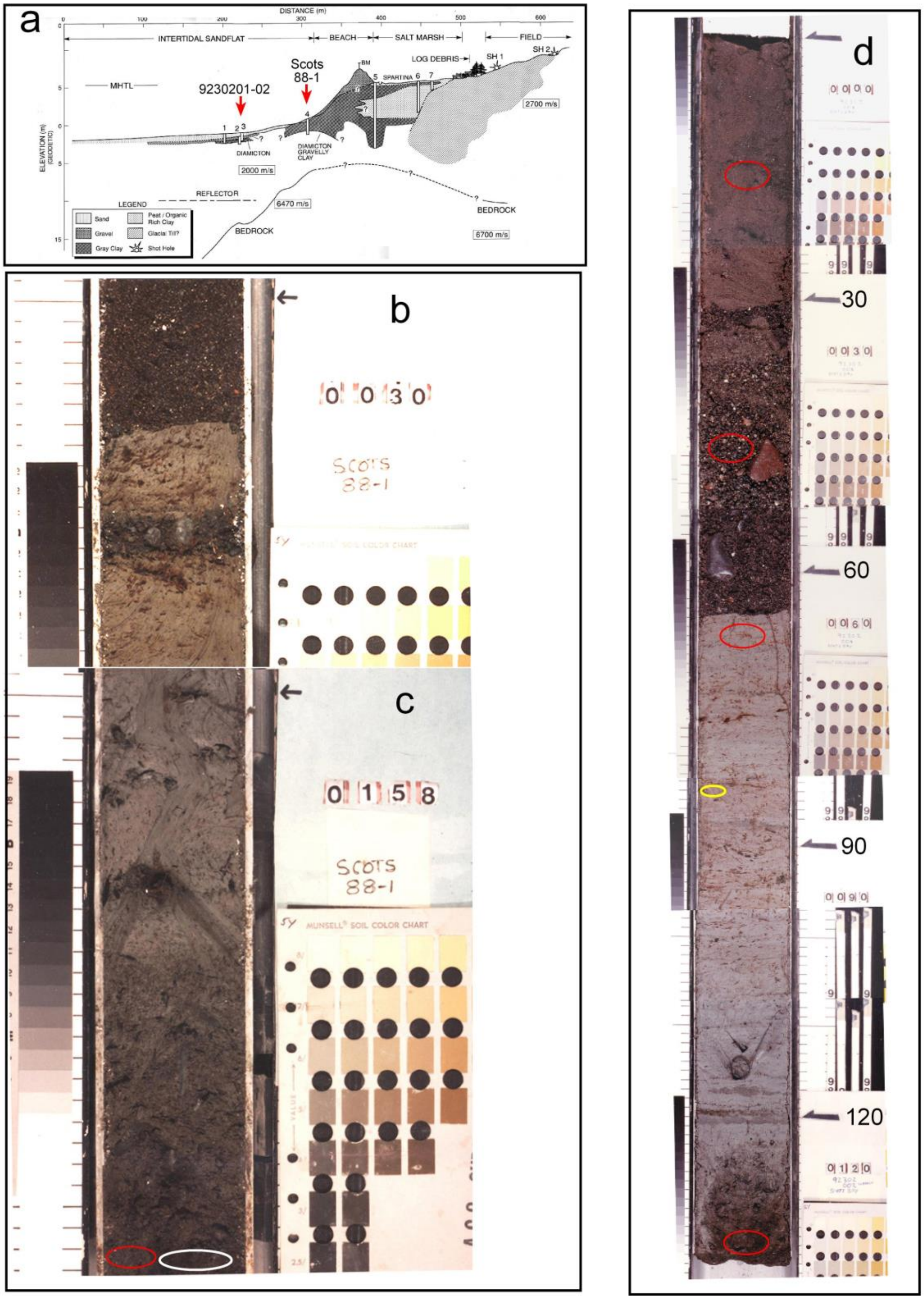


Figure 25. Map of borehole locations (a) and photos (b, c) of core 4 (Scots 88-1) and (d) combined cores 2, and 3 (9230201-02) beneath the upper intertidal flat at Line 4, Scots Bay Beach. A number of subsamples were collected from the cores for textural analysis (red circles) C^{14} dating (yellow circle) and organic carbon content (white circle). (b, c) Close-up photos of core 4 (Scots 88-1) highlight the intersect of wave reworked sand and clay facies at 36 cm. The narrow bed of pebble and sand within the clay at 40-42 cm suggests burial by a broken piece of clay. (d) the well-polished and rounded granule-pebble and sand facies between 44-64cm depth overlies a truncated bed of fibrous grey clay. The base in cores (c) and (d) highlight a possible diamicton.

amplitude expanded, accelerated scouring of the seabed triggered rapid growth of salt marshes in the last 3400 years by supplying copious amounts of sediment. The volume of sediment sequestered in salt marshes was comparable to the amount eroded from Minas Passage scour troughs. In Chignecto Bay, Shaw and Ceman (1999) studying the marshes at the head of Cumberland Basin found a 7.5 m increase in elevation of high marsh edge in 2900 years (mean rate of 25.9 cm/100 years) and the plot of salt marsh aggradation approximates the plot of HHW rise (Fig. 9b).

