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Résumé de l'article

Processus des plates-formes littorales de l'est du Canada. Une plate-forme littorale d'argilites soumise à des marées modérées à Mont Louis en Gaspésie, Québec, et des plates-formes soumises à des fortes marées dans les basaltes de Scots Bay et les grès de Burncoat Head de la Nouvelle-Écosse furent étudiées. Des échantillons de roches ont été soumis à des cycles de mouillage et de séchage et d'haloclastie. Le profil des plates-formes a été mesuré, la dureté des roches a été établie par le test du marteau de *Schmidt*, les vagues ont été mesurées sur le terrain et le taux d'usure vertical a été quantifié à 56 stations avec des appareils détectant la micro-érosion, le tout sur une période d'un à trois ans. L'altération est le processus dominant à Mont Louis, bien que la plate-forme horizontale ait été entaillée par les vagues au maximum des marées hautes. L'usure horizontale par les vagues était plus importante que l'usure verticale par altération durant l'Holocène à Scots Bay. L'extraction de grands blocs par les vagues ne se produit toutefois de nos jours que sur quelques abrupts et, en l'absence de matériel abrasif, une lente usure verticale domine maintenant sur la plupart des plates-formes. Les vagues ont probablement aidé à éliminer les grains de sable produits par l'altération à Burncoat Head, contribuant ainsi à l'usure verticale de la plate-forme. L'abrasion est également importante à certains endroits, mais les données indiquent que l'usure horizontale par les vagues, et aussi par le gel, a été un peu plus importante que l'usure verticale par l'abrasion et l'altération durant l'Holocène.

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SHORE PLATFORM PROCESSES IN EASTERN CANADA

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ABSTRACT This research is conducted on a mesotidal, argillite shore platform at Mont Louis in Gaspé, Québec, and on macrotidal platforms in the basalts of Scots Bay and the sandstones of Burncoat Head in Nova Scotia. Rock samples have been subjected to wetting and drying and to salt weathering cycles. The platforms were surveyed; rock hardness was determined with a Rock Test Hammer; waves were recorded in the field; and downwearing rates were measured at 56 micro-erosion meter stations over 1 to 3 years. Weathering is the dominant process at Mont Louis, although the horizontal platform may have been cut by waves at the high tidal level. Wave backwearing was much more important than downwearing by weathering during the Holocene at Scots Bay. Wave quarrying only occurs on a few scarps today, however, and without much abrasive material, slow downwearing now dominates over most of the platform surface. Waves probably help to remove loosened sand grains at Burncoat Head, thereby contributing to platform downwearing. Abrasion is also important in places, but the data suggest that backwearing by wave quarrying and probably frost has been a little more important than downwearing by abrasion and weathering during the Holocene.

RÉSUMÉ *Processus des plates-formes littorales de l'est du Canada.* Une plate-forme littorale d'argilites soumise à des marées modérées à Mont Louis en Gaspésie, Québec, et des plates-formes soumises à des fortes marées dans les basaltes de Scots Bay et les grès de Burncoat Head de la Nouvelle-Écosse furent étudiées. Des échantillons de roches ont été soumis à des cycles de mouillage et de séchage et d'haloclastie. Le profil des plates-formes a été mesuré, la dureté des roches a été établie par le test du marteau de *Schmidt*, les vagues ont été mesurées sur le terrain et le taux d'usure vertical a été quantifié à 56 stations avec des appareils détectant la micro-érosion, le tout sur une période d'un à trois ans. L'altération est le processus dominant à Mont Louis, bien que la plate-forme horizontale ait été entaillée par les vagues au maximum des marées hautes. L'usure horizontale par les vagues était plus importante que l'usure verticale par altération durant l'Holocène à Scots Bay. L'extraction de grands blocs par les vagues ne se produit toutefois de nos jours que sur quelques abrupts et, en l'absence de matériel abrasif, une lente usure verticale domine maintenant sur la plupart des plates-formes. Les vagues ont probablement aidé à éliminer les grains de sable produits par l'altération à Burncoat Head, contribuant ainsi à l'usure verticale de la plate-forme. L'abrasion est également importante à certains endroits, mais les données indiquent que l'usure horizontale par les vagues, et aussi par le gel, a été un peu plus importante que l'usure verticale par l'abrasion et l'altération durant l'Holocène.

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INTRODUCTION

There has been considerable debate over the last century on the occurrence and origin of two types of shore platform. Gently sloping platforms extend from the cliff base to below the low tidal level without any marked breaks in slope, other than those that are local expressions of structural or lithological influences. Gently sloping platforms are particularly common along the shores of the North Atlantic and in other stormy, mid-latitude environments, and they have generally been attributed to mechanical wave erosion (Everard *et al.*, 1964; Trenhaile, 1972; Sunamura, 1992). Subhorizontal shore platforms terminate abruptly seawards in low tide cliffs that are often several metres in height. Most of the literature on subhorizontal platforms has been concerned with Australasia, although these platforms are common in many warm temperate and tropical regions. Because waves operate over a range of elevations, according to tidal and weather conditions, some workers have contended that horizontal platforms are the product of weathering processes (Bartrum, 1916; Bird and Dent, 1966; Healy, 1968; Stephenson and Kirk, 2000a).

