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Chapter 11

Tidal Flat-Barrier Spit Interactions in a Fetch-Limited, Macro-tidal Embayment, Lubec, Maine, USA

Joseph T. Kelley, Daniel F. Belknap, and J. Andrew Walsh

Abstract This report describes two sand and gravel spits and associated tidal flat environments in a fetch-limited, macrotidal setting in Lubec, Maine, USA. The spits have been remarkably dynamic since the late eighteenth century despite the low wave energy. The beaches were originally sourced from erosion of glacial and post-glacial bluffs, but the contemporary spits are apparently growing from clasts reworked from former barrier sites on the tidal flat. Attached algae coupled with strong tidal currents permits landward-directed floating and dragging of cobble-sized clasts that could not otherwise move, underscoring the potential importance of algal-assisted transport. This paper underscores the unexplored potential of algal transport across macrotidal flats as a mechanism to permit barriers to transgress in a punctuated manner from one location to another.

11.1 Introduction

> Sometimes these plants (seaweeds) attach themselves by their root-like bases…which are not in fact roots, for they serve only for support-to shells which lie prone or are fixed upon the bottom. More commonly they adhere to a pebble left on the sea-floor by the melting glacial sheet, or drifted out in the "pan-ice" which in winter forms along the sea margins. All these sea-weeds have floats which hold them upright in the water, and as they increase in size, they pull on their bases with constantly augmenting force. As the waves roll over them, they increase the tugging action, until finally, in some time of storm, the plant lifts the stone from its bed and floats it in the water, buoyed up by the vesicles of air contained in its fronds. The plant and upturned stone are together borne in by the heave of the sea onto the shore. Coming into the breakers, the weed is quickly beaten to pieces, and the pebble enters the mill where so many of its fellows have met their fate. The close observer after a storm may find any number of these bowlders along a pebbly shore which still show traces of the sea-weeds which bore them to the coast…On a quarter of a mile of the Marblehead (MA) beach I have estimated that as much as 10 tons of these seaweed-borne pebbles

AU1 AU2

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> came ashore in a single storm. Many of the beaches, which are so adequately provided with pebbles from the neighboring shores where the waves are attacking the firm land that they could not be maintained from that source alone, are sufficiently fed by the means of supply afforded by the action of marine plants. (N.S. Shaler 1895, p. 55)

Gravel barriers are much less studied than their sandy counterparts, yet along rocky shores and in formerly glaciated regions (paraglacial coasts), gravel barriers are common and often still front the eroding deposits which sourced them, or they are attached as spits to those sources (FitzGerald and Van Heteren 1999; Boyd et al. 1987). Although gravel barriers in differing wave and tidal regimes have been reviewed, the range of conditions under which gravel barriers occur has not been fully explored (Antony and Orford 2002). Gravel barriers in meso-macrotidal (2 to >6 m) regions have appeared in some case studies and reviews (Short 1991; Antony and Orford 2002; Masselink and Short 1993; Orford et al. 2012), but gravel barriers in fetch-limited embayments, where tidal amplitude is large relative to wave height (Type 3 barriers in Short's (1991) nomenclature), are very rarely discussed. In such locales, a tide-dominated flat environment commonly occupies the lower foreshore, and a wave-dominated beach rests in the mid-high tide level (Antony and Orford 2002). There seems to be general agreement that in such settings "increasing tide range retards the rate at which sediment transport and morphological changes take place" (Masselink and Short 1993; p. 788). This is because there is limited time for waves to break on the beach. AU3

In wave-dominated, paraglacial settings, where tides seem less important, sand and gravel barriers are often very dynamic and shift position relatively rapidly as old sediment sources are depleted and new ones exposed (Boyd et al. 1987). Details on mechanisms of sediment transfer from one barrier location to another are scarce, but presumably abetted by extreme storms with high wave energy (Orford et al. 1996, 2003). The dynamics of sediment transport and morphological change in fetch-restricted, paraglacial embayments with large tidal ranges is presumably much less, but relatively unexamined. Although most reports on meso-macro tidal barriers describe sandy mid-low-tide environments, the lower beach-tidal flats of macrotidal, paraglacial gravel barriers are seldom described.

In this study we describe two sand and gravel barriers and an associated tidal flat in a highly fetch-restricted, macrotidal setting. The barriers have been historically very dynamic despite the restricted wave energy. We examine the lower foreshore-tidal flat in detail and consider its interaction with the beach to find mechanisms capable of affecting rapid shoreline change.

11.2 Geological Setting

Lubec, Maine is near the easternmost point in the United States (Fig. 11.1), along the border with Canada. The embayment is sheltered from swells from the Atlantic Ocean (Gulf of Maine) by West Quoddy Head and from local waves by Campobello Island and other, local headlands. The most common summer winds are from the

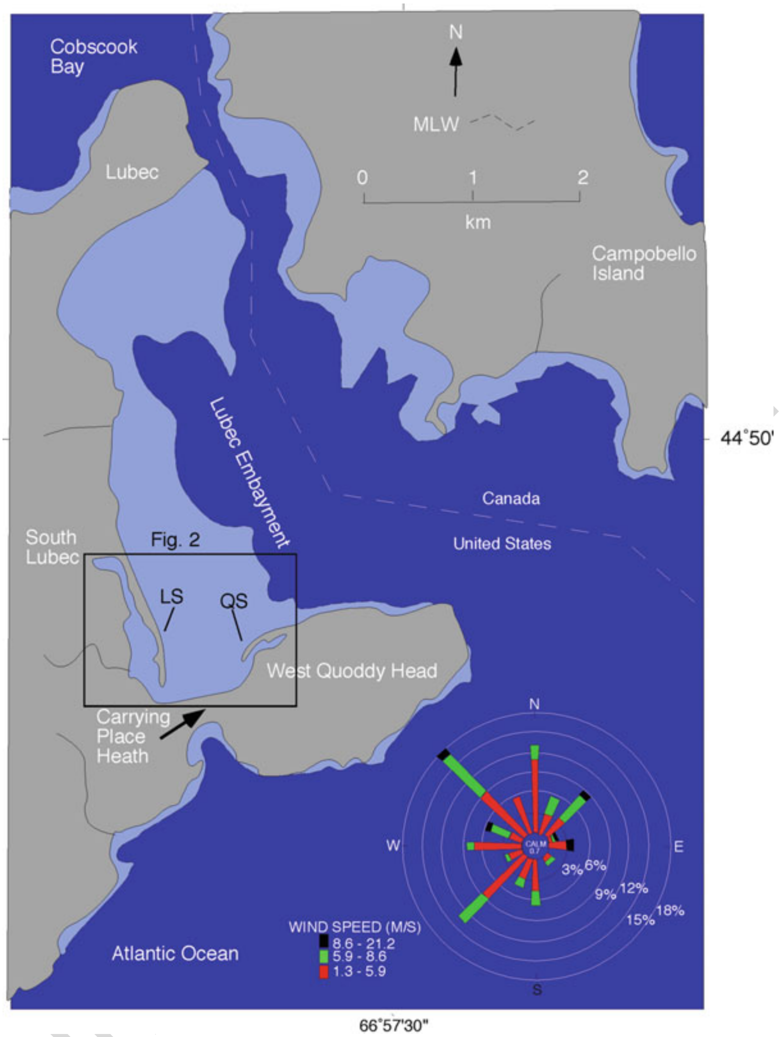

Fig. 11.1 Location map for Lubec, Maine (Modified from Walsh 1988). The wind rose is from http://www.wrcc.dri.edu/cgi-bin/wea_windrose.pl?laKEPO. Some small intertidal islands in Canada were left out for the sake of simplicity

south-southwest, while the winter-fall (and annual average wind) wind is mostly from the northwest. The strongest winds are from the east during winter storms that occur several times per year (http://www.wrcc.dri.edu/cgi-bin/wea_windrose.pl?laKEPO; Hill et al. 2004).