Table 9. A comparison of radiocarbon dates for samples of wood collected from marshes at the head of Chignecto Bay from similar elevations as the sample collected and dated at Scots Bay, N.S.

Location	**Age (14C years BP)**	**Lab No.**	**Material**	**Elevation (m) Geodetic Datum**	**Reference**
Beausejour	3520 ± 140	GSC-975	wood	-1.6	Grant 1970
Fort Lawrence	3050 ± 70	Isotopes Inc.	wood	-1.5	Harrison and Lyon 1963
Fort Lawrence	2970 ±80	Isotopes Inc.	wood	-1.7	Harrison and Lyon 1963
Scots Bay	3160 ± 50	Beta 112052	wood	-1.7	This paper

At Scots Bay there are insufficient dates from the marsh to provide good control on marsh aggradation or landward beach migration; however, the one wood date collected at an elevation of -1.69 m is similar to those collected from marshes at the Head of Cumberland Basin. Using primarily the seismic reflection, borehole data and the position and age of the wood sample collected, the following hypothesis for the evolution of Scots Bay Beach is presented.

It is known that at 3100 years BP, a piece of wood was deposited near the base of the marsh clay 147 m seaward from the present beach crest. Therefore a beach must have existed at least 147 m and probably farther seaward to allow the marsh to build. Tidal range at 3 ka BP was roughly 85% of the present range, i.e. 11.5 m, based on tidal modelling by Gehrels et al. 1995. Marsh cores at Scots Bay were at least 8.8 m thick which yield rates comparable to the marsh aggradation rates at Amherst Point, Cumberland Basin (Shaw and Ceman 1999). Therefore elevations for past higher high water elevations are taken from the Chignecto Bay curve (Shaw et al. 2010, Fig. 9b). Absolute elevations (relative to geodetic datum) of salt marsh vegetation boundaries increase toward the head of the Cumberland Basin because of increasing high tide elevations (Gordon et al. 1985). Therefore, when comparing known salt marsh elevations in Cumberland Basin to Scots Bay the difference (~2 m) in present marsh elevations at the two sites were applied to paleo marsh surfaces (Table 10). The relationships of present beach crest elevation to back barrier marsh elevation and mean sea level to tidal flat elevation were also assumed the same over time. The present beach crest exists within 2 m of HHTL; the marsh is 1 to 1.5 m lower than HHTL and the tidal flat / beach face intersection approximates mean sea level. The reconstructions are also checked against the average rate of marsh aggradation presented by Shaw and Ceman (1999).

Given marsh surface and sea level elevations for the past 3 ka it is possible to locate vertically the beach position at 1, 2 and 3 ka respectively. However little is known about beach stability and migration in the past, therefore the horizontal position of the beach is not easily constrained. If we assume at 3100 BP a beach was just seaward of where the wood was collected it provides an indication of the minimum extent of back barrier marsh at that time. However marsh deposits were observed in a reconnaissance coring program at least 235 m seaward from the beach line marker. Furthermore the beach crest migration rate between then and present day would work out to be extremely small at -0.05 m/a. Therefore, it is concluded that the beach in 3100 BP probably existed farther than 235 m offshore. Based on the stratigraphic record observed in cores 92302-01 to -03 it is known the marsh deposits have been scoured downward and less than 0.4 m of marsh remains at that location. Depth of wave scouring /reworking at the base of the present beach face is roughly 0.8 m based on repetitive surveys. Using a marsh surface elevation of 3 m and a beach profile similar to the present barrier, one can slide the 1 ka beach seaward and landward to any number of positions. The only constraint is that the beach crest at 1 ka could not have been closer than 115 m seaward of the present beach otherwise the marsh deposits and wood sample would have been eroded. The resultant beach migration rate becomes 0.1 m/a which is more reasonable.