The traditional literature has largely attributed global differences in shore platform morphology to climate and wave conditions, but recent work has emphasized the importance of tidal range. Trenhaile (1987, 1999, 2000, 2001) has proposed that the tendency for mean regional platform gradient to increase with tidal range reflects the degree to which wave generated forces are concentrated within the vertical plane. Tidal range also determines the frequency of inundation and the length of the wetting and drying periods at different elevations within the intertidal zone. The range of the tide may therefore control the vertical efficacy of weathering processes and provide an additional, or alternate, explanation for the relationship between platform gradient and tidal range (Trenhaile, 2003, 2004). This paper describes a series of ongoing investigations concerned with the relationship between platform processes, tidal range and shore platform morphology in eastern Canada.

STUDY AREAS

The enormous variation in tidal range in eastern Canada has produced regionally dominant horizontal platforms, extending over a hundred kilometres or more in some areas, and sloping platforms in others. Studies are being conducted on sloping platforms in the Bay of Fundy, in Triassic basalts at Scots Bay (Crosby, 1962) and in soft Middle Triassic sandstones at Burntcoat Head. A horizontal platform in Middle Ordovician argillites (low grade metamorphosed shale) of the Cloridorme Formation is being studied at Mont Louis in Gaspé, Québec (Enos, 1969; Fig. 1).

Tidal regimes in the study areas are semi-diurnal, although there is generally some inequality in the height of the two daily high tides at Mont Louis. The Large Tide Range (Table I) is 13.5 m at Scots Bay, 16 m at Burntcoat Head (the highest range in the world), and 3 m at Mont Louis (Canadian Hydrographic Service, 2006). In the Bay of Fundy, wave direction is most frequently southwesterly, westerly and northwesterly. Almost half the deep water waves have a significant wave height of less than 0.5 m, and a peak wave period of less than 4 s. Shore-fast sea ice protects the coast from storm waves from January to April. Waves approach the Gaspé coast most frequently from the west and northwest. About 15% of the deep water waves have a significant wave height of less than 0.5 m,

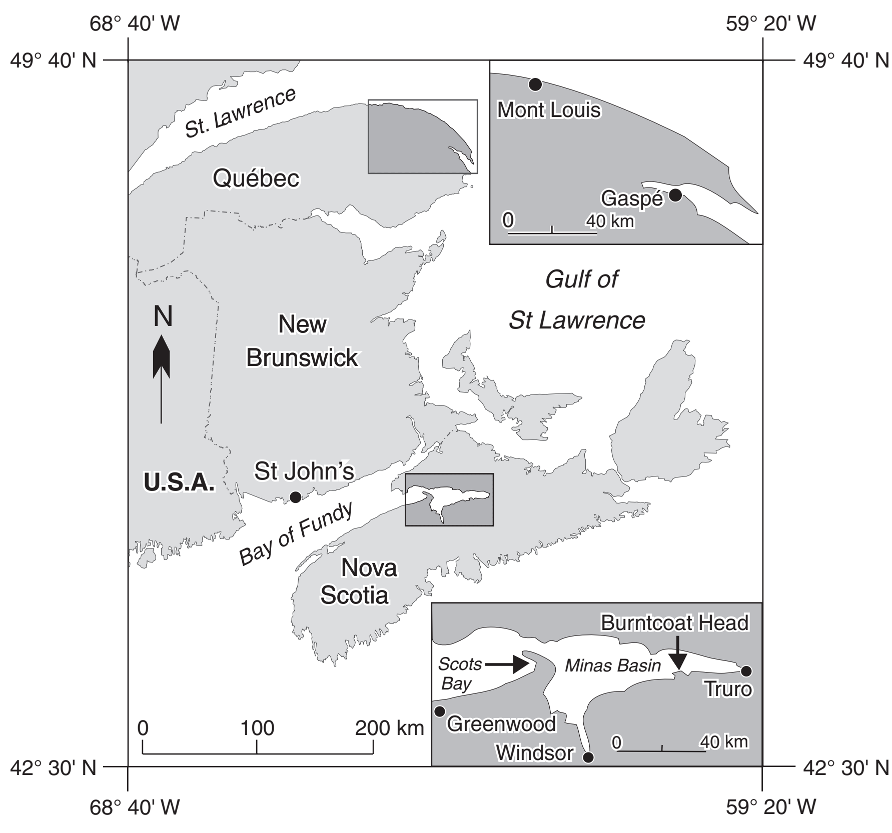

FIGURE 1. The study areas at Mont Louis, Québec, Scots Bay and Burntcoat Head, Nova Scotia.

Les régions étudiées à Mont Louis, Québec, Scots Bay et Burncoat Head, Nouvelle-Écosse.

and about 46% of the peak wave periods are less than 4 s. The coast is protected from high waves by ice in winter, but there are less frequent periods of high waves in spring and fall (Eid *et al.*, 1991).

The exposed portion of the Scots Bay platform, which is from 100 to 120 m in width, extends from the landward end of a sandy tidal flat, 1-2 m below the mid-tidal level, up to a grass covered rock bluff, a few metres in height, near the High High Water Large Tide level (HHWLT) (Table I). The study area has a concave-upwards profile, with a gradient of about 7.5° in the upper part of the platform, 4.25° in the central portion and 3.5° in the lower part. The platform at Burntcoat Head is between 375 and 450 m in width. The profile in the study area is irregularly concave upwards, with a gradient of 2.5° in the upper portion and between 1° and 1.5° in the lower portion. The platform is backed by a steep, active rock cliff about 20 m high. The Mont Louis platform is horizontal, between 170 and 200 m in width, and at an elevation about 1 m above the mid-tidal level. The low cliff is a few metres in height and there is a steep coarse-grained beach at its foot; the platform terminates abruptly seawards in a low tide cliff of unknown height (Figs. 2-3).

