Article

Sea-cliff Erosion with Rising Sea-Level along Shores Exposing Glacial Material in Atlantic Canada: The Effect of Bedrock Slope and an Example from Isle Madame, Nova Scotia

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SUMMARY
Rapid retreat rates of sea cliffs exposing glacial material are a widespread problem, especially in Atlantic Canada, and one that will continue. Prediction of retreat rates at specific sites involves many variables, but a factor that has commonly been overlooked in such prediction is the slope of the bedrock surface under the glacial material. A glaciated bedrock platform is generally necessary to establish a stable situation of temporary equilibrium, and as sea-level rises, the bedrock slope determines the location of the new equilibrium position. An example from Nova Scotia shows that bedrock slope is so low on some coasts that the only long-range limiting factor is kinetic, i.e. how fast hydrodynamic energy can remove glacial material. Prediction of coastal retreat scenarios requires better information on the bedrock surface than is commonly available.

SOMMAIRE
Les taux de retrait rapide des falaises qui exposent des matériaux glaciaires est un problème très répandu et qui va perdurer, surtout dans le Canada atlantique. La prévision des taux de retrait sur des sites spécifiques comporte de nombreuses variables et, la pente du substratum rocheux sur lequel reposent ces matériaux glaciaires et une variable qui a souvent été négligée. L'existence d'un substratum rocheux glacié est généralement une condition nécessaire pour l'établissement d'une situation d'équilibre stable temporaire, et lorsque le niveau de la mer monte, la pente du substratum rocheux a une influence déterminante sur le lieu de la nouvelle position d'équilibre. Un exemple en Nouvelle-Écosse montre que la pente du substratum rocheux est si faible sur certaines côtes que le seul facteur déterminant à long terme est la cinétique, c'est-à-dire la vitesse d'abrasion du matériau glaciaire correspondant à l'énergie hydrodynamique. La prévision des scénarios de retrait de la ligne côtière requière une meilleure connaissance du substratum rocheux.

INTRODUCTION
Rates of shoreline retreat have been startlingly rapid – locally over a metre a year – at a number of monitored sites on Atlantic coastlines of eastern Canada and elsewhere, notably the northeastern United States. At most such locales, retreat results from the rapid erosion of glacial material forming cliffs and bluffs (Wang and Piper 1982; Taylor et al. 1985; Boyd et al. 1987; Carter et al. 1990a, b; Shaw et al. 1993a; Manson 2002; Himmelstoss et al. 2006). Adjacent beaches reconfigure to keep pace. Many of us, from homeowners to planners, would like to have a basis for predicting patterns of retreat where sea-level continues to rise at rapid rates.

Significant parts of these shores expose remnants of glacial drumlins or other unconsolidated glacial material resting atop low shore platforms of bedrock extending out to sea (Fig. 1), commonly as undulating 'whalebacks', locally still showing glacial striae (Stea et al. 1992; Grant 1994). Indeed, the position of the shore generally depends on the protection provided by this bedrock in a stable state of temporary equilibrium relative to wave erosion, but rapid retreat of some adjacent shores show that even this apparent stability is fragile and transient.

This situation lends itself to analysis of successive configurations of these coastlines during expected future sea-level rise. Such analysis uses the late Holocene history of the same shores based on offshore features and of the shorefaces themselves, but is shown to depend on a variable that has not previously been incorporated into these analyses, namely the slope of the upper surface of bedrock, i.e. a subsur-

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Figure 1. Annotated photo (from the southwest) of Cap laRonde, Isle Madame, Nova Scotia, by Wallace R. MacAskill in ca. 1932, (MacAskill 1937; the ca. 1932 date of the photo is established by Automobile Legal Association 1932). The photo illustrates profiles and locations of the sea cliff in subsequent years, derived from dated snapshots and aerial photographs. Note the progressive steepening of the profile. To the right of the cape is the bouldery shoal left by retreat of the seacliff into the former drumlin, cored by plucked bedrock remnants of a whaleback outcrop. Photographer's position is currently at sea.

face feature of the adjacent land surface.

In coming decades, if shore stability is further disturbed by sea-level rise, better prediction of retreat rates and distribution could be valuable. The purpose of this article is to employ more information about the bedrock underpinning these cliffed shores, specifically the geometry of its upper surface, to enable such prediction.