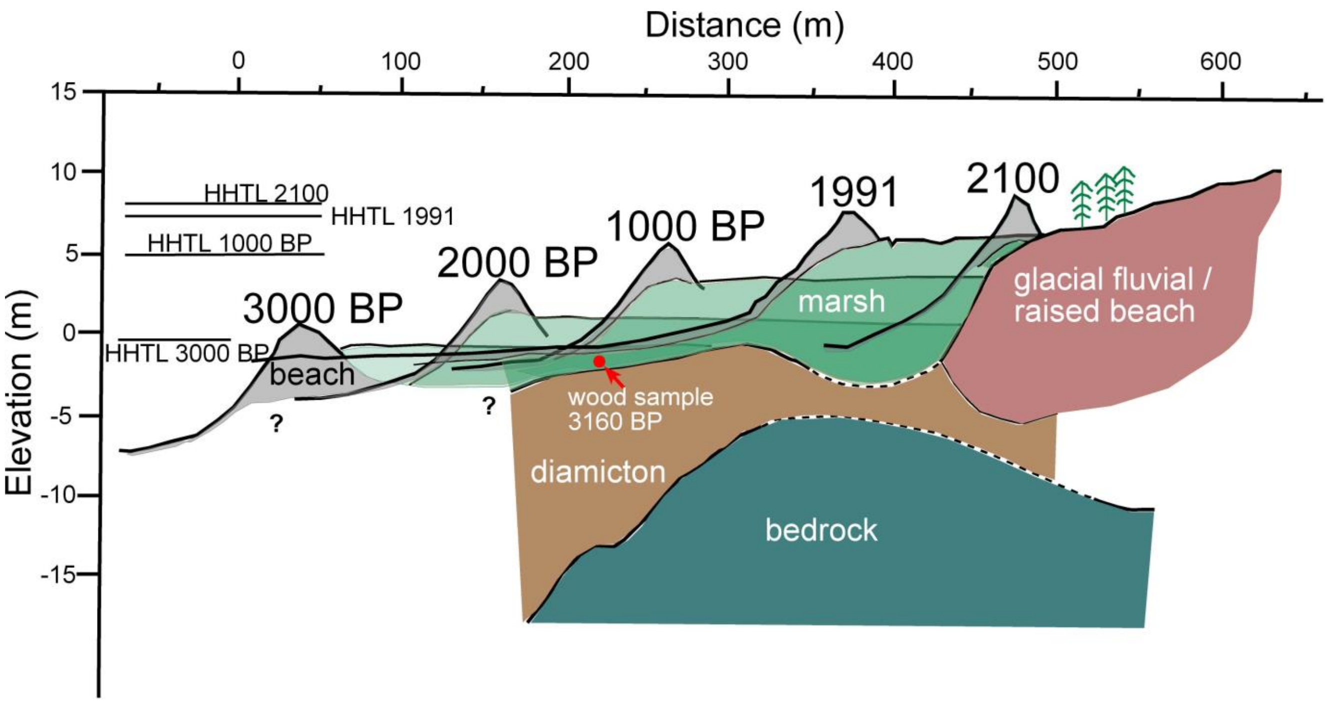


Figure 26. Sketch of a possible evolution for Scots Bay Beach since tidal range began increasing after 3500 yrs BP (Shaw et al. 2010). Illustrated are: the present beach and location of a wood sample in marsh clay C^{14} dated at 3160 yrs BP (red dot). The position of the marshes and HHTL at 1 ka, 2 ka and 3 ka are based on known elevations for a marsh in Cumberland Basin (from Shaw and Ceman 1999). Given a beach profile for these older macrotidal beaches similar to the present beach, the 1 ka beach could not have existed further landward without eroding the marsh clay and wood fragment sampled. Similarly the 3 ka beach would have had to be seaward of the wood sample but the distance is unknown. The position of the paleo beaches is based on a landward migration of the 1 ka beach to the present beach. The position of the beach in 2100 is predicted based on present rates of shoreline change and the predicted rise in relative sea level (James et al. 2014).

A sketch was drawn of possible paleo-locations of Scots Bay Beach by applying a similar landward migration rate and the elevations for marsh surfaces at 2 ka and 3 ka, (Fig. 26). The 2 ka and 3 ka beaches may have existed at 250 m and 350 m seaward of the present beach. However there are many unknowns; therefore, this sketch is only intended to serve as a rough guide of beach evolution and encouragement for future discussion and more stratigraphic surveys.

The present beach which consists of a thin wedge of pebble cobble clasts, is migrating landward over a nearly 9 m thick sequence of estuarine clays and salt marsh. Seismic refraction surveys revealed that Scots Bay Beach is founded on Quaternary deposits over bedrock and that Quaternary deposits to either side of the beach may be different in sedimentary character. Repetitive cross-shore surveys during the past 30 years indicate that at least 90% of the beach deposits have been mobilized in that period, most transported landward leaving only a thin facies of transgressive polished granule and pebble gravel and scattered boulders in the tidal flat as the beach migrates landward.

A beach can aggrade higher and remain more stable where it is anchored in position by bedrock. Little is known about long term sediment supply to Scots Bay Beach but it appears to be re-cycling itself as it migrates landward. Since the 1940s, rates of landward beach migration have been 0.5 to 0.8 m/a which is larger than paleo-rates. However, if the reports from local residents that large scale beach sediment extraction occurred in the 1940s to1960s are accurate, then the greater rates of beach migration observed today were caused by the depletion of beach sediment reserves. The migration rate also may have been accelerated as the beach was pushed landward from former wharves that anchored it.