TABLE I

Canadian Tidal definitions
(from Canadian Hydrographic Service, 2006)

Large Tide Range	The difference between higher high water (HHWLT) and lower low water (LLWLT) at large tides
Mean Tide Range	The difference between higher high water (HHWMT) and lower low water (LLWMT) at mean tides
HHWLT	The average of the highest high waters, one from each of 19 years of predictions
LLWLT	The average of the lowest low waters, one from each of 19 years of predictions
HHWMT	The average of all the higher high waters from 19 years of predictions
LLWMT	The average of all the lower low waters from 19 years of predictions

The study areas in the Bay of Fundy are experiencing crustal subsidence associated with glacio-isostatic adjustment. According to Andrews (1989), relative sea level has risen by more than 6 m in the last 2000 years, and it is presently rising at a rate of 2 m per 1000 years. There has also been an accompanying change in tidal range in the Bay of Fundy (Amos, 2004). Historical and tidal gauge records indicate that relative sea level has risen by 40 cm in the last 100 years. Dionne (2001) reasserted that glacio-isostatic uplift has generally

FIGURE 2. The shore platforms: (A) Mont Louis, Québec, (B) Scots Bay, Nova Scotia, (C) Burncoat Head, Nova Scotia.

Les plates-formes littorales : (A) Mont Louis, Québec, (B) Scots Bay, Nouvelle-Écosse, (C) Burncoat Head, Nouvelle-Écosse.

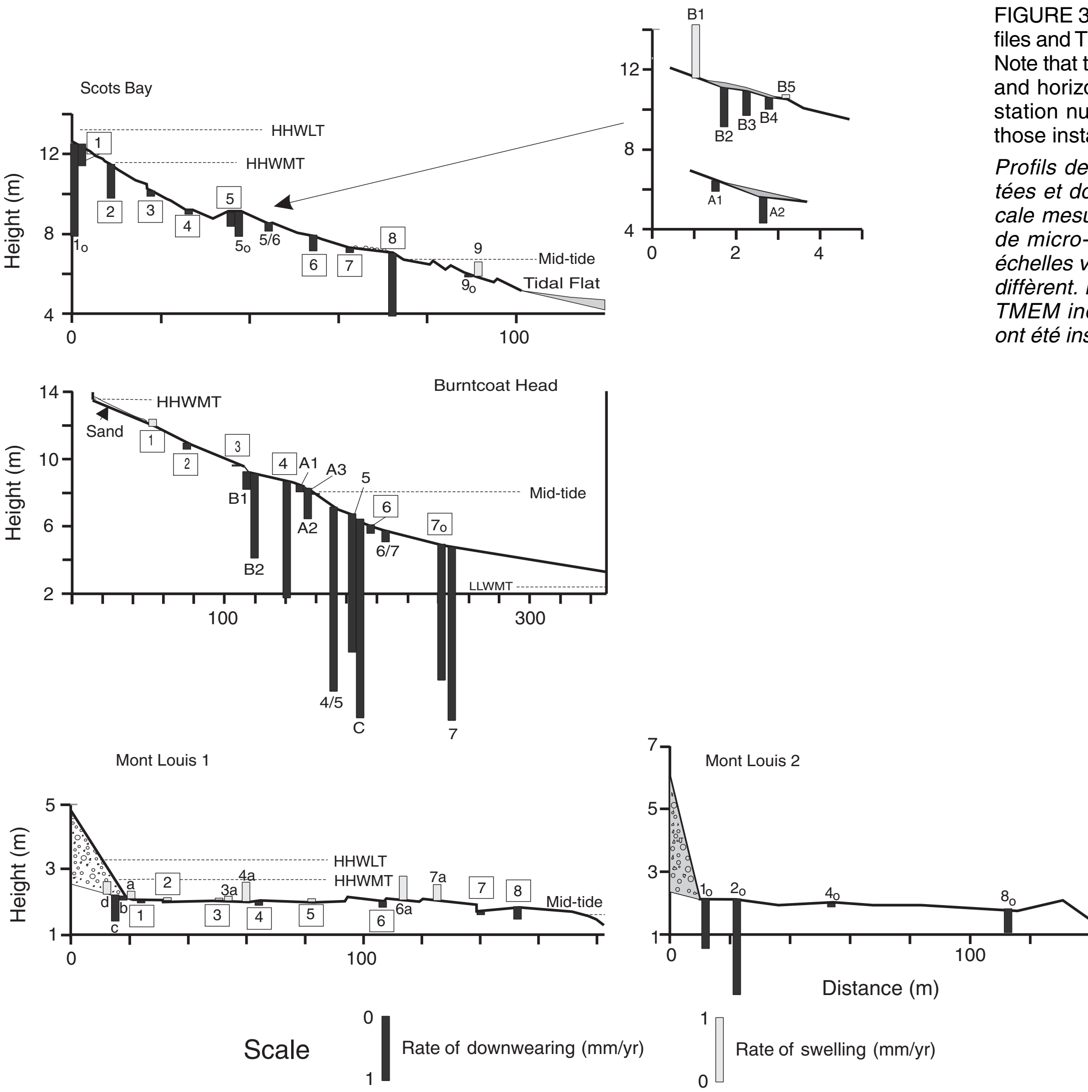

FIGURE 3. Surveyed platform profiles and TMEM downwearing data. Note that there are different vertical and horizontal scales. The TMEM station numbers in squares were those installed in May 2003.