The Spring tidal range is just less than 7.0 m and tides are semi-diurnal. Wave height in the Lubec Embayment is fetch limited because storm waves generally come from the east (Fig. 11.1). When large storms do occur in the winter, much of the embayment is typically choked with sea ice, further impeding wave attack.

Maximum fetch direction for waves approaching the Lubec Spit is northerly, for which the typically strongest winds of 6–9 m/s occur less than 3 % of the time. The fetch across the embayment at high tide from the north is about 4 km, but it is only about 1.7 km at low tide. The highest likely waves impacting the spit are between 0.2 and 0.3 m (Coastal Engineering Research Center 1984), but these would occur infrequently and for a short duration (<2 h). The large tidal range interacts with the limited fetch to severely restrict wave energy in this embayment.

Paleozoic igneous and metamorphic rocks define the shape of the environment, and crop out on the tidal flat and along the shoreline (Bastin and Williams 1914; Osberg et al. 1985). Glacial till directly overlies bedrock. Owing to isostatic depression of the land at the time of deglaciation, marine submergence led to the deposition of muddy glacial-marine sediment over till. Radiocarbon dates from marine fossils just above till deposits in the Lubec Embayment average around 15.5 (calibrated) ka B.P. (Dorion et al. 2001). A coarse-grained, layered sand-gravel deposit uncomformably overlies the glacial-marine mud in the southeastern upland of the embayment (Figs. 11.2 and 11.3). This regressive deposit was formed by waves as post-glacial sea level fell across the area. A wave-eroded hill of till and bedrock mark the highstand shoreline in this area just east of the present coast (Fig. 11.3a). The wave-cut, sand and gravel platform is uniformly eroding on its seaward side today. Sea level fell to a lowstand of −60 m by 12.5 (cal.) B.P., and has risen to the present day (Kelley et al. 2010).

To the southwest of the raised marine sand and gravel deposits, an ombrotrophic bog (Carrying Place Heath) borders most of the southern side of the embayment. The peat deposits of this bog unit overlie glacial-marine mud and are rapidly eroding, with a 3 m scarp exposed today along the border with the tidal flat.

11.3 Methods

Paleogeographic reconstructions of the Lubec Embayment were made from a time series of historic maps and vertical aerial photographs (Walsh 1988). All maps were reduced to an approximately common scale with a Kelch plotter. Errors inherent in antique maps range from survey errors and use of an uncertain datum to a promotional bias in emphasizing valuable landforms on old maps, and render these maps useful for depicting only gross landform changes. The entire spit and tidal flat were also surveyed with a conventional theodolite with observations gathered from every significant slope change and at all contacts between landforms (approximately every 50 m across the area; Walsh 1988). The most recent maps of the area are available from Google Earth since 1996.

Thirty-seven bottom samples were collected from throughout the area and subjected to grain size analyses by settling tube and pipette (Folk 1974). More than 50 Dutch and vibracores were collected, mostly from the salt marsh.

To evaluate the role of algal dragging of clasts, 16 stations were established across the tidal flat. At each station six algal-colonized clasts (*Fucus vesiculosis*)

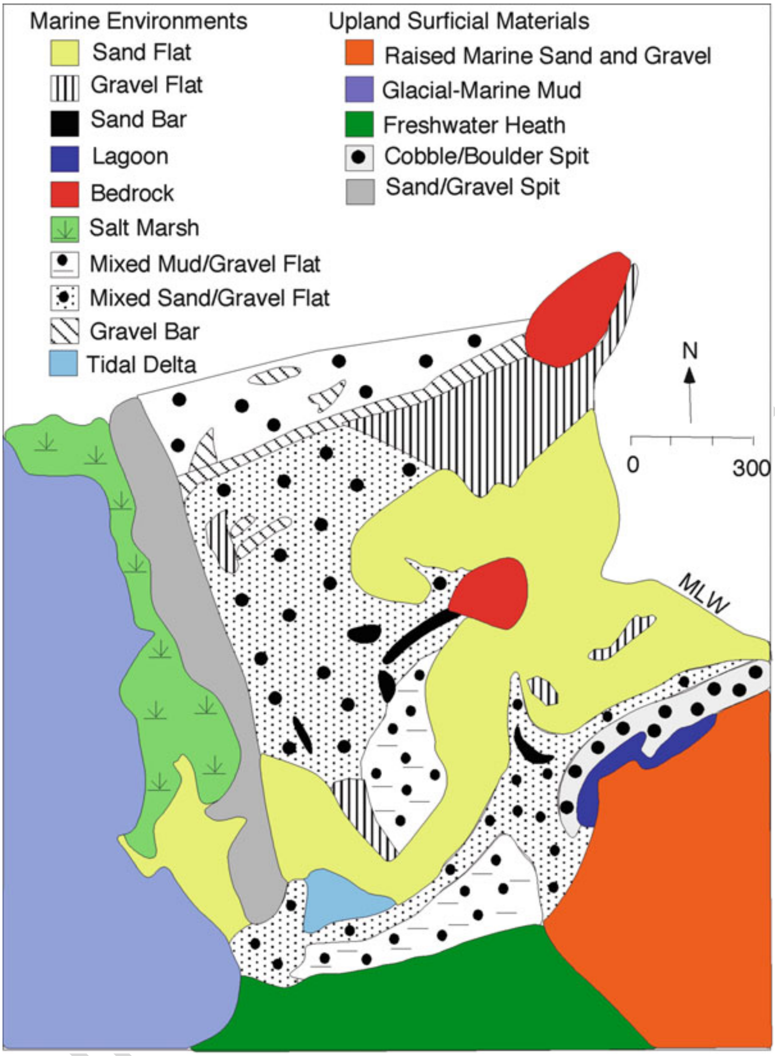

Fig. 11.2 Quaternary landforms of the Lubec Embayment (Modified from Walsh 1988)

were painted with fluorescent orange paint, labeled and sealed with a durable marine varnish. The clasts were selected from the tidal flat and ranged between −5 and −7 phi in size (32–128 mm); great care was spent to avoid harming the algae during drying and painting. Clasts were monitored for eight consecutive low tides after the June 22, 1986 deployment, and then at 1–3 week intervals for the next 2 months, followed by a final check on October 25, 1986. Clast motion was measured with a tape measure from the clast position to a stake located at the station from which the clast originated.