REQUIREMENTS OF SUCCESSIVE EQUILIBRIA WITH SEA-LEVEL RISE

The cliffed shores retreating most rapidly are clearly out of equilibrium with their hydrodynamic environments. The eroding glacial material can form overall slopes of about 70°, and erosional undercutting locally forms overhangs. Commonly, individual storms cut new profiles landward of the previous profiles, and/or trigger slump-block subsidence. Generally, a plume of muddy seawater, short-lived boulders of till in the surf, and slabs of overturned turf at the base of the cliff mark the location of the most severe erosion.

Similar shores with slopes of about 45°, generally somewhat vegetated, retreat much more slowly and seem to represent a state closer to equilibrium. Since this state is the one desired by most people, we need to understand the factors that allow it to occur. The more stable shore sectors generally consist of till resting on, or immediately adjacent to, shorefaces of bedrock, high enough to protect the till from rapid wave erosion and of course tough enough to resist its own erosion. The height of such shelves in these more-stable sectors varies from place to place, depending mostly on the local height of storm waves (W), the tidal range (T), and susceptibility to storm surges (S) (Fig. 2). The requisite height of bedrock shelves based on these three variables is shown as $0.5(T+W)+S$, represented on Figure 2 as the difference between line 1 (mean sea-level) and line 2, assuming net sediment removal (i.e. requiring a headland-like situation), tough bedrock, and friable till. Note that coastal sectors with only moderate wave energy may still require high bedrock shorefaces if the tidal range is high, allowing smaller waves to reach unprotected till (as in 'flower-pots' along the Bay of Fundy). Where storm surge is appreciable and/or frequent there may be a similar result.

If in Figure 2 an arbitrary rise in sea-level disturbs this seemingly stable situation (new mean sea-level at line 3 on Figure 2), every aspect of the shore would have to adjust to reach a new state of stability, and the new stable bedrock shoreface height would be at line 4. As this new equilibrium height is projected into the cliff, the point at which it intersects bedrock is the new stable shore position. The position of this point depends on the slope of the surface between bedrock and overlying friable glacial till. Two contrasting scenarios of eventual shore retreat, based on different bedrock slopes, are presented (Fig. 2). If the seaward slope of the contact is steep, the point of intersection (the new stable shore position) is near the present shore, at point A. If instead the slope is very low, the point of intersection is

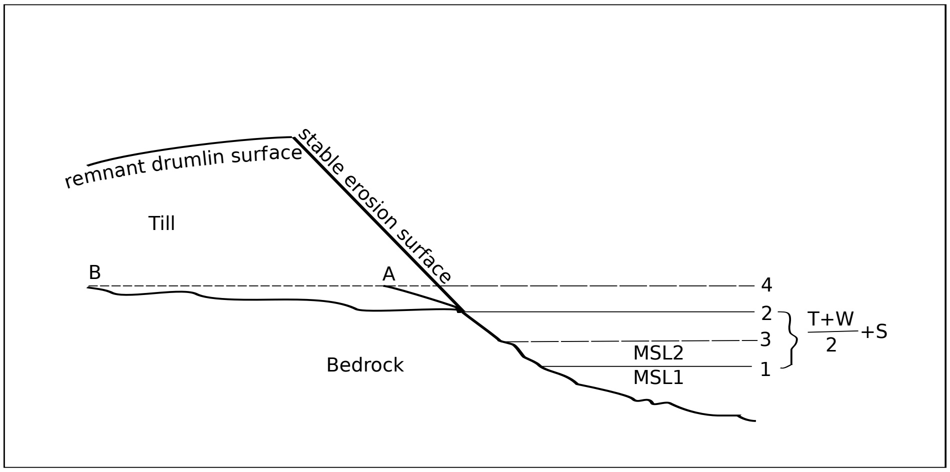

Figure 2. Cross-sectional diagram of a drumlin shore showing the height of bedrock shoreface needed for erosional stability, i.e. temporary equilibrium, showing also the effect of higher sea-level stand assuming two different attitudes of subsurface bedrock contact. Stability requires the bedrock shoreface to extend 0.5(*T*+*W*) +*S* above mean sea-level (MSL1, line 1); this stable position is line 2. If mean sea-level rises to line 3 (MSL2, line 3), the new stable bedrock shoreface height is at line 4. See text for discussion. *W* = local height of storm waves (*W*); *T* = tidal range (*T*); *S* = height of storm surges.

much farther back, and the shore remains unstable until retreat has reached that point (point B). That is, the magnitude of retreat (in map view) varies with the cotangent of the bedrock slope angle. Note that local undulations (Fig. 2) in the bedrock surface could make shore retreat rates vary greatly.