Profils des plates-formes arpentées et données de l'usure verticale mesurée avec des appareils de micro-érosion. Notez que les échelles verticales et horizontales diffèrent. Les numéros de station TMEM indiqués dans les carrés ont été installés en mai 2003.

caused relative sea level to fall over the last 10 000 years in Gaspé (Locat, 1977; Lortie and Guilbault, 1984), but he identified several marked fluctuations over the last 8000 years, with periods of regression and transgression and sea levels higher and lower than today's (Fig. 4). Present changes in relative sea level are poorly known in Gaspé, and the data derived from tidal gauges in different locations are often contradictory, although geomorphological evidence suggests that relative sea level is rising slowly today (Dionne, 2001).

METHODOLOGY

Experiments have been conducted on tidally induced rock weathering in the laboratory, and platform downwearing has been measured in the field.

LABORATORY

Tidal simulators were used to study the effect and rate of operation of tidally induced wetting and drying and salt weathering on shore platforms, with particular reference to the three study areas in eastern Canada (Fig. 5). On each simulator, pumps and timers circulated water from a reservoir into three basins so that rock samples were inundated for either 11, 6 or 1 h, and exposed to air for the remainder of each 12 h tidal cycle, thereby simulating conditions at the low, mid- and high tidal levels, respectively. The experiments were therefore conducted under real-time conditions with no acceleration of the erosive processes. De-ionised water was used in the wetting and drying experiments and commercial artificial sea water in the salt weathering experiments. The sea water, which is produced by Aquarium Systems Inc., has an approximate salinity of 35‰ and contains 28 ions and elements in concentrations that are similar to their occurrence in natural seawater. The temperature and relative humidity of the air were recorded almost every day.

Several slabs of rock were collected from each of the study areas and cut into samples of suitable size in the laboratory. Most samples were in the form of cylindrical cores, 1.9 cm in diameter and 2 cm in length, but because of their friability, the

Burntcoat Head sandstones were cut into cubes with 2 cm long sides. The surface of the rock samples was gently dried each month for weighing, and the loss in weight, relative to core density and surface area, was used to calculate equivalent rates of surface downwearing. The experiments are continuing, but at the time of writing, 675 basalt, sandstone and argillite cores and cubes have experienced almost 1 400 wetting and drying cycles in de-ionized water over a 23 month period. In the salt weathering experiments, 225 cores and cubes have experienced more than 1 000 salt weathering cycles over a 17 month period, and 150 basalt, 96 sandstone and 75 argillite cores and cubes have experienced almost 200 cycles over a three month period. Kanyaya and Trenhaile (2005) found that almost no downwearing took place in most of the cores and cubes in the first few months of the experiments with de-ionized water. Therefore, although the experiments with de-ionized water have been conducted for 6 months longer than those with artificial sea water, we only used data from the first 17 months of each type of experiment in order to compare the effects of wetting and drying and salt weathering.

FIELD

A micro-erosion meter (MEM) consists of an engineer's dial gauge that measures the downward extension of a needle-like probe. The gauge and probe sit on a low, triangular frame that, in use, is positioned on three metal bolts (a MEM station) permanently embedded in the rock surface (High and Hanna, 1970; Robinson, 1976). The instrument allows precise measurements to be made of slow rock downwearing (erosion in the vertical plane) and several workers have used it in the supra- and intertidal zones of rocky coasts (Kirk, 1977; Robinson, 1977; Gill and Lang, 1983; Mottershead, 1989; Stephenson and Kirk, 1998; Foote *et al.,* 2001; Andrade *et al.,* 2002). Unlike the MEM, which allows only three measurements to be made at each station, a traversing micro-erosion meter (TMEM) permits numerous measurements to be made within the triangular frame of the instrument (Trudgill *et al.,* 1981; Stephenson, 1997).

Traversing micro-erosion meter stations were installed along surveyed, shore-normal profiles at Scots Bay, Burntcoat Head and Mont Louis in August 2002. Although many of the bolts soon rusted or broke, a number did remain in good condition and downwearing data were obtained in May 2003 from 8 stations along two profiles at Mont Louis, 3 stations along a profile at Scots Bay and 4 stations along a profile at Burntcoat Head. The original TMEM stations were then abandoned and