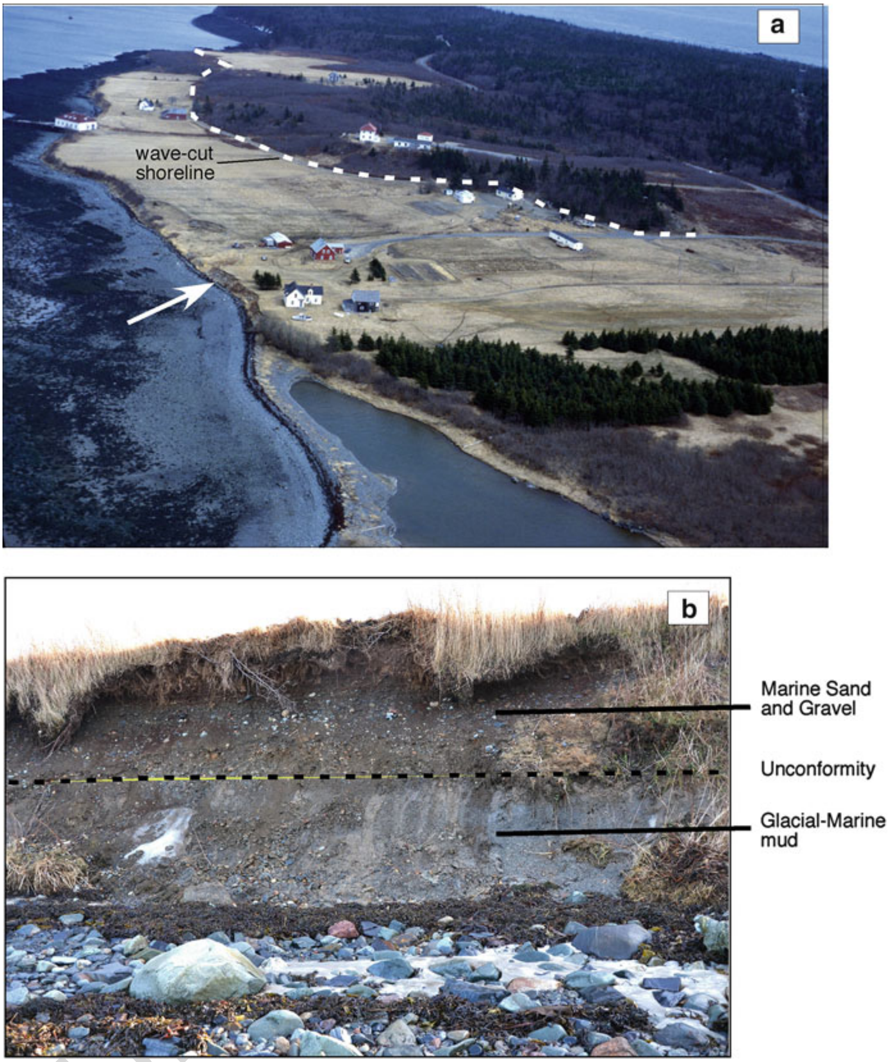

Fig. 11.3 Late Quaternary deposits: (**a**) Aerial photo of late Pleistocene raised shoreline and wave-cut platform, Lubec, Maine. *Dashed line* shows wave-eroded shoreline position. A wave-cut platform lies seaward of the paleo-shoreline. Note the abundance of algae attached to pebbles and cobbles on the modern high-tide shoreline; (**b**) photo of raised sand and gravel nearshore marine deposit. Section is located on Fig. 11.3a with *arrow*

11.4 Results

11.4.1 Time Series Changes in the Lubec Embayment

One of the earliest (ca. 1785) high-resolution maps of the Lubec Embayment (1:48,000) shows a peninsula that projects northward, the opposite direction of the modern Lubec Spit (Fig. 11.4a). It is curved in outline, and more than 2 km long. Other maps from this period also depict a beach extending northward (Walsh 1988).

By 1805, this spit was broken up, and only an island with a trailing intertidal bar remained near the former spit's connection to the mainland (Fig. 11.4b). North of the island, a new spit is shown in the shape of the present spit, though more seaward. This new spit appears to have attached to the island by 1830 (Fig. 11.4c), and formed a broad basin behind the spit. Marston's Dike was constructed to render the high salt marsh suitable for agriculture, a common practice at the time (Smith et al. 1989), and is visible to the present day. This spit broke up by 1840 (Fig. 11.4d) and a barrier island more than 0.5 km long was left where the spit existed seaward of 1830s "Basin". The breakup occurred at the northern bend of the 1830 map. By the middle of the nineteenth century (Fig. 11.4e), a looped barrier enclosed a lagoon on the site of the Quoddy Barrier. The Lubec Spit had re-established itself in the location of the present barrier and was well developed. This spit grew rapidly and structures were built on it by 1907 (Fig. 11.4f). A large recurvature marks the 1907 position of the spit, which is notable today (Fig. 11.5). An extensive low salt marsh community has formed behind the 1907 barrier, but no substantial marsh has yet colonized the tidal flat south of the 1907 spit tip. Buildings disappeared on maps after 1907, though posts project from the lower beach today. A proposal to develop

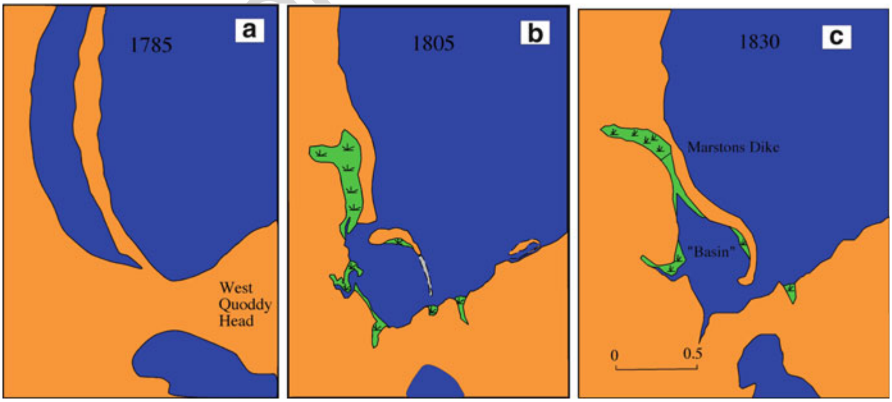

Fig. 11.4 Historic maps of Lubec Embayment: (**a**) 1785 (Putnam et al. 1785); (**b**) 1805; Fifth Division, 1805); (**c**) 1830 (Colby 1881; date of publication, not survey); (**d**) 1840 (Walling 1861; date of publication, not survey); (**e**) 1862; (U.S. Coast Survey 1862); (**f**) 1907 (U.S. Geological Survey 1908 date of publication, not survey) (Modified from Walsh 1988)

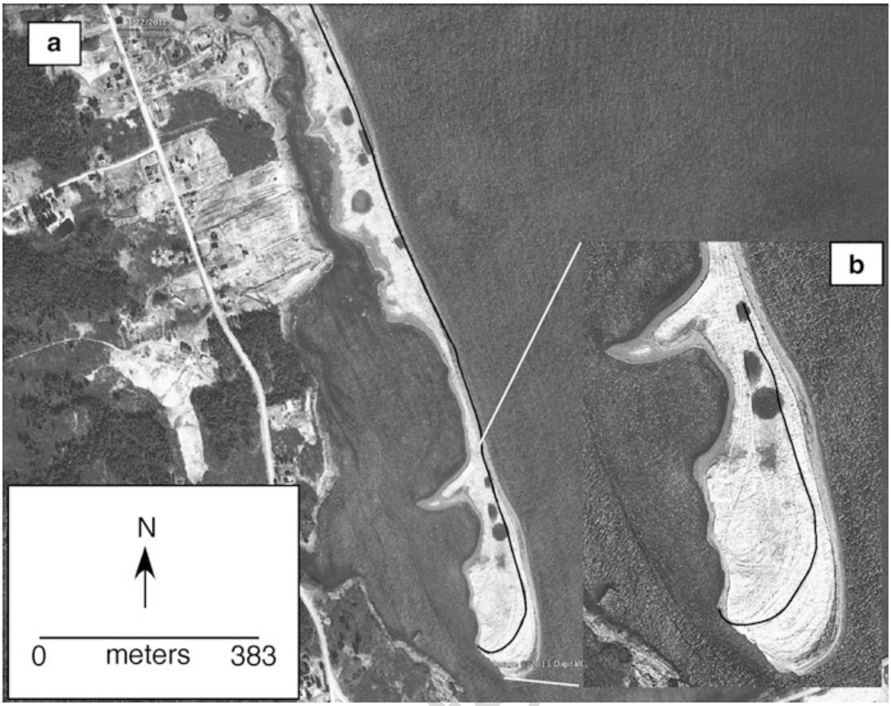

Fig. 11.5 Lubec spit 3-22-12 with dune edge digitized from 5-15-1-96 (*black line*). (**a**) The entire length of Lubec Spit; (**b**) close up of the tip of Lubec Spit (Images from Google Earth)

recreational homes on the spit was denied by the State in the 1990s as too dangerous, and the spit is owned by the State of Maine today.