For the future, global mean sea level is projected to rise 74 cm at 2100 for the largest emission scenario (Representative Concentration Pathway (RCP) 8.5) according to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2013). In a recent publication, James et al., 2014 projected that local relative (median) sea level in Saint John N.B would rise by 44.2 to 70.8 cm at 2081–2100 relative to 1986–2005. Furthermore, based on data from the tide gauge at Saint John N.B., Godin (1992) concluded, that the M_2 component of Bay of Fundy Tides has been increasing since the 1940s at a rate of 10–15 cm/century and expected to accelerate because of rising sea level and the redistribution of sediments in the Minas and Cumberland Basins at the head of the Bay of Fundy.

By 2100 if present rates of landward beach migration are maintained or accelerated because of rising sea level, the beach is predicted to retreat roughly 92 m landward and build against the higher backshore. As a consequence, marsh behind the northern barrier would disappear but would continue to exist along the central and southern barrier where the marsh is presently much wider and rates of beach migration are slower. Marsh deposits back of the northern barrier could also be transferred southward to augment building of the remaining marsh. It is also possible that the coarse sediment supply could increase and beach building augmented if Quaternary deposits below the present beach (Fig. 24, 26) become exposed to waves. Beach stability would improve and landward migration slowed. If the present outlet continues to infill, and streams feeding the outlet break through the barrier creating new outlets, the continuity of the beach would be negatively impacted.

In the future, rates of beach migration at Scots Bay may be monitored using repetitive airborne Lidar or aerial drones instead of manual surveys. These new methodologies could improve our knowledge of rates of beach migration and changing flood limits. Wave run-up during storms can exceed the elevation of the present beach crest and maximum flood levels could reach the back edge of the marsh making this area vulnerable for human activity. It was observed that the access road to Scots Bay

Beach and the beach itself were flooded after water levels reached elevations of 8.5 m (Chart Datum) or higher at the tide gauge in Saint John New Brunswick and high water coincided with strong westerly winds, e.g. Oct.30, 2015. Therefore, tide gauge recordings in Saint John, New Brunswick could provide a warning of potential flooding at Scots Bay Beach. Fortunately, the barrier beach and marsh will continue to provide a protective buffer for the community of Scots Bay from storm waves and flooding until the end of this century.

Table 10. Paleo-marsh and sea level elevations based on the HHW rise in Chignecto Bay (Shaw et al 2010), the increase in tidal amplitude predicted by modelling (Gehrels et al. 1995) and marsh elevations surveyed in Cumberland Basin (Shaw and Ceman, 1999) and Scots Bay (present study). The difference in marsh surface elevation at the two locations is based on the difference observed at the present. Present tidal water level (1991) is based on ground surveys. Elevations presented for 2100 are estimates based upon present literature (James et al., 2014 and Godin, 1992).

Year	**Water Levels (m) Scots Bay Beach**				**Marsh Surface Elevation (m)**	
	Tidal Range	**LLWL**	**HHWL**	**MSL**	**Chignecto Bay**	**Scots Bay**
3000 BP	11.5	-12.0	-0.5	-6.3	1.0	-1.0
2000 BP	12.7	-10.2	2.5	-3.9	2.8	~0.8
1000 BP	13.2	-8.2	5.0	-1.6	5.0	~3.0
Present	13.5	-6.7	6.8	0.3	7.6	5.6
2100	*13.6*	*-6.7*	*7.2-7.5*	*0.74-1.0*	----	---

Summary

Scots Bay Beach is one of the largest bay head, gravel barrier beaches within the inner Bay of Fundy that are exposed to waves generated along the length of the bay. The outer shores of Scots Bay consist of low rock cliffs, intertidal platforms and little source of sediment supply for beach building. Scots Bay Beach is a single crested, 60 m wide barrier, consisting of less than 3 m of pebble cobble overtop of marsh clay which is often exposed across the mid to lower beach face. The steep sloping beach face is fronted by an 800 m wide, intertidal flat (Table 11). The beach is backed by washover and dune deposits and a 100–200 m wide salt marsh. The marsh is drained by tidal creeks which enter the sea through an outlet near the centre of the beach. Field surveying and sediment sampling began in 1984 and continued until 2008 at three locations along Scots Bay beach. Line 1 crossed a backshore dune, Line 2 crossed a low wave overwashed area and Line 4 crossed a gravel storm ridge with a driftwood cap.

- **Coastal Stratigraphy**

Terrestial seismic reflection and refraction surveys, vibracoring and marsh boreholes reveal a complex coastal stratigraphy. Landward of the salt marsh about 18 m of lower velocity sediment interpreted as glaciofluvial or raised beach deposits overlie bedrock. Thickest marsh deposits cored were 8.8 m but core penetration was limited because of abundant driftwood buried in the marsh. The intertidal flats within 200 m of the beachface consist of wave reworked sands, granules and pebbles over a wedge of salt marsh clay and an intermediate velocity deposit interpreted as a diamicton. It extends to bedrock which slopes steeply westward, to a depth of 19 m beneath the sandflat.