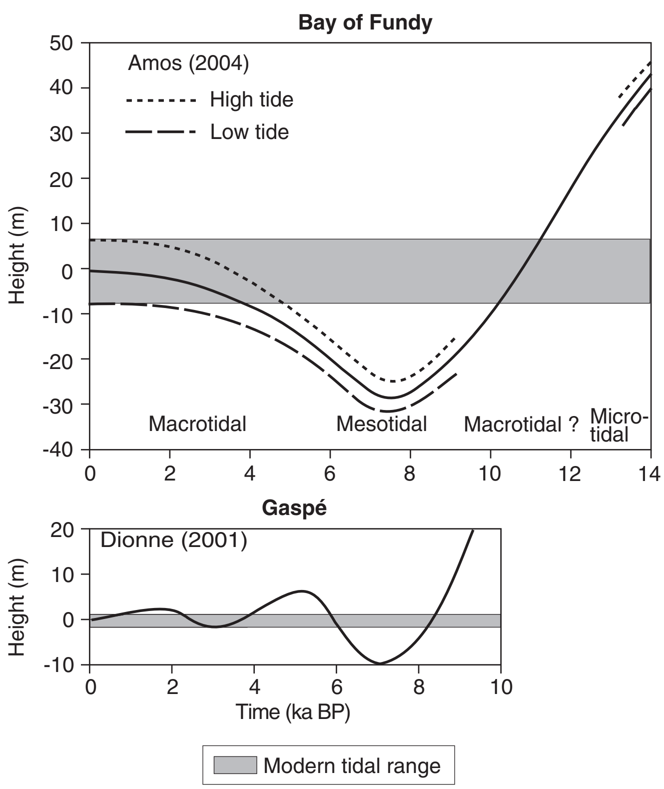

FIGURE 4. Changes in relative sea level on the south shore of the St. Lawrence Estuary (Dionne, 2001) and in the Bay of Fundy (Amos, 2004).

Changements du niveau marin relatif sur la rive sud de l'estuaire du Saint-Laurent (Dionne, 2001) et dans la Baie de Fundy (Amos, 2004).

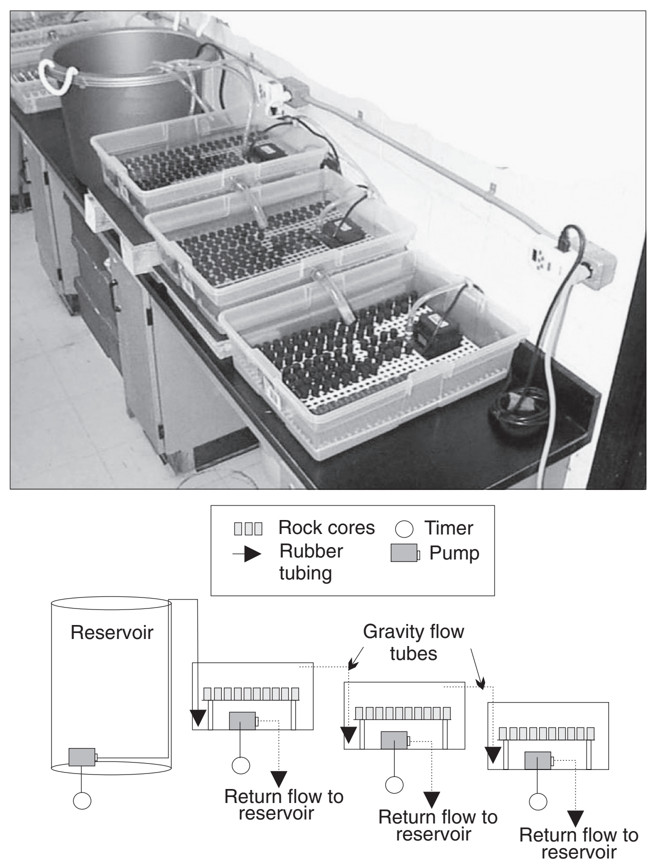

FIGURE 5. Example of a tidal simulator. Four simulators were used to measure rates of downwearing generated by wetting and drying and salt weathering.

Exemple d'un simulateur de marées. Quatre simulateurs ont été utilisés pour mesurer le taux d'usure verticale causé par le mouillage et le séchage, et l'haloclastie.

replaced by 22 new stations, using a higher-grade stainless steel bolt of a more rugged design. These new stations were installed in the three study areas in May 2003, and measurements were made in June 2004. An additional 23 stations were installed in May 2003, and measurements were made at all existing sites in July 2005 (Fig. 3). Data from another 30 stations, which were installed in July 2005, were not available at the time of writing. Mean annual downwearing rates (mm/yr) are reported in this paper from 56 TMEM stations, covering a period from 1 to 3 years. These rates are the means of the seven readings that were made at different points at each TMEM station, calculated from the time of installation to the most recent period of measurement.

The TMEM stations in eastern Canada occupy three types of site, extensive areas of bare rock, the edges of pockets of sand, gravel and other potentially abrasive material, and rock surfaces beneath various thicknesses of beach material. The stations were generally located at roughly equal intervals along surveyed, shore-normal profiles, although it was sometimes necessary to install sites off profile in order to measure the abrasive effect of localized beach deposits. Because of the distance to the study areas and the occurrence of thick sea ice in winter, it has only been possible so far to take measurements each summer.

Several workers have used compressive strength, or the related Schmidt Rock Test Hammer rebound value, to represent rock resistance to coastal processes, and to measure the spatially variable effect of weathering on the strength of the rock (Tsujimoto, 1987; Sunamura, 1992; Haslett and Curr, 1998; Trenhaile *et al.*, 1998, 1999; Stephenson and Kirk, 2000a, 2000b; Andrade *et al.*, 2002; Dickson *et al.*, 2004). In eastern Canada, 30 measurements were made at each TMEM station with an N-type Rock Test Hammer, and the mean of these values was used to represent rock strength at each site.

Waves have been measured over complete tidal cycles at Scots Bay and Mont Louis, using graduated steel poles and video-recorders. Significant and maximum wave height and period were determined at each tidal stage, and nearshore wave equations were used to estimate breaker type, height and period, surf zone width and the dynamic force exerted by the broken waves under more extreme storm conditions (Trenhaile and Kanyaya, in press). Waves were not recorded at Burntcoat Head because the high cliff prevents access to, or escape from, the back of the platform during high tide.