Lubec Spit has continued to grow at a rate up to 3 m/year between 1996 and 2012, and averaging 0.4 m/year of growth at its terminus since 1907. This growth has required at least 1100 m^3/year of sand and gravel. At the same time, the spit has widened near its tip, while narrowing slightly along most of its length (Fig. 11.5). Quoddy Spit is more difficult to assess. Some historical maps fail to depict this spit, while others only show the most recent spit and not the lagoon-enclosing barrier. Since 1996, there has been no obvious growth, but its unvegetated tip is impossible to discern from the adjacent tidal flat (Fig. 11.6).

11.4.2 Sedimentary Environments and Geomorphology of the Lubec Embayment

Gravel is very abundant in the Lubec Embayment. It occurs as the dominant component of the gravel flat, gravel bar, and Quoddy Spit environments (Figs. 11.2 and 11.7). In the northern part of the study area, a topographically

Fig. 11.6 Air photo of the modern Lubec Spit. An *arrow* marks the 1907 spit terminus. The freshwater bog is at the *bottom* of the photo. Scale varies across the image, but it is about 120 m from the seaward edge of dune vegetation to the landward edge of vegetation on the 1907 recurve tip

high gravel flat crops out over a large area (Fig. 11.8a). Here it is a very poorly sorted, bimodal deposit (modes near -2 phi and <4.5 phi; 4 mm- >24 mm) (Table 11.1). Boulders are rare, with many well rounded pebbles and almost no mud. Many of the larger clasts are colonized by algae and are typically embedded in the deposit. No bedforms exist on the surface of the gravel flat, and pits that occur across the gravel flat (Fig. 11.8a) were dug by people harvesting the soft-shell clam, *Mya arenaria*.

Gravel, grading from boulders and cobbles (proximal end; Fig. 11.8b) to cobbles and pebbles (distal end, Fig. 11.8c), form the Quoddy Spit (Figs. 11.2 and 11.7). The spit crest varies from 7.4 m (proximal) to 6 m (distal) in height with a steep slope (>80 % grade ($>40°$)) into the lagoon and a gentle one (10 % grade (5.7°)) onto the tidal flat (Fig. 11.8a, b). No sedimentary structures occur on the spit, and algal-covered clasts line the lower beach face (Figs. 11.3a and 11.8b). Algae with attached clasts and freshwater peat blocks are also common on the spit.

Sand and gravel bars (Fig. 11.2) are topographically raised, curvilinear landforms up to 1.5 m above the surrounding tidal flat. They appear to be relatively static landforms and not migratory on decadal time frames. Pebble-sized gravel is a common sediment size, with subordinate coarse sand and rare boulders, making the features poorly sorted. In many areas sand is segregated from gravel and is most abundant over large areas. The 1 km-long predominantly gravel bar connecting the

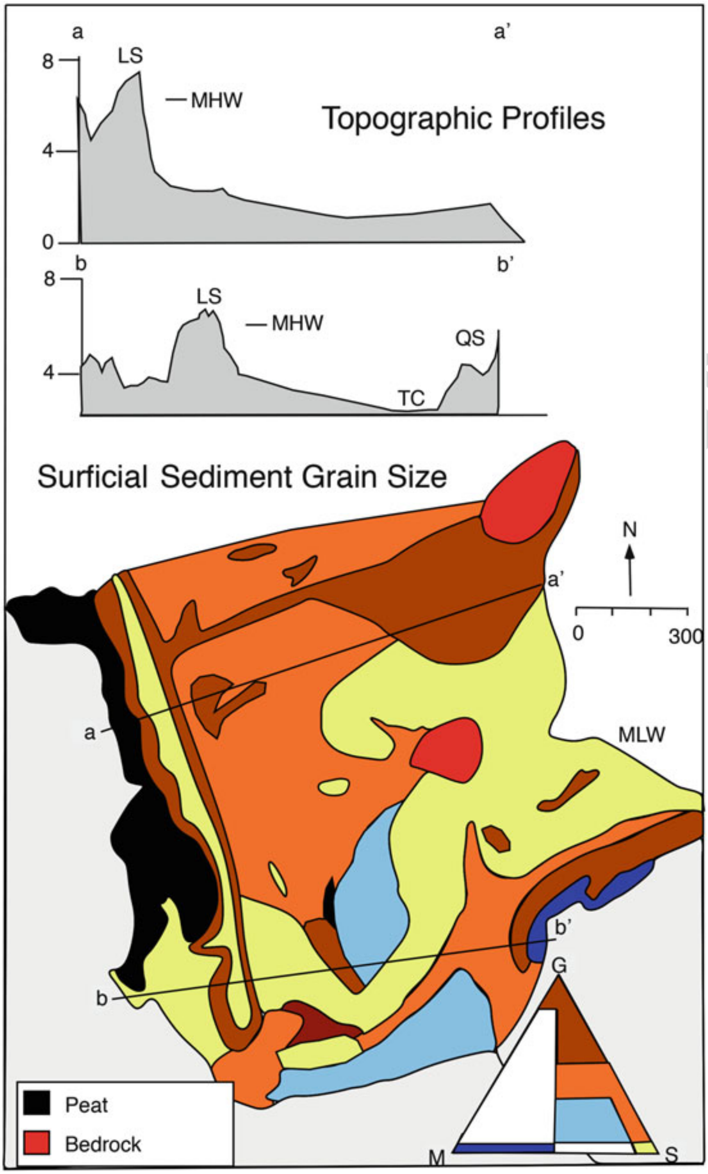

Fig. 11.7 Surficial material of the Lubec Embayment (Modified from Walsh 1988). Topographic cross sections are located on map as a-a’ and b-b’. LS means Lubec Spit, QS means Quoddy Spit, TC means tidal channel, MHW is the approximate location of mean high water. The triangular diagram depicts the relative amounts of Sand, Gravel and Mud. Topographic profiles end at approximate low water mark. The map scale precludes showing the location of the numerous bedforms and scattered bedrock outcrops