- **Cross-shore Zones**

Scots Bay Beach was divided into seven distinct cross-shore zones. In a landward direction, the zones included: the tidal flat (lower and upper), beach face (low-mid and mid to upper), beach crest, backbarrier slope and salt marsh. The lower tidal flat is a featureless, soupy mud that is dominated by surface and subsurface drainage. Vertical surface sediment fluctuations vary from ±0.05 to 0.2 m. Across the upper tidal flats larger seasonal sand accumulations produce better defined sand bedforms cut by better defined drainage channels. Sand accumulations inshore against the beach face were highest in late summer and fall and least in the spring. Sand also tended to build higher against the central and northern beach lines than the southern one, i.e. Line 1. In winter the surface sand was frozen in many areas. The beach face consists of a cobble boulder frame along the lower part which changes to a better sorted pebble along the upper beach face. Grey clay underlying the beach face prevents normal seepage of swash and backwash resulting in higher velocities, accelerated erosion and sediment transport of all sizes of clasts. Upper beach morphology can include ridge and swale, a convex slope (building phase) or a concave slope (erosional). The beach crest is a single gravel ridge or dune that may be partially to well vegetated depending on sediment composition. The highest beach crest varied from 6.9 to 7.6 m elevation and appeared to have a rhythmic wavelength of 310 to 320 m longshore. Oscillations in beach crest elevation are less than 0.5 m and are often controlled by the accumulation of driftwood particularly along the central and northern beach. Driftwood can be completely swept off the crest into the marsh during storms that coincide with higher high tides. Wave washover deposits are wider and more extensive along the northern and central beach whereas more intermittent ribbon washover flows cross the southern beach where a sand dune exists. Washover fans are outlined by steep slip faces where they flow into the marsh. The salt marsh varies from 5.6 to 6.2 m elevation and is 100 to 200 m wide. Rates of marsh sedimentation are not available from Scots Bay however, paleo marsh levels are assumed to have risen with time similar to other marshes documented in the Cumberland Basin by Shaw and Ceman (1999). The tidal outlet which cuts through the beach was constrained in its position and sedimentation by wharfs along both shores between the early 1900s and 1950s. Since the mid-1980s the ebb shield has increasingly migrated back and forth alongshore but with a net southward drift. The base of the outlet lies well above mean sea level which suggest that it has infilled over time.

- **Coastal Flooding**

Today the large tidal range at Scots Bay is 13.5 m (CHS 1999). However macrotidal conditions only began ca. 4000 BP (Amos and Zaitlin, 1984-1985, Fig. 9). Modelling suggests that 85% of the present tidal range was reached in the Bay of Fundy by 3000 BP (Gehrels et al. 1995). Because of the large tidal range the duration of time that waves can rework a beach is longest at high and low tide. The highest part of the barrier is only impacted by episodic storms that coincide with higher high tides (Table 3). Fortunately, wave attack on the backshore is reduced during cold winter periods when shorefast ice forms along the upper beach, e.g. March 1992. Since the year 2000 at least nine storms have impacted Scots Bay Beach. Wave run-up during storms can exceed the elevation of the present beach crest and maximum flood levels reached 6.4 m along the back edge of the marsh (Table 11). Therefore human safety is vulnerable within this area during storms. It was observed that the access road to Scots Bay Beach and the beach itself were flooded after water levels reached elevations of 8.5 m (Chart Datum) or higher at the tide gauge in Saint John New Brunswick, and high water coincided with strong westerly winds, e.g. Oct.30, 2015. Therefore, tide gauge recordings in Saint John, New Brunswick could provide a warning of potential flooding at Scots Bay Beach.

- **Landward Shore Migration**

Exposures of marsh clay beneath and seaward of the beach suggest the beach is migrating landward and is in a transgressive phase of evolution. Paleo-beach position can be reconstructed at 1 ka, 2 ka and 3 ka BP using paleo-marsh elevations, sea level curves and a radiocarbon date of ~3100 BP from a vibracore collected within 150 m of the present beach face. The beach at 1 ka BP was no closer than 115 m from the present beach face and the 3 ka beach was a minimum of 150 m seaward and probably more than 300 m seaward of the present beach face using a beach migration rate of 0.1 m /a.

Historical rates of landward beach migration were documented by comparing repetitive air photography taken between 1945 and 1987. The landward edge of the barrier beach migrated 22 to 47 m during the 42 years of observation, a rate of 0.5 to 1.1 m/a, most along the central part of the barrier and least toward its north and south ends (Table 11). Wharf structures which extended offshore on both sides of the outlet from the early 1900s to the early 1950s played a significant role in anchoring the beach and position of the outlet. Another activity that may have impacted beach stability was the reported excavation of beach sediment in the 1940s to 1960s for highway construction. The excavation would have depleted the natural sediment reserves required to naturally rebuild the beach following storms.