Several complications to this simple model are common. First, where glacial material is resistant, erosion rates may be insufficient to prevent the hypothetical equilibrium. For example, where glacial till is exceedingly bouldery, displaced boulders may form a lag at the base of the eroding scarp that is resistant to further erosion (cf. Manson 2002). The resulting talus ramparts may slow shore retreat at constant sea-level, but as sea-level rises, stepover may occur to form bouldery retreat shoals just offshore of the new cliff position.

Second, sediment transported along the shore may be deposited in the plane of the cross-section (Fig. 2) and protect the shore from erosion. Locally, progradation may occur despite sea-level rise, especially between headlands and along their distal flanks (Wang and Piper 1982; Boyd et al. 1987; Shaw et al. 1993a). Thus the geometric model of Figure 2 is most applicable to headlands and their flanks, though beaches tangent to these headlands are also affected.

Third, bedrock toughness varies from place to place. Analysis here assumes that bedrock projects into the wave zone, preserving some semblance of its upper surface. This generally requires considerable induration, more than is shown by most post-Windsor sedimentary rocks of Nova Scotia, for example.

Fourth, bedrock slopes are seldom uniform. Whalebacks separated by bedrock lows are a common arrangement, and this morphology may form cores of the drumlins above. Consequently, coastal drumlin erosion tends to occur at varying rates, depending on the vagaries of nearby bedrock protection.

HOLOCENE SEA-LEVEL HISTORY AND OFFSHORE CONSEQUENCES

In the Holocene, the eustatic sea-level history in the Maritime Provinces of Canada, like that of other coastal areas worldwide, shows a rapid rise of about 1.2 m per century (or about 12 mm/yr) until about 6 Ka, followed by a slower rise (until the last few decades) of about 1.8 mm/yr. In Atlantic Canada, eustatic rise was complicated by postglacial crustal rebound, represented regionally by a moving crustal forebulge and adjacent sag (Quinlan and Beaumont 1981). This non-eustatic but natural factor differs between localities, but in parts of Nova Scotia results in sea-level rise on the order of 2.5 mm/yr. Additional acceleration of sea-level rise beginning in the 20th century, presumably spurred by anthropogenic activities (IPCC 2007), is on the order of 1.3 mm/yr. In some areas the sum of these factors, i.e. the measured modern rates of sea-level rise (about 5.6 mm/yr in the Canso Straits area of Nova Scotia) is about half the rapid early Holocene postglacial rates – thus the urgency to better understand and predict coastal retreat rates (Boyd et al. 1987; Shaw et al. 1993a, b, 1998; Taylor et al. 2011).

The morphology of offshore platforms records the eventual consequences of sea-level rise along drumlin-dominated coasts. Most commonly, the drumlin landforms, so prominent onshore, are obliterated or partially planed-off just offshore, even if Pleistocene material is still extensively exposed (Wang and Piper 1982; Piper et al. 1986; Stea 1997).

The geometric model of potential retreat on drumlin-dominated shores presented herein (Fig. 2) implies that any given rise of sea-level has different expected magnitudes of regional headland retreat depending on the slope of bedrock platforms underlying glacial material. Modern rates of sea-level rise in the region permit this rise to be converted to expected rates of coastal retreat, or elapsed times corresponding to a given magnitude of retreat.

EROSION RATES AND EQUILIBRIUM STATES

Modern rates of coastal retreat on shores exposing glacial material are locally rapid in Atlantic Canada and adjacent northeastern United States. Erosion rates of more than one m/yr have been recorded at a number of localities (Taylor et al. 1985; Boyd et al. 1987; Carter et al. 1990a, b; Shaw et al. 1993a; Manson 2002; Himmelstoss et al. 2006). Some of these are in parts of Nova Scotia where the rate of modern sea-level rise is thought to be on the order of 0.5 m per century.