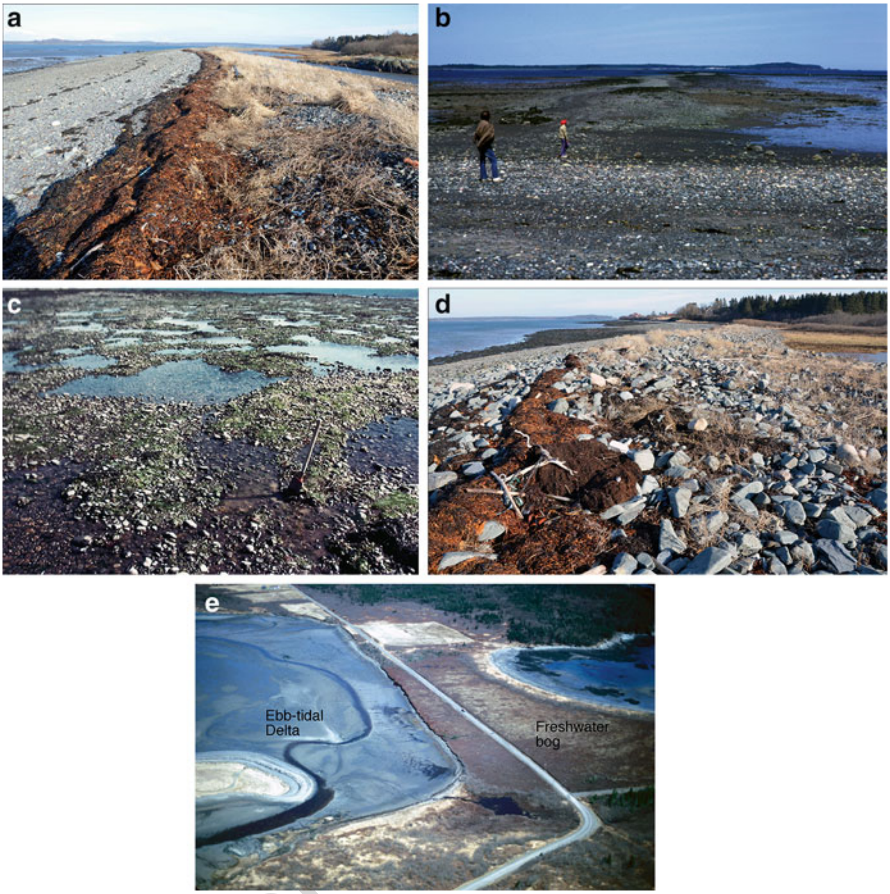

Fig. 11.8 Photographs of environments within the Lubec Embayment: (**a**) Gravel flat from the northwest part of the embayment. Water-filled depressions were created by people harvesting shellfish (*Mya arenaria*); the shovel is 50 cm high (Modified from Walsh 1988); (**b**) Quoddy Spit, proximal end. The sediment consists of boulders and cobbles; the freshwater peat block in the foreground is approximately 0.3 m long. Note the steep boundary with the lagoon and the more gentle slope (*left*) to the tidal flat with its abundance of algae-covered clasts; (**c**) The distal end of the Quoddy Spit, with a steep slope into the lagoon. Here the sediment ranges from pebbles to cobbles; (**d**) Intertidal tombolo-like bar connecting the Lubec Spit with a bedrock outcrop 1 km seaward. It is used as a low-tide road by shellfish harvesters today, but is not a human construction. Note the patchiness of the grain size and abundance of algae; (**e**) A gravel-sand flat with abundant oscillation ripples and covered by algae-covered cobbles; (**f**) Air photo showing tip of Lubec Spit and surrounding environments. Note the bend that the tidal channel makes around the ebb-tidal delta (*arrow*) and the raised (*lighter color*) channel margin linear bars. The freshwater bog, crossed by a road, is to the *right*

northern bedrock outcrop with the Lubec Spit is the largest bar (Fig. 11.8d). It has the form of an intertidal tombolo, with a flat, sandy upper surface and coarse gravel clasts (often covered with algae) lining the margins. The predominantly sandy bar

Table 11.1 Sediment grain size

Sample	Environment	Mean (phi)	Sorting (phi)	%Gravel	%Sand	%Mud
1	Sandflat	2.2	0.4	0.0	99.5	0.5
2	Sandflat	2.1	0.5	0.35	99.5	0.1
3	Sandflat	2.0	0.5	1.7	98.3	0.1
4	Sandflat	1.7	0.5	0.5	99.5	0.0
5	Mixed Flat	2.0	1.0	13.3	86.3	0.4
6	Mixed Flat	0.06	2.8	31.8	68.0	0.3
7	Mixed Flat	1.37	1.4	13.5	86.1	0.4
8	Mixed Flat	−0.38	2.6	39.4	60.4	0.2
9	Mixed Flat	2.12	1.4	6.9	86.9	6.1
10	Mixed Flat	−0.1	2.2	36.1	63.2	0.7
11	Sand/Grav Spit	−0.07	2.0	38.3	61.7	0.0
12	Sand/Grav Spit	−0.47	2.5	38.3	61.5	0.0
13	Sand/Grav Spit	−1.53	2.4	62.3	37.7	0.0
14	Sand/Grav Spit	−2.7	1.8	87.8	12.2	0.0
15	Sand/Grav Spit	−2.1	0.7	91.7	8.3	0.0
16	Sand/Grav Spit	−2.7	1.3	90.8	9.1	0.1
17	Sand/Grav Spit	−1.4	2.5	69.5	30.5	0.0
18	Sand/Grav Spit	−3.4	1.9	84.4	15.6	0.0
19	Sand/Grav Spit	−2.4	2.6	68.2	31.5	0.3
20	Sand/Grav Spit	−2.6	2.2	79.8	20.2	0.0
21	Gravel Flat	−2.1	2.6	68.1	31.8	0.1
22	Gravel Flat	−2.6	2.3	78.5	21.5	0.0
23	Gravel Flat	−1.7	2.7	59.5	40.3	0.2
24	Gravel Flat	−1.9	2.5	65.3	34.5	0.2
25	Gravel Flat	2.0	2.6	61.5	38.5	0.0
26	Gravel Bar	−3.5	0.7	99.2	0.8	0.0
27	Gravel Bar	−0.9	2.4	50.5	49.3	0.2
28	Gravel Bar	−2.3	2.3	73.0	26.9	0.1
29	Mixed Mud/Grav	−2.6	2.2	67.8	32.1	0.1
30	Mixed Mud/Grav	3.7	5.7	5.8	67.4	26.8
31	Mixed Mud/Grav	2.6	1.5	3.1	83.7	13.2
32	Dune	1.7	0.7	0.02	99.84	0.14
33	Dune	2.0	0.4	0.02	99.9	0.08
34	Salt Marsh	5.2	3.9	3.0	10.0	87.0
35	Salt Marsh	5.6	3.7	0.0	11.3	88.7
36	Lagoon	7.0	3.3	3.0	12.0	84.4
37	Lagoon	5.9	3.5	0.8	8.1	91.2

extending landward from the eastern bedrock outcrop clearly shows the influence of wave refraction in the opposite orientations of algae and drag marks on the east and west sides of the feature.

Sand, mixed with subordinate-dominant quantities of gravel, is the most texturally abundant sediment type in the Lubec Embayment. A mixed sand-gravel flat (Figs. 11.2 and 11.7) lies seaward of most of the Lubec Spit and continues north of the study area. The surficial sediments are extremely heterogeneous, and algal-covered pebbles and cobbles are common (Fig. 11.8e). Small depressions exist in places, and small ripples are locally common. Very crude stratification of sand pods and gravel layers occurs in the subsurface, but as with the gravel-dominated environments, there is little distinctive and continuous stratification.

On the seaward opening of the tidal inlet, an ebb tidal delta occurs (Figs. 11.2 and 11.8f). It is composed of distinct channel margin linear bars of sand and a main body of mixed gravel and sand (Figs. 11.2, 11.5, and 11.8f). Discrete ebb and flood channels bound it and are bordered by the linear bars. The tidal creek (ebb channel) makes two 90° bends around the landform, which stands 1.5 m above it. Historical aerial photographs show that the bend in the creek has increased as the spit tip and inlet have migrated to the south (right in the image).