RESULTS

The laboratory experiments showed considerable variation in the rate of breakdown by wetting and drying in de-ionized water between cores and cubes from different rock slabs, and between cores and cubes from the same slab. Nevertheless, the results demonstrated that the argillites are much more susceptible to wetting and drying than the sandstones or basalts (Fig. 6). Mean rates of argillite downwearing increased with elevation in the intertidal zone, and there was a commensurate increase in the proportion of the cores that experienced breakdown. Nevertheless, downwearing rates for individual cores ranged from 0 to more than 3.2 mm/yr. Rates of sandstone cube downwearing, which ranged from 0 up to an extreme of 0.58 mm/yr, were much lower than in the argillites. Sandstone downwearing was fastest at the high tidal level. Although a higher proportion of the cubes experienced breakdown at the mid- than at the low tidal level, the mean rate of downwearing was higher at the low than at the mid-tidal level. A fairly high proportion of the basalt cores experienced some breakdown, especially at the high tidal level, but downwearing rates, ranging from 0 up 0.58 mm/yr, were the lowest of the three types of rock. Mean rates were less than 0.1 mm/yr, and were highest at the mid-tidal level.

The breakdown of rock cores and cubes in artificial sea water is accomplished by salt weathering and alternate wetting and drying, and probably also by some chemical weathering. Nevertheless, wetting and drying in de-ionized water caused

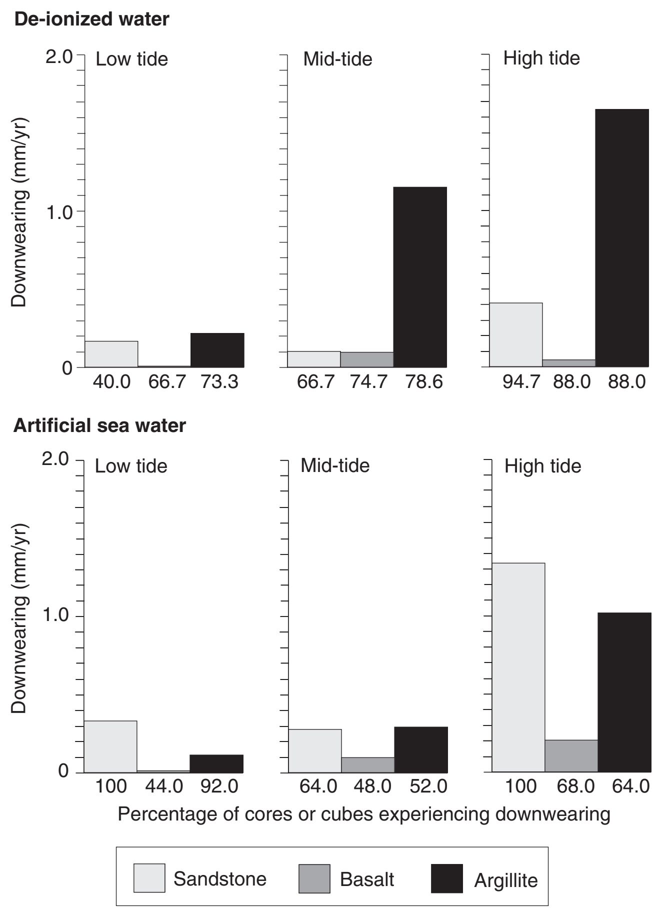

FIGURE 6. Downwearing rates measured over 17 months in de-ionized and artificial sea water. Negative values, caused by increased water retention, and possibly associated with surface swelling, were omitted from the analysis. The numbers listed beneath each column represent the percentage of each rock type sample, at each simulated tidal level, that experienced downwearing.

Taux d'usure verticale mesurés sur une période de 17 mois dans de l'eau déminéralisée et de l'eau de mer artificielle. Les valeurs négatives causées par la rétention d'eau accrue et possiblement associées au gonflement de la surface ont été omises de l'analyse. Les chiffres sous chaque colonne représentent le pourcentage de chaque type de roche qui, à chaque niveau de marée simulée, a subit de l'érosion.

more rapid breakdown of the argillites than the combined effect of these three mechanisms in artificial sea water (Fig. 6). The results therefore suggest that the presence of salts in some way inhibits the effect of wetting and drying in this type of rock, although the experiments need to be run for a longer period to confirm that this unexpected relationship is real. Rates of argillite breakdown in artificial sea water ranged from 0 to almost 2.3 mm/yr. As in the experiments with de-ionized water, breakdown was fastest at the high tidal level and slowest at the low tidal level, although there was a much greater frequency of core breakdown at the low than at the mid- or high tidal levels. The sandstone cores were the most susceptible to downwearing in artificial sea water, and rates, and generally frequencies, of breakdown were significantly higher than in de-ionized water. Downwearing rates ranged from 0 to 2.65 mm/yr, and were consistently high at the high tidal level, where all 25 cubes experienced some breakdown. Rates of basalt downwearing were also higher in artificial sea water than in de-ionized water, although breakdown was less frequent. Rates of downwearing ranged from 0 to 0.73 mm/yr and increased with elevation within the intertidal zone.

The TMEM data often show considerable variation in downwearing rates from one year to the next, and sometimes between adjacent sites that are on the same rock stratum and at essentially the same elevation. Therefore, although the number of TMEM sites and the period over which the data have been collected surpass that of most previously published studies of this type, the downwearing data should be treated with some caution until measurements have been made for a much longer period and from more TMEM stations.