Recent landward shore migration has been measured at three locations using repetitive cross-shore surveys. Since 1984, beach crest migration was 12 to 18 m, an average rate of 0.5 to 0.8 m/a. The beach crest can experience short term building phases and remain fairly stable for several years at a time, e.g. 1986-1991. The beach crest is pushed landward episodically, only when westerly storms coincide with higher high tides, e.g. Feb 1976 and Oct 2015, resulting in sheet overwash of the entire barrier beach. The entire beach, including coarse clasts at the base of the beach face has migrated landward over the marsh. A slight loss in beach sediment volume has been recorded at all three locations surveyed and no net accumulation across the tidal flats. Some of the sediment that is unaccounted for may be infilling drainage channels in the marsh.

A sedimentary signature of a transgressive macro-tidal barrier beach is suggested based upon observations at Scots Bay. It consists of scattered boulders and a thin bed of well-rounded polished granule and fine pebble over truncated marsh deposits observed beneath the intertidal flat.

- **Future Shore Changes**

By 2100, much of the marsh, particularly behind the northern barrier, will be squeezed out and disappear as the beach migrates landward and builds against the higher backshore. Some of the eroded marsh deposits may be added to the marsh existing behind the central and southern end of Scots Bay Beach. The continuity of the barrier beach and marsh is unknown particularly if the streams cut new outlets through the beach. However, the barrier beach and marsh will continue to be present and provide a protective buffer for the community of Scots Bay from storm waves and flooding until the end of this century.

Table 11. Summary statistics of physical shoreline changes at Scots Bay, Kings County, N.S.

Shoreline Monitoring

24	max. number of years spanned by repetitive beach surveys (1984-2008)
06	max. number of repetitive surveys at one location (Line (L) 2)
03	number of cross-shore survey lines

Shore Morphology

7.6	highest elevation of beach crest on survey lines, (m geod#.) (L4 1996; L1 2008)
7.6	highest primary dune elevation (m geod#.) (L1 2008)
29.3	max. width (m) of upper beach (HHWM * to crest) (L2 1984)
60.6	max. width (m) of backshore (HHWM to edge marsh) (L2)
10	width (m) of present tidal channel (at HHWM)
17.5	width (m) of icefoot (L4 Mar. 1992)
6.1	highest elevation of icefoot (m geod.#) (L4 Mar. 1992)
0.9 to 2.7	beach gravel thickness (m) over marsh clay
5.5° to 6.5 °	slope- mid to upper beach face
< 0.5° to 1.5°	slope- Intertidal flats
830	width (m) of intertidal flats exposed at low tide

Beach Changes

	max. landward migration (m) of beach-marsh boundary
11.6	in a 24 year period (1984-2008, L4) (0.5 m/a)
22 to 47	in a 42 year period (1945-1987) (0.5 to 1.1 m/a)
	max. landward crest retreat (m)
No data	in a single storm event
-17.1	in a eight year period (L2 1996-2004)
-13.5	in a 20 year period (L2 1984-2004)
- 0.7	mean. rate (m/a) of beach crest retreat (1984-2004)
5.2	max. seaward building (m) of crest (L2 1984-86)
± 0.5	max. vertical range in beach crest elevation (1984-2004) (m)
-18.2	max. retreat (m) in beach position at HHWM (4.9 m) (L2 1984-2008)
- 1.7	max. rate (m/a) of horizontal beach change at HHWM (L2 2004-08)
- 0.6	average rate of horizontal beach change at HHWM (m/a)
- 0.9	max. net vertical change (m) in outer sandflat surface (L2 1986-2004)

Shore Cliff Changes

-6 to -18	cliff top retreat (m) (1945-1987) south along cliff, north of beach (0.1 to 0.4 m/a)

Flooding and Wave Run-up Extent

6.4	Max. flood level elevation (m. geodetic) to back of marsh
147	Max. landward limit (m) of flood waters from high tide level (6.1m)
7.6	Max. elevation (m geod.#) of wave run-up across beach
8.5	water level (**chart datum)** in Saint John (13:30 30 Oct. 2015) that floods beach crest and access road to beach. (i.e. Strong west winds and waves at Scots Bay caused flooding at 15:13 when water level at Saint John was 8.5 m, photos J. Huntley, pers. comm. 2015).

#Geodetic Vertical Datum (geod.)   *Higher high water-mean (HHWM)

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References

Amos, C. L. 1977. An Hypothesis on the Evolution of the Tides in the Bay of Fundy; Report of Activities, Part B, Geological Survey of Canada Paper 77-1B, 47-48.

Amos, C. L. 1978. Post-glacial evolution of the Minas Basin-a sedimentological interpretation; Journal of Sedimentary Petrology, 48, 965-982.