The Lubec Spit is a large mixed sand and gravel deposit, with a mantle of wind-blown sand less than a meter thick (Fig. 11.7). The spit crest ranges from 6.6 to 6.2 m in height from proximal to distal ends, and widens to more than 30 m where spit recurvatures occur. The grain size has modes at 2.25 and −3.4 phi, but surficial sediment is generally very spatially and temporally heterogeneous (Fig. 11.9a–c). Alternating sand and gravel beds form layers within the steep beachface, but these have limited spatial continuity (<1 m). A high frequency (500 mHz) Ground Penetrating Radar line along the upper beach failed to record any coherent reflectors within the beach or spit recurvatures. In the winter, the beach is often covered with ice and an ice foot develops during extremely cold periods (Fig. 11.9c).

Well-sorted fine-medium sand dominates the lower, outer flat (sand flat, Figs. 11.2 and 11.7) and tidal channel that crosses the flat. It represents 25 % of the study area and its surface is covered with numerous ripples and other bedforms created by time-varying current and wave directions (Fig. 11.9d). Cobbles are relatively rare here, but those that occur usually contain attached macroalgae (most commonly *Fucus vesiculosis*).

Muddy sediment dominates in the salt marsh and back-barrier lagoons, but mud is also an important constituent of the mixed mud-gravel flat at the southern margin of the embayment (mixed gravel-sand-mud flat, Figs. 11.2 and 11.7). Here, a veneer of algal-covered cobbles rests over a thin (<40 cm) deposit of muddy sand (Fig. 11.9e). The gravel-sand-mud flat forms a shallow basin, with modern mud resting uncomfortably over glacial-marine muddy sediment. On one edge of the flat, a freshwater peat deposit with a 15 cm high scarp crops out (Fig. 11.9f).

11.4.3 Algal Transport of Clasts

The algal-covered clast transport experiment involved: (1) outer and topographically lower tidal flat locations (stations 1–3, elevation MLW-1.5 m); (2) mid-tidal

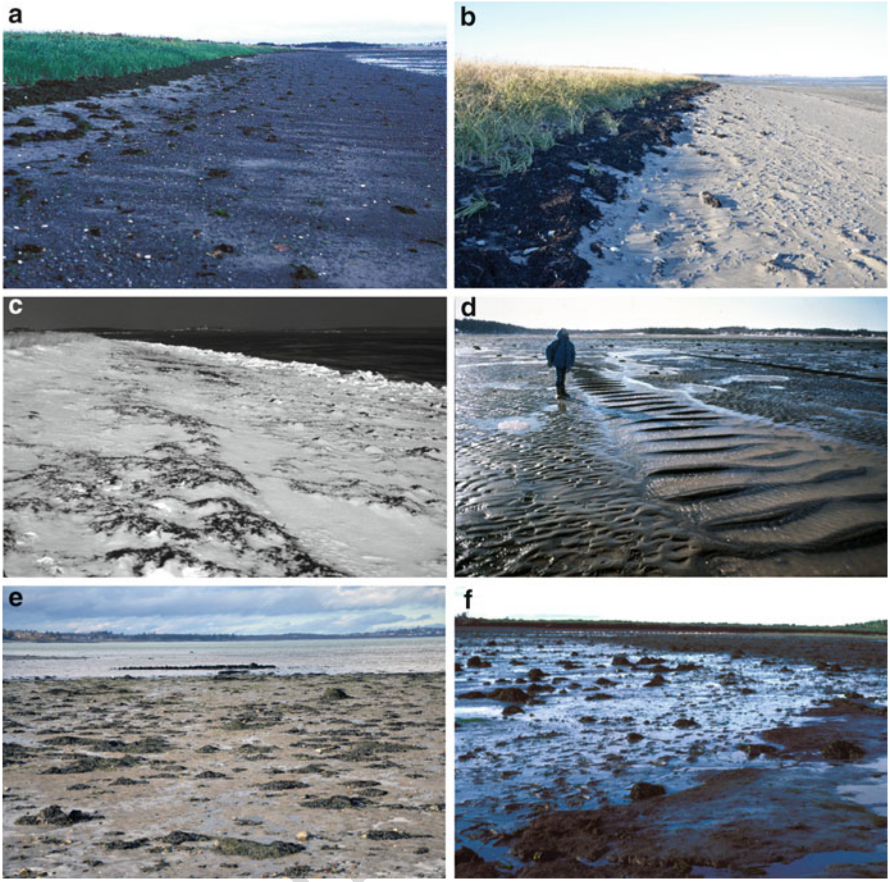

Fig. 11.9 Photographs of environments within the Lubec Embayment: (**a**) Lubec Spit following a spring high tide. Note the concentration of algae, all of which have attached gravel clasts, at the base of the sand dunes; (**b**) Lubec Spit a few days after a spring high tide. The algal wrackline borders the dune edge as in Fig. 11.9a, but wind-blown sand covers gravel on the beach. This is very near Fig. 11.9a; (**c**) Lubec Spit during a winter freeze. This is approximately the same position as Fig. 11.9a, b. Note the thick algae deposits beneath the ice and the well developed ice foot at the base of the beach; (**d**) Sand Flat showing complex bedform assemblage near the mean low water line (Modified from Walsh 1988; (**e**) Mixed mud and gravel flat viewed from the freshwater heath. The substrate is soft mud mixed with cobbles and pebbles. Algal-covered cobbles are very abundant on the flat. Note the shipwreck in the background. This is the position of the "Basin" from 1830 (Fig. 11.4c); (**f**) eroding freshwater peat deposit with a 10 cm high scarp (see Fig. 11.6 for location of peat)

flat locations (stations 4–9, elevation 1.5–3.0 m above MLW); (3) upper tidal flat locations (stations 10–14, elevation 3.0–4.0 m above MLW); and (4) back-barrier locations (stations 15, 16, elevation >4.0 m) (Fig. 11.10). Of the 98 algal-colonized clasts deployed between June 22–24, 1986 88 % were observed during the July 9–10 survey, 81 % during the August 20–22 survey and 31 % in the final October

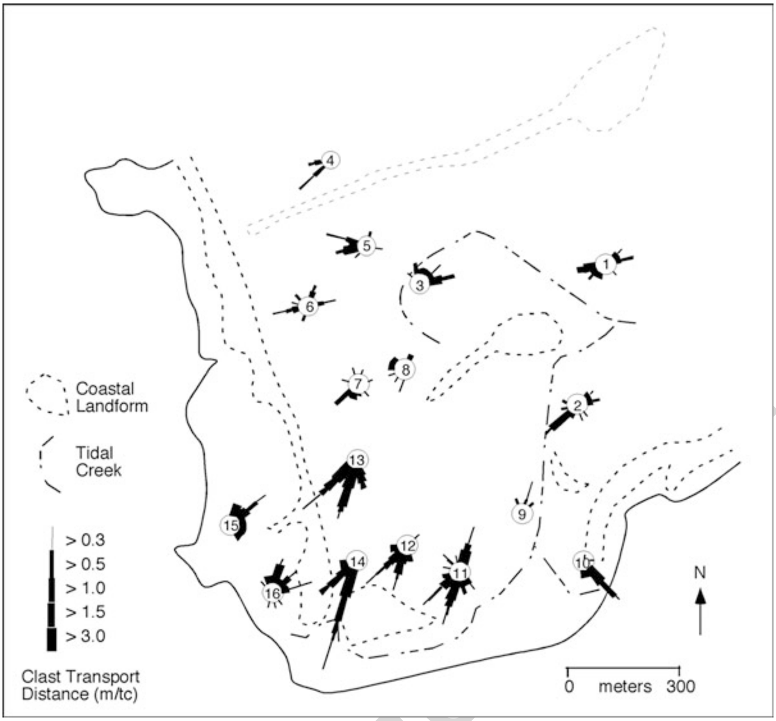

Fig. 11.10 Location of the algal-clast movement experiment and direction and distance of clast movement. The tidal creeks and landform outlines of Lubec and Quoddy Spits are included for spatial reference (From Walsh 1988)

25 check. Because of the poor recovery rate in October, comments are confined to the June–August observations. All clast movements were monitored following an ebb tide.