The highest downwearing rates were recorded at several TMEM stations near the mid-tidal level in the sandstones at Burntcoat Head (Fig. 3). There was no significant correlation between rock hardness, as measured with the Schmidt Rock Test Hammer, and rates of downwearing in the area extending from TMEM stations 3 to 7, although abrasion may account for fairly rapid erosion at: station B2, which is under about 5-7 cm of sand; station 4-5, which lies a short distance landwards of a pocket of sand; and station C (downwearing of 3 mm/yr) which is in a shallow pothole and under 1-2 cm of sand. The absence of abrasive material in the lower part of the platform eliminates the potential effect of this factor at stations 7_o and 7 (downwearing of 2.09 and 2.66 mm/yr, respectively), and although there is sand in the area around stations 4 and 4-5 (downwearing of 1.76 and 2.83 mm/yr, respectively), their local elevation about 0.5 m above the general platform surface suggests that abrasion is also probably ineffective in these areas. Low downwearing rates at stations 1, 2 and 3 in the upper portion of the profile, where the laboratory data suggest that wetting and drying and salt weathering are most effective, may be attributed to the occurrence of a thin, protective veneer of mud, which is absent at lower elevations.

Downwearing rates were much lower in the basalts of Scots Bay than in the sandstones of Burntcoat Head. Rates ranged from a high of 1.42 mm/yr at station 1_o, to lows of 0.06 and 0.07 mm/yr at stations 4 and 7, respectively. There was only a very low correlation between rock hardness and downwearing rates at Scots Bay. Rates were consistently low below the High High Water Mean Tide level (HHWMT) (Table I), with the exception of station 8, which is on a ridge that stands about 0.5 m above a boulder-covered section of the platform. Although the topography suggests that the rock at station 8 is more resistant than its surroundings, this conclusion is belied by a fairly high rate of downwearing, and a Rock Hammer Rebound Value of 26, compared with 31 at stations 6 and 7.

TMEM data are also available at Scots Bay for 7 stations that were installed about 200 m west of the main profile in the summer of 2004. Stations B1 to B5 are situated along a short, shore-normal line, about 2 m long, in the mid-tidal zone. Stations A1 and A2, which are also shore-normal and mid-tidal, are about 2 m apart and situated approximately 15 m to the east of the B1-B5 stations. Stations B2 to B4 and A2 are beneath several centimetres of basaltic gravel ranging up to about 1 cm in diameter. In each case, downwearing over the last year has been greater at stations under the abrasive material than at exposed stations located on the same rock surface and at similar elevations (Fig. 3). Although there is generally little loose material on the platform at Scots Bay, the data therefore suggest that abrasion is an effective erosional process on the basalt where abrasives are available.

Rates of downwearing at Mont Louis ranged between 0.01 to 1.57 mm/yr, although they were generally quite low, and there was only a very weak correlation with rock hardness. A few workers have reported negative MEM values caused by rock surface elevation or swelling at some stations. Swelling events, ranging in some extreme cases up to several millimetres, can persist for a few months up to a couple of years. They have been attributed to salt crystallization, although wetting and drying is thought to play a less important role (Kirk, 1977; Mottershead, 1989; Stephenson and Kirk, 2001). Only a few TMEM stations on the sandstone and basalt platforms in the Bay of Fundy recorded mean rates of platform swelling (rock surface elevation between measurement intervals), but they were common on the argillite platform at Mont Louis (Fig. 3). This may be partly the result of the uneven yet overall horizontal nature of the platform surface at Mont Louis, which allows shallow, intertidal pools to persist on the platform for long periods. Recent work, however, suggests that negative TMEM values are largely a reflection of the swelling capacities of the argillite's dominant chlorite and illite clay minerals (Trenhaile, 2006).

To study the effect of abrasion, four TMEM stations (a to d) were installed at the rear of the Mont Louis platform in summer 2004. The stations are on the same rock outcrop, roughly aligned along a shore-normal profile, about 3 m long. Station a, which is furthest seawards, and station b are on bare rock surfaces, a metre or so from the foot of the steep, predominantly argillite, beach. Station c is under about 8 to 12 cm of sediment and station d, which is furthest landwards, is under about 25-35 cm of material: these sites have to be excavated from beneath the sediment in order to make the TMEM measurements. Over the last year there has been slight surface expansion at station a, slight downwearing at station b, much more downwearing at station c and expansion at station d (Fig. 3). It is tempting to suggest that fairly fast downwearing at station c is the result of abrasion under a thin deposit that can be mobilized during storms, whereas the lack of erosion at station d reflects the occurrence of a thicker, more immobile deposit (Robinson, 1977). It is questionable, however, whether argillite fragments are effective abrasives, and as the rock surface is kept very wet under the beach, it may be that patterns of downwearing and swelling are, instead, the result of water absorption, salt crystallization, or chemical processes; laboratory experiments are being designed to investigate these possibilities.

There was little relationship between rates of downwearing and rock hardness in each study area, and rock strength accounted for only about 1/4 of the variation in downwearing when the data for all three sites were combined (Fig. 7). Surface elevation determines how often an area is covered by the tide, and the resulting duration of the periods of exposure and inundation. There was no relationship between TMEM station elevation and downwearing rates for the combined data for the three areas, however, although there were significant, albeit fairly weak, relationships between these variables for the basalts of Scots Bay and the sandstones of Burntcoat Head (Fig. 7).