Amos, C.L., and Long, B.F.N., 1980. The Sedimentary Character of the Minas Basin, Bay of Fundy; *in* The Coastline of Canada, S.B. McCann, (ed.); Geological Survey of Canada, Paper 80-10, 153-180.

Amos, C.L., and Zaitlin, B.A., 1984–1985. The effects of changes in tidal range on a sublittoral macrotidal sequence, Bay of Fundy, Canada. Geo-Marine Letters V. 4, No. 3-4, 161-169.

Amos, C. L., Buckley, D. E., Daborn, G. R., Dalrymple, R. W., McCann, S. B. and Risk, M. J. 1980. Geomorphology and Sedimentology of the Bay of Fundy; Halifax, ‘80, Geological Association of Canada / Mineralogical Association of Canada Joint Annual Meeting, Field trip Guidebook 23, 82 p.

Bleakney, J.S., and Davis, D. 1983. Discovery of an undisturbed bed of 3800-year-old oysters (Crassostrea virginica) in Minas Basin, Nova Scotia. Proceedings of the Nova Scotian Institute of Science, 33: 1–6.

Carrera, G., Vanícek, P., and Craymer, M.R., 1990. The Compilation of a Map of Recent Vertical Crustal Movements in Canada. Unpubl. DSS Research Contract 50SS23244-7-4257.

Canadian Hydrographic Service (CHS), 1983. Chart 4010, Atlantic Coast -Bay of Fundy (inner Portion) 1:200,000; Fisheries and Oceans Canada.

Canadian Hydrographic Service (CHS), 1999. Canadian Tide and Current Tables Atlantic Coast and Bay of Fundy, Volume 1, Fisheries and Oceans Canada, Ottawa, 96 p.

Church, A. F. 1872 Topographical Township Map of Kings County Nova Scotia. Entered into law on the twenty fourth of March A. D. 1864. A. F. Church & Co., Halifax.

Dashtgard, S. E., White, R. O., Butler, K. E., and Gingras, M. K. 2007. Effects of relative sea level change on the depositional character of an embayed beach, Bay of Fundy, Canada; Marine Geology, 239, 143-161.

Deal, M. 2004. An Archeological Survey of Scots Bay Mills and Shipyards, Archeology Unit, Memorial University of Newfoundland. http://www.ucs.mun.ca/~mdeal/MillSurvey/millsurvey.htm

Folk, R.L. 1974. Petrology of Sedimentary Rocks, University of Texas, Geology 370K, 383L, 383M laboratory manual, Hemphill Publishing Co., Austin, Texas, 182 pp.

Forbes, D. L. and Taylor, R. B. 1987. Coarse-grained beach sedimentation under paraglacial conditions, Canadian Atlantic coast. In: Glaciated Coasts (FitzGerald, D.M. and Rosen, P.S., editors). Academic Press, San Diego: 51-86.

Galbraith, P. W. 1979. Atlantic Region Storm Surge Project. Preliminary report, Atmospheric Environment Service, Technical Note MAES 79-2, 30 p.

Gehrels, W. R. Belknap, D. F., Pearce, B. R. and Gong, B. 1995. Modelling the contribution of the M_2 tidal amplification to the Holocene rise of mean high water in the Gulf of Maine and Bay of Fundy. Marine Geology 124, 71-85.

Godin, G., 1992. Possibility of rapid changes in the tide of the Bay of Fundy, based on a scrutiny of the records from Saint John. Continental Shelf Research, V. 12, N. 2/3, 327-338.

Gordon D.C. Jr. Cranford, P., and Desplanque, C. 1985. Observations on the ecological importance of the salt marshes in the Cumberland Basin, a macrotidal estuary in the Bay of Fundy. Estuarine, Coastal and Shelf Science 20, 205-27.

Grant, D. R. 1970. Recent coastal submergence of the maritime provinces, Canada; Canadian Journal of Earth Sciences 7, 676-89.

Grant, D. R. 1980. Quaternary Sea Level Change in Atlantic Canada as an Indicator of Crustal Delevelling. In: Mörner N.A. editor, Earth Rheology, Isostasy and Eustasy. London, John Wiley.

Grant, D. R. 1985. Glaciers, Sediment and Sea Level; Northern Bay of Fundy, N.S. Field Trip B, 14th Arctic Workshop, Dartmouth, Nova Scotia; 42 p.

Harrison, W. and Lyon, C.J. 1963. Sea level and crustal movements along the New England Acadian shoreline, 4,500 to 3,000 BP. The Journal of Geology, 71(1) 96-108.

IPCC, 2013. Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [T. F., Stocker, D.Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

James, T. S., Henton, J. A., Leonard, L. J., Darlington, A., Forbes, D. L., and Craymer, M., 2014. Relative Sea-Level Projections in Canada and the Adjacent Mainland United States; Geological Survey of Canada Open File Report 7737, 72 p.

Miller, R. O. and Fader, G. B. J. 1990. Cruise report 89-009 Phase C-Sandwave field-Scots Bay, *FRV Navicula*, Geological Survey of Canada Open File Report 2298, 28 p.