All low tidal flat stations (1–3) were on sandy substrates (Figs. 11.6 and 11.10). Clast movement here was more bi-directional than at higher elevations, with some clasts moving generally landward and others seaward. Algal-covered clasts in the area were few, but most had flood-oriented fronds when observed following ebb tide. Clasts from stations 1 to 2 moved in a net landward direction; those from station 3 went seaward. The mean distance traveled over the study was 0.5 m/tidal cycle (m/tc).

Stations on the mid-tidal flat were on mixed sand and gravel substrates (Figs. 11.6 and 11.10), though station 8 was on a small sand/gravel bar. Clasts averaged a short transport distance of 0.1 m/tc with a high degree of directional variability. Stations 4 and 5, on opposite sides of the intertidal tombolo, showed the probable effects of wave refraction, with clasts converging on the bar. The net motion of clasts from all stations, except station 9, was generally towards land. Station 9 was located near a tidal creek, and though movement was limited, clasts went in a seaward direction in the apparently ebb-dominated channel.

The high-tidal flat stations were on sand (stations 11, 13, 14) or sand and gravel substrates (stations 10, 12, 14) (Figs. 11.6 and 11.10). All were near the tidal inlet and displayed strong net landward (towards inlet) movement of clasts with an average rate of 0.6 m/tc). All but station 11 showed unidirectional movement. Clasts from several stations, and all from station 14, collected into "algal bars. These bars possess up top 15 cm of relief and contain a large quantity of pebbles and cobbles attached to the algae (largely *Fucus vesiculosis*). The algal bars migrate towards the tip of the Lubec Spit where the algae and associated sediment add to the growth of the spit at its terminus.

The back-barrier stations (15, 16) were on sandy substrates (Figs. 11.6 and 11.10) and most clast movement was toward the Lubec Spit. The average transport rate was 0.2 m/tc.

11.5 Discussion

11.5.1 Shoreline Changes

Contrary to expectations (Masselink and Short 1993), both the Lubec and Quoddy Spits have been very dynamic since the eighteenth century (Fig. 11.4). The Quoddy Spit grew southwest since the earliest map depictions and may still be growing, though only slightly. The Lubec Spit changed its orientation 180° in the same time interval, broke up twice into barrier islands and spits and migrated almost half a kilometer landward. Its growth has permitted infilling of its backbarrier region by a salt marsh, and deflected the drainage from its backbarrier region (Figs. 11.4 and 11.8f). In the sense of Orford et al. (1996), the Lubec Spit appears to have transitioned from a "consolidated" domain in the eighteenth century through a "breakdown" domain and is now in a "reformation" phase, whereas the Quoddy Spit may be in an "inception" domain of slow growth. Although Orford et al. (1996) implied no evolutionary sequence in domains, their terminology aptly describes the historic dynamics of the spit systems in Lubec (Fig. 11.11).

All barrier spit growth is towards the southeast corner of this embayment, towards a raised freshwater peat bog. The bog margin is retreating at about 1.0 m/year (Mansfield 2013), and the U.S. Army Corps of Engineers built a stone revetment along a small part of its length in 2012 to safeguard the road across the top. It is not possible to evaluate historic changes to the tidal flat because there are no prior maps of this environment. A block diagram (Fig. 11.12) shows that the Holocene sediment is generally less than 1.0 m thick except beneath the barrier and salt marsh. Residual freshwater peat crops out in the central flat (Figs. 11.6 and 11.9f), demonstrating the formerly greater extent of that environment.

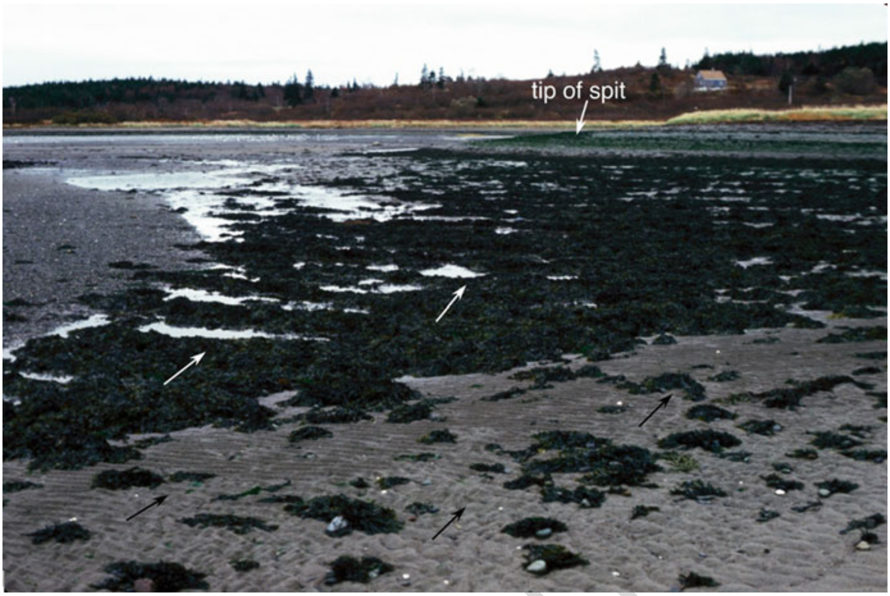

Fig. 11.11 Structures informally termed “algal bars” collect in the flood tidal channel near the tip of the spit. *Arrows* point in the direction of transport, towards the spit tip

11.5.2 Intertidal Environments

Tidal flats are typically zoned with outer sandy regions and inner muddy areas with mixed texture deposits grading between these margins (Eisma 1998), although Holland and Elmore (2008) have noted the importance of “mixed tidal flat” environments (mixed grain sizes) and summarized literature on the subject. In Lubec, there are “normal” outer sandy and inner muddy regions, but bedrock crops out in several locations and gravel-sized material exists throughout the embayment (Fig. 11.7). The largest gravel flat occurs around the outermost bedrock outcrop (Figs. 11.2, 11.7, and 11.8a) and appears to be a reworked till deposit resting on bedrock and overlain by modern sand and gravel (Fig. 11.12). Dense mud is visible beneath some large boulders, though the surface of the till is armored and largely obscured by algae-covered boulders and cobbles. Sand, apparently reworked from the till, covers the gravel on part of the outer flat (Fig. 11.12), though cobbles with attached algae are common on the sand. An extensive gravelly sand deposit (with minor mud) dominates the northern central and inner portion of the embayment and algae-covered cobbles cover its surface (Fig. 11.8e). Gravelly sand similarly covers the area surrounding Quoddy Spit. Sand forms a very thin cover along much of the tidal channel in the south, and continues into the back-barrier flat.