These figures can be directly related where bedrock slope controls erosion rate. For example, retreat rates of one m/yr at a sea-level rise of 0.5 m per century correspond to bedrock slopes of 0.5% given the conditions shown in Figure 2. Faster retreat rates would imply a lack of sufficient bedrock platform under the glacial material, slower ones steeper bedrock slopes, or any of the complicating features described above that prevent an approach to equilibrium.

To examine whether such conclusions are consistent with known bedrock configurations, an area in southernmost Cape Breton Island will serve as an example.

THE NORTHEASTERN ISLE MADAME EXAMPLE

Regional Context

Isle Madame, which is separated from Cape Breton Island, Nova Scotia by Lennox Passage and St. Peters Bay (Fig. 3), has drumlin-dominated coastal sectors in its northeastern corner, like many other nearby coastal sectors on Cape Breton Island (Wang and Piper 1982). Because this corner's position was (and is) important for navigation, its morphology has been intermittently recorded since 1770, at first via maps and profiles (Fig. 4), then air photos and landscape photos beginning in the 1930s. The Holocene record of deposition and erosion has been described at greater length by Force (2012).

Drumlins in the study area are typically as much as 300 m long, 100 m wide and 25 m high. Where these drumlins are eroding, glacial till is exposed as cliffed coastal headlands like those described above, and comprises a semi-indurated reddish aggregate of boulders, pebbles, grit, sand, silt and clay, in roughly equal proportions. Where the drumlins are better protected from erosion, some are partially submerged, forming an archipelago (Fig. 5). Bedrock is exposed under some cliffed drumlin remnants and consists of north-dipping clastic rocks of Carboniferous age (Force and Barr 2006; Giles et al. 2010). Rock exposure is restricted to the shore, commonly as whaleback outcrops.

The most prominent headland of the area is Cap laRonde (Fig. 1), now tied to the shore by a tombolo, i.e. the cape is attached to the mainland only by oppositely facing beaches. It is a remnant of a drumlin, and as an elongate bedrock outcrop is exposed at low tide offshore of its long axis, it must have been rock-cored to some degree. This and other headlands are linked by steep shingle beaches, behind which are lagoons ('barachois' in local terminology). The only large spit in the area, shown as the Goulet beach/island in Figure 5, is recurved and consists of gravel and seasonal sand accumulations. It is accreting by extending northwestward, and at times in its history it has become an island. Sand and gravel have been excavated on both the Goulet and on other beaches adjacent to Cap laRonde, so that a significant fraction (Force 2012) of recent sediment transport has been in trucks.

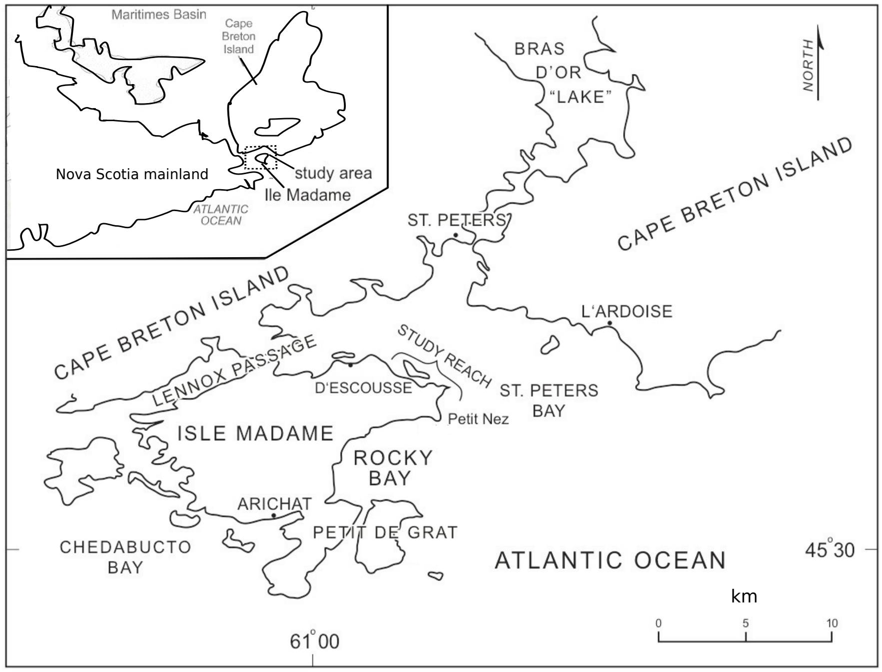

Figure 3. Location of the Isle Madame, Nova Scotia example.