Owens, E. H., 1977. Coastal Environments, Oil spill and Clean-up Programmes in the Bay of Fundy; Department of Environment, Environmental Protection Service Report 3-EC-77-9, 175 p.

Owens, E. H. and Bowen, A. J., 1977. Coastal Environments of the Maritime Provinces; Maritime Sediments, V. 13, No. 1, 1-31.

Parkes, G. S., Ketch, L. A. and O'Reilly C. T. O, 1997. Storm Surge Events in the Maritimes. In: Proceedings 1997 Canadian Coastal Conference, 21-24 May 1997, Guelph, Ontario, 115-129

Ruffman, A. 1999. The Saxby Tide of October 4-5, 1869: A possible geological marker around the Bay of Fundy. Abstracts 1999 Colloquium and Annual General Meeting, Atlantic Geoscience Society; Atlantic Geology 35, p 102.

Ruffman, 2004. Hurricanes of Renown, Extended abstract, Maritime Museum of Atlantic Hurricane talk series, Sept. 21, 2004, Halifax, 9 p.

Scott, D.B. and Greenberg, D.A., 1983. Relative sea-level rise and tidal development in the Fundy tidal system; Canadian Journal of Earth Sciences v. 20, 1554–1564.

Shaw, J. and Ceman, J. 1999. Salt-marsh aggradation in response to late-Holocene sea-level rise at Amherst Point, Nova Scotia, Canada; The Holocene 9, 439-451.

Shaw, J., Amos, C. L., Greenberg, D. A., O'Reilly, C.T., Parrott, D.R. and Patton, E. 2010. Catastrophic tidal expansion in the Bay of Fundy, Canada; Can. J. Earth Sci. 47, 1079-1091.

Shaw, J., Todd, B.J., Li, M.Z., Wu, Y. 2012. Anatomy of the tidal scour system at Minas Pasage , Bay of Fundy, Canada; Marine Geology, 323-325, 123-134.

Stea, R. R., Scott, D.B., Kelley, J.T., Kelley, A.R., Wightman, D.M., Finck, P.W., Seaman, A., Nicks, L., Bleakney, S., Boyd, R. and Douma, M. 1987. Quaternary Glaciations, Geomorphology and Sea Level Changes: Bay of Fundy Region; NATO Advanced Course on :Sea level Correlations and Applications, Centre for Marine Geology, Dalhousie University, Halifax, Nova Scotia, Field Trip Guidebook, 79p.

Stea, R.R., Forbes, D.L. and Mott, R.J. 1992. Quaternary Geology and Coastal Evolution of Nova Scotia Field Excursion A-6 Guidebook; Geological Association of Canada/ Mineralogical Association of Canada Joint annual Meeting, Wolfville, Nova Scotia, 125 p.

Stea, R. R., Conley, H. and Brown, Y. (compilers) 1992. Surficial Geology of the Province of Nova Scotia; Nova Scotia Department of Natural Resources Map 92-3, scale 1:500,000.

Swift, D.J.P., and Borns, H.W. Jr. 1967. A Raised Fluvial Outwash Terrace, North Shore of the Minas Basin, Nova Scotia; Journal of Geology, V.75, 693-710.

Taylor, R. B., Forbes, D.L., and Shaw, J., 1991. Surficial Geology and Physical Properties 8: Coastal Geology; *in* East Coast Basin Atlas Series: Scotian Shelf; Atlantic Geoscience Centre, Geological Survey of Canada, p.125

Taylor, R. B., Shaw, J., Todd, B. J. and Burns, R. A. 1992. Coastal stratigraphy of Scots Bay Beach, Nova Scotia [abstract and poster]. In: Abstracts Volume, Geological Association of Canada/ Mineralogical Association of Canada, Joint annual meeting, v. 17, p. A11.

Taylor, R. B. and Frobel, D. 1993. Aerial video Surveys, The Coastline of Nova Scotia, Part 1 Bay of Fundy and Gulf of Maine (New Brunswick Border to Yarmouth) Geological Survey of Canada Open File Report 2705, 50 p. and 4 tapes.

Taylor, R.B. Frobel, D., Forbes, D.L. and Parlee, K.1995. Coastal Stability and the Monitoring of Physical Shoreline Changes in Nova Scotia; In Proceedings Canadian Coastal Conference, Halifax, N.S., vol.2 , 829-843

Wedler, E. 1984. Environmental and Resource Study of the Scots Bay and Blomidon Peninsula area, Nova Scotia; unpublished report, 93-97.

Welsted, J.E. 1974. Morphological Maps of the Fundy Coast; Maritime Sediments, V. 10, No. 2, 46–51.

Welsted, J.E. 1979. Air-photo interpretation in coastal studies- Examples from the Bay of Fundy, Canada; Photogrammetria, V. 35,1-27.