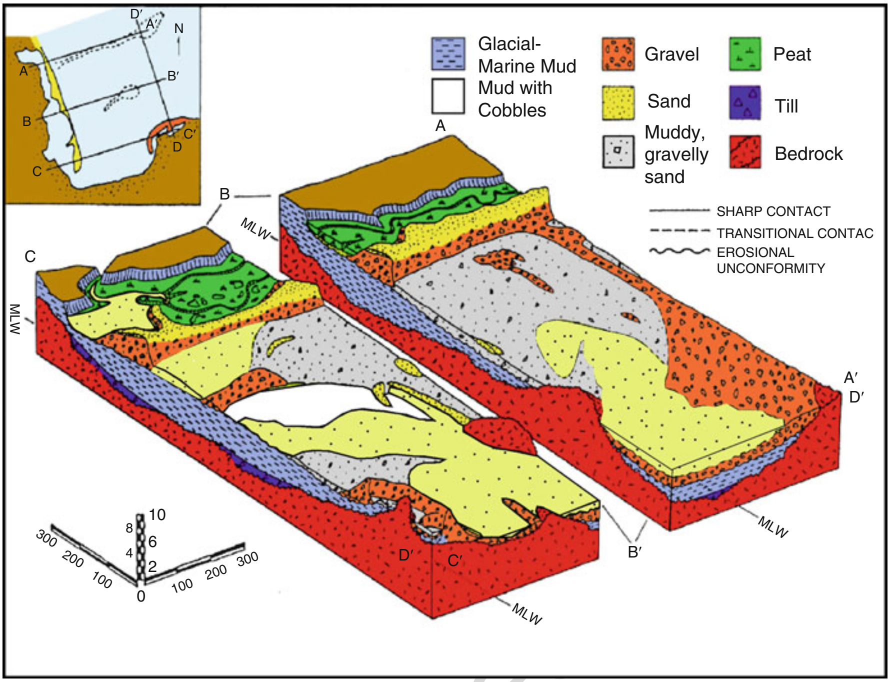

Fig. 11.12 Block diagram of tidal flat, spits and associated salt marsh. The *vertical* and *horizontal* scales are in meters. Note how thin the Holocene tidal flat sediments are above the Pleistocene material (From Walsh 1988). The main tidal channel runs directly on glacial-marine, muddy sediment

These sandy/gravelly deposits rest on glacial-marine mud, but reflect the former position of historic barriers (Fig. 11.4) and are likely reworked remnants of those barriers. The small freshwater peat outcrop should be older than the gravel deposits, but it is an erosional remnant with overlying materials removed (Fig. 11.9f). Scattered throughout the embayment are sand and gravel bars (Fig. 11.2). The only predominantly muddy areas are along the southern margin of the embayment where glacial-marine mud lies close the modern sea floor and crops out at the base of the fresh water peat (Fig. 11.7). Even here, cobbles and boulders with attached algae are common (Fig. 11.9e).

Coarse-grained flats such as Lubec are not well described in the literature except from high latitude regions where ice processes dominate (Dionne 1988). Lubec, Maine is on a paraglacial coastline and glacial effects linger in the form of eroding, raised gravel beach deposits and intertidal till and glacial-marine mud materials. Just as wave-dominated beaches elsewhere recycle material during a general transgression (Boyd et al. 1987), so here in Lubec, and likely other paraglacial localities, sand and gravel traverse the tidal flat as they connect former and present locations of beaches and bluffs.

11.5.3 Sediment Source(s)

The primary source of sediment to the beaches of the embayment is from erosion of sand and gravel, along with glacial-marine mud, bluffs along the margin and from reworking remnant till deposits in the intertidal and shallow subtidal region. Bluffs of peat, glacial-marine mud and regressive sand and gravel are all eroding along the southern margins of the embayment (Fig. 11.3), but the peat is presumably being oxidized and/or dispersed into the marine environment, while the mud is probably collecting in the back-barrier salt marsh. The peat bluff is retreating at up to 1.0 m/year (Mansfield 2012), and the linear shape of the margin suggests that all bluffs are retreating at roughly equal rates.

Remnant till deposits crop out around bedrock outcrops in the intertidal region, and drag marks on the flat and the tracer experiment indicate that some of this material is moving towards the spits. The raised gravel flat and sand and gravel bars also suggest that reworking of flat deposits remains an active process.

Carbonate sediment was not examined specifically, but qualitative observations indicate that shell fragments are concentrated in patches and are unlikely to comprise more than 5 % of flat and beach sediment.

11.5.4 Transport Mechanism(s)

The most remarkable aspects of the sand and gravel barriers in Lubec Embayment are their rapid historic breakdown and reorganization in a location with relatively low wave energy. The current growth of the Lubec Spit at more than a meter per year is also notable in an area with such a small fetch. Growth of the beach since the 1907 recurvature (Fig. 11.6) has required approximately 1,100 m^3/year for more than a century. Waves clearly deliver and move some sediment to the beach, especially sand (Fig. 11.8). The <20 cm waves, with only an hour or so each day they can effectively influence the spit, cannot move cobble-sized clasts along Lubec Spit, however. There is also no size sorting along the Lubec Spit to suggest wave-driven longshore transport.

The Quoddy Spit, on the other hand, does display size sorting along its length (Fig. 11.8b, c), with coarsest gravel near the eroding bluff source. Quoddy Spit is more exposed to waves. It directly faces the dominant wind direction and its position adjacent to the outer flat means that the water offshore is deeper than at Lubec, and larger waves have an opportunity to strike the beach longer. Most of the large clasts, and many attached smaller sand and gravel grains on Quoddy Spit are attached to algae, and wracks of algae and stones cover the spit (Fig. 11.8b, c).

Shaler (1895) was one of the first observers to see the potential for algal transport of clasts, though few others have continued a study of this process. In one early paper Emery and Tschudy (1941) considered both onshore and offshore transport of cobbles by kelp and discussed how important this mechanism was for both the deep sea and coast. Ben Avraham (1971) thought that algae introduced onto sandy Cape Cod (USA) beaches could transform them into gravel strands by algal transport of larger clasts. Kudrass (1974) and Gilbert (1984) were the first to begin quantitative studies, noting that the algae had to be three times the mass of the stone to float it, but that both floating of smaller rocks and dragging of larger ones brought material largely towards land. More recently Garden and Smith (2011) found that 27 % of all seaweed on a New Zealand beach was still attached to gravel.

Despite the unanimity of the few authors who noted how significant algal transport of clasts to beaches is, no study has developed a sediment budget involving algal transport. Although we do not yet have the means to do this in Lubec Embayment, clearly algal transport occurs there and could be a significant component of the sediment budget. Furthermore, algal transport appears to be an important mechanism for moving large clasts across tidal flats (and potentially shallow subtidal regions) from one depleted bluff source or unstable barrier position to another. This mechanism has not been discussed for other areas (Boyd et al. 1987), but may possibly be even more important in a regime with larger waves. Though lacking large waves, in Lubec, algal transport benefits from the powerful tidal currents in this macrotidal setting.

Ice transport is another important process in northern regions (Dionne 1984) and though not quantified in Lubec, was observed to carry blocks of tidal flat sediment onto the beaches and salt marsh (Walsh 1988; Wood et al. 1989). Ice may also be important in facilitating algal transport by pushing boulders and large clasts around on former barrier sites and till localities and, thus, releasing trapped clasts buried by larger rocks and abetting subsequent algal transport.

11.6 Conclusions

In a fetch-limited, macrotidal embayment gravel spits have undergone growth and rapid dynamical changes through the historic period. The tidal flat is modified from a "normal" textural zoning from outer to inner flat by reworking of older glacial and post-glacial deposits possibly by ice and certainly through transport of gravel clasts by attached algae. Gravel-sized clasts with attached algae abound all over the tidal flat and line the tip of Lubec Spit, which is still lengthening rapidly. Ice is also a factor in this north temperate location and ice may annually move large stones around, freeing up algae attached clasts to later transport.

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AU5

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