The important natural processes of the area are marine; little sediment is contributed to this coastal sector by fluvial processes. The coast is mesotidal, with 1–2 m tides. Maximum wave energy differs greatly within the area because of variably protected shores. In adjacent open seas, winter waves are generally 1.5–2.5 m, but some waves of greater height are recorded in most years (Wang and Piper 1982; Shaw et al. 1993a). Tropical storms and coast-following circulatory storms can be accompanied by storm surges as much as 1.5 m high (Shaw et al. 1993a).

Headland Erosion

Rates of retreat of the cliff at Cap laRonde were measured at least twice yearly from 2001 to 2010 (Fig. 6) using navigational aids as fixed markers. Shoreline positions in the study area prior to 2001 were established using air photos from 1936, 1953, 1969, 1975, 1983, 1993, and 1998. Published information on events such as successive lighthouses falling into the sea was also useful. Information on shoreline position prior to 1936 was obtained from maps by H. W. Bayfield ca. 1850's (Great Britain Admiralty, 1898), and by DesBarres (1777-81). These maps lack the precision of air photos, but they can be registered with the more recent photo information – a testament to the dedication of the mappers. Plat maps from 1842 and 1877 were also available. Profiles of ca. 1770 landscape features of the area drawn by DesBarres (Fig. 4) and ca. 1932 photographs by Wallace R. MacAskill (Fig. 1) have also proved useful.

The rate of erosion of Cap laRonde is nearly constant over the ten years of measurement, averaging 1.53 m/yr. In detail, the loss is stepwise, related to storm events and to the shifting locus of cliff-top collapse, but

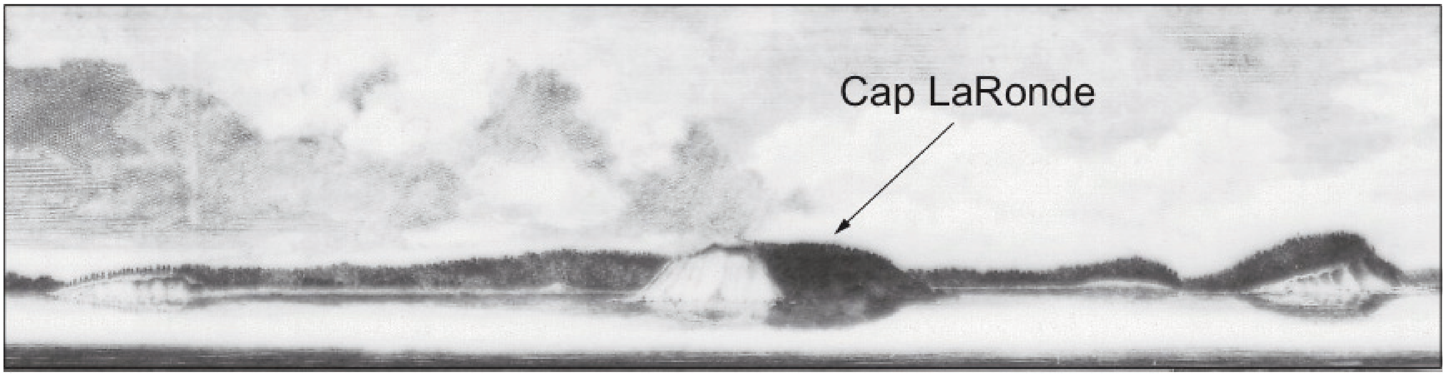

Figure 4. Profile of Cap laRonde and adjacent features, included in the map of DesBarres (1777-81) as an aid to navigation into St. Peters Bay. (The reduced figure resolution is a result of the enlargement of an historic document.)

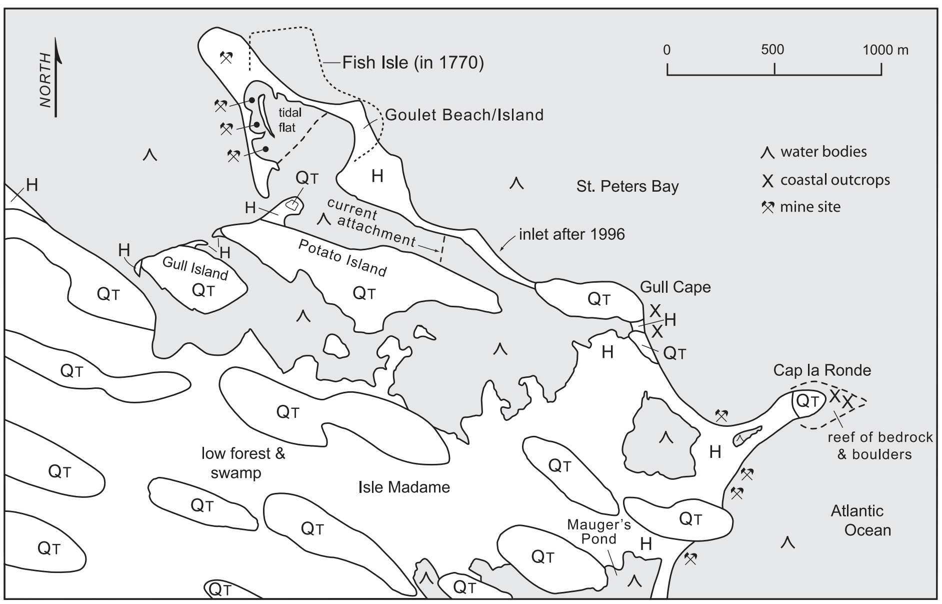

Figure 5. Map of geologic features in the Cap laRonde-Goulet Beach/Island area. QT = Quaternary till; H = Holocene coastal deposits; x = bedrock outcrop. Also shown are beach excavation (mine symbol) locations, changes in the status of Goulet Island that post-date the 1975 base, and the approximate former location of 'Fish Isle' (dotted; from DesBarres 1777-81).

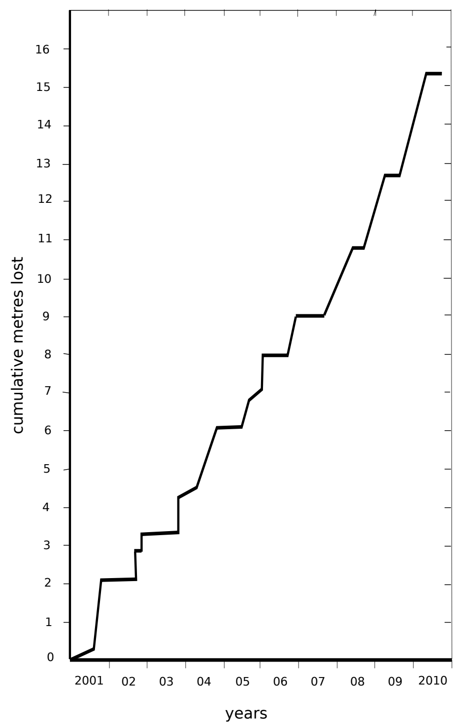

Figure 6. Graph showing progressive retreat of Cap laRonde clifftop from 2001 to 2010. Horizontal and vertical segments document periods of stability and rapid retreat (mostly during storms), respectively; slanted segments represent time intervals that bracket measured retreat positions.

departures from linearity are relatively minor. Rates of retreat this great are startling to local residents (and to scientists from elsewhere). Retreat rates of a few other steep headlands in the area are up to half as rapid as at Cap laRonde, based on less exact measurements.

Measurements from air photos suggest approximate average rates of retreat of Cap laRonde of 0.76 m/yr from 1936 to 1975, and 2.31 m/yr from 1975 to 1998 (National Air Photo Library rolls A5451, 75018, and 98304 for 1936, 1975, and 1998, respectively). Successive cliff positions have been superposed on Figure 1, which also shows that the sea cliff became steeper between 1965 and 1972. The DesBarres map and profile (Fig. 4) have sufficient detail to approximate the position of the cliff out toward the end of the drumlin in 1770. The map suggests that about 80% of the drumlin remained at that time, implying an average cliff retreat for the entire 240-year period of about 0.7 m/year. Thus both lines of evidence suggest that ca. 1970 appears to mark a significant change in the rate of erosion at Cap laRonde, from relatively slow cliff retreat before that time, to a rate that is about double or more afterward. This acceleration of retreat rates corresponds to dramatic changes in the adjacent double-tombolo beaches, which narrowed from about 120 m in 1847, 1877 (these from plat maps), and 1936, to about 100 m in 1975, and 60 m at present (Figure 7 in Force 2012), partly because of mining excavations on the beach (mostly after 1970). The unnamed bluff south of Cap laRonde, which did not project into the ocean until after 1936, subsequently became a cape by retreat of adjacent beaches; for example, the beach at its southeast cor-

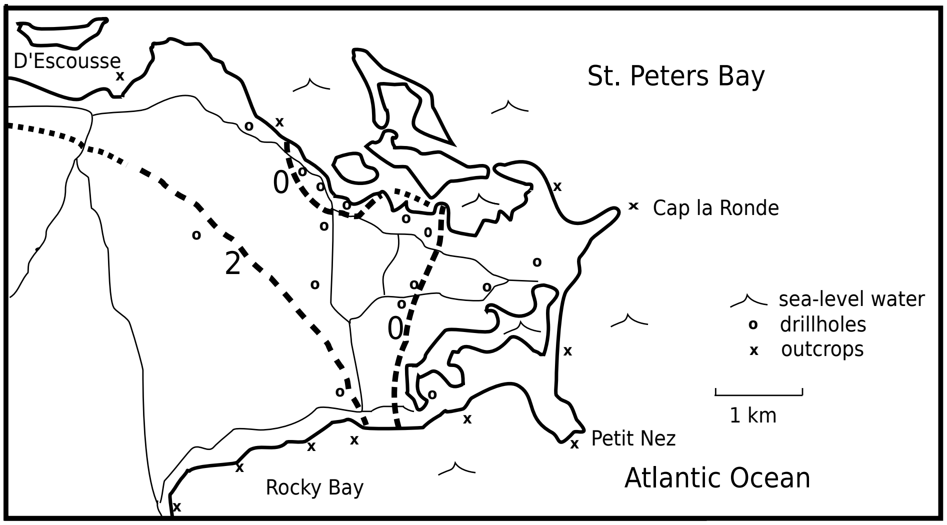

Figure 7. Map of the northeastern part of Isle Madame showing approximate contours in metres (0 m, 2 m; heavy dashed line, dotted where uncertain) of the bedrock surface above sea–level. Controls from outcrops (all coastal) and water wells (drillholes) are shown. Light lines are roads.

ner moved back about 50 m between 1969 and 1975. The acceleration of shore retreat around 1970 is probably the result of a combination of beach excavations, the pullback of the eroding cliff from its bedrock base, and accelerated sea-level rise.

Looking back over the 240-year period of observation, entire former coastal landforms have vanished with few traces. For example, the map of DesBarres (1777-81) shows Fish Isle (Fig. 5) north of the modern Goulet beach; this island is now represented only by intertidal boulder shoals that mark its former flanks (cf. Taylor and Shaw 2002) and by chenier-like progradational accumulations in its former lee, now fossilized behind Goulet beach (Figure 9 in Force 2012). The vanished Fish Isle is a link between studies of current retreat rates and the Holocene history of planation of glacial features as sea–levels rose to impinge on them.

Subsurface Information

The Cap laRonde study area makes an interesting test case of coastal retreat governed by a number of factors that vary spatially over small distances. The most obvious include wave regime and sediment supply (or anthropogenic extraction!). Another is the morphology of bedrock surface on which the retreating cliffs rest; where these are whaleback-shaped, their seaward slopes may erode very slowly, and the distribution of bedrock outcrops influences the distribution of coastal retreat. These local factors together might be thought to control the morphologic evolution of a coastal sector, and in a purely mechanical sense they do, but the regional bedrock surface might exert a longer-term influence.

Publicly available water-well information from the Cap laRonde peninsula can be used to supplement the known distribution and height of coastal outcrops to help delineate the bedrock surface (Fig. 7). Quality of well location and lithologic description vary; only fourteen properly-located wells are known to intersect the bedrock – overburden contact. They show significant variation from a simple planar bedrock surface, apparently due to bedrock-cored drumlins. Six wells show a bedrock surface lying above sea-level, to which can be added the coastal outcrops, especially the high outcrops along Rocky Bay. However, in eight wells, the bedrock surface lies at or below sea-level (Fig. 7). Tracts of a square kilometre or more can be delineated where available bedrock protection at current sea-level is scanty at best. An east-west cross-section from the center of the Cap laRonde peninsula toward its eroding coastal segments shows an average bedrock slope of about 0.22%.

Rapidly eroding coastal drumlins, many of which rest on isolated bedrock highs, are temporarily protecting the interior of the peninsula, where the bedrock surface is commonly below sea-level. In this sense, much of the interior is already vulnerable with respect to coastal erosion; as each drumlin bulwark is eroded and its rock core by-passed, an entire tract behind will be eroded without cliffs being formed, possibly as a retreating beach. This process has apparently occurred before, as when Fish Isle was eroded.

Over the course of the next century, local sea-level will probably rise about 0.56 m. Given the calculated average slope and contours shown in Figure 7, coastal retreat in the area should average about 255 m. Several additional square kilometres of land will be vulnerable, although the degree of risk varies with the kinetics and distribution of erosion. Current retreat rates of 1.53 m/yr at Cap laRonde translate to a loss of only 153 m in this period, but considering that the areas behind some of these retreating headlands – notably behind Cap laRonde – are not only low and offer little resistance, but also are characterized by bedrock surfaces below current sea-level, erosion of these headlands can be seen as a rate-limiting step, depending on how fast sediment can be removed from the entire peninsula. The retreat predicted by bedrock slope and that based on current observations differ by a factor of 1.67, not a large discrepancy considering the many variables involved. The rate based on bedrock slope and that based on comparison of 1975 – 1998 air photos differ very little. From the perspective of regional bedrock slope, the current galloping retreat of Cap laRonde is actually less than it might be despite the effect of beach excavations.

A CIVIC IMPLICATION

Generally, upper surfaces of bedrock slope seaward throughout the regions addressed here, as this slope basically controls the distribution of land and sea. The degree of seaward slope varies widely, however, and the northeastern Isle Madame example shows that regional bedrock slope may be quite small and surpassed by local variations. In such cases, shore retreat is potentially rapid, limited mostly by the kinetics of removal of the glacial material that forms the more obvious cliffs and bluffs.

Eventual shore positions depend on the configuration of the bedrock surface, as bedrock in the shoreface is required to slow or halt retreat. Along many vulnerable shores, systematic information on the bedrock surface is lacking. Mapping of this surface under the land along coasts fronted by glacial material is needed, in order to predict coastal retreat scenarios. A first step in such subsurface mapping can be comprehensive use of existing water-well logs, which in many coastal communities are sufficiently numerous to outline areas of greatest vulnerability.

CONCLUSION

Most coasts exposing glacial material are at best in fragile states of temporary equilibrium with respect to wave energy, tidal range, and storm surges; they are stable only if they are protected by platforms of tough bedrock on which glacial debris rests, by short-lived talus ramparts, or by locally abundant sediment supply. The height of the bedrock platform is an essential part of the equilibrium condition. As sea-level rises, the equilibrium position of the shoreline must move to maintain the same bedrock protection. How much it must move is a function of the slope of the upper bedrock surface under glacial material.

An example shows that some rapidly eroding coastal segments are significantly out of equilibrium already, but are temporarily relieved by slow kinetics; i.e., the bulk rates of removal of glacial material and eroded debris are limited. Rising sea-level in many areas could change coastal morphology significantly if the new equilibrium position is far different and kinetic rates are accelerated – and they can be accelerated by human activity. Systematic inventory of subsurface bedrock position is needed in evaluating these risks along drumlin-dominated and other glaciated shores.

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