Basaltic rates of downwearing, measured in the field and in the laboratory (in artificial sea water), are fairly consistent, and rates of breakdown in the field, as predicted in the laboratory, are higher at the high than at the mid-tidal level (the lower portion of the platform at Scots Bay is beneath a tidal flat). Sandstone downwearing rates at Burntcoat Head are also fairly consistent with the range of values obtained in the laboratory experiments. The highest downwearing rates are around the mid- rather than the high tidal level, however, which is contrary to the experimental results: TMEM data from the Lower Low Water Mean Tide level (LLWMT) (Table I) were not available at the time of writing. The platform at Mont Louis is horizontal and although the surface is uneven in places, there is little variation in the elevation of the TMEM stations. Rates of downwearing in the field were quite low and consistent with those recorded in the laboratory at the mid-tidal level.

DISCUSSION

The platform at Mont Louis is dry or under shallow water for most of the tidal cycle, and waves break on, or over, the low tide cliff. Deeper water allows fairly large waves to cross the platform during high spring tides, but the cliff base is protected by a coarse-grained beach and only a few upstanding ridges of resistant rock are exposed to wave action at this elevation (Trenhaile and Kanyaya, in press). Nevertheless, there is effective wave erosion at the base of vertical and undercut cliffs all along the Gaspé coast where there are no protective beaches. Given the general absence of abrasive material and the lack of smooth abraded surfaces, this implies that the Mont Louis platform was initially cut by waves near the high tidal level and subsequently lowered by weathering to its present elevation. Although weathering dominates on the platform today, backwearing by waves and frost will gradually assume greater importance. This is, in part, because argillite downwearing rates decline with decreasing platform elevation, and also because weathering by wetting and drying and salt crystallization can not operate today on the floors of the large, shallow pools that cover much of the platform surface. Renewed

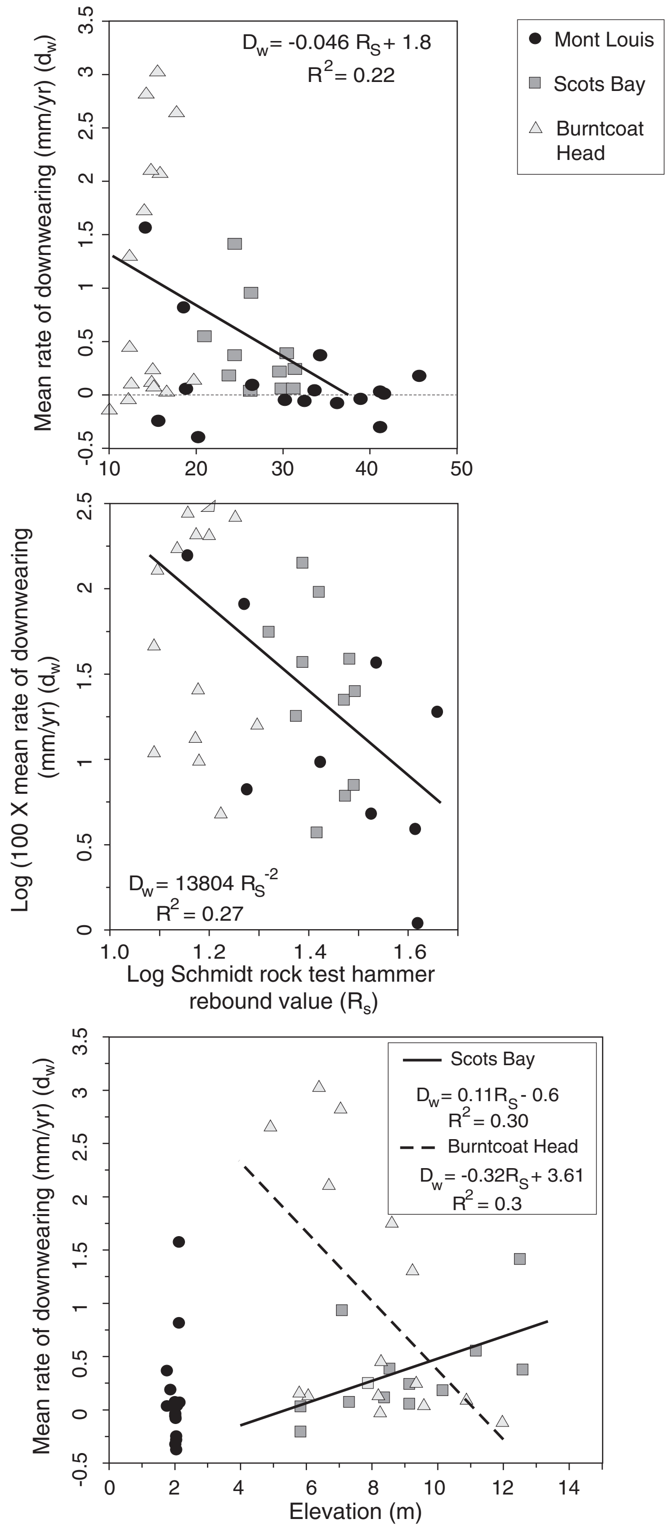

FIGURE 7. Relationships between rock strength, TMEM station elevation and rates of downwearing in the three study areas.

Relations entre la dureté des roches, la hauteur des stations de mesure de micro-érosion et le taux d'usure verticale pour les trois régions étudiées.

downwearing of the weak argillites in these water-filled depressions must therefore wait until the pools are drained, which requires removal of the more resistant, intervening ridges by wave and frost quarrying.

Large joint blocks have been undercut and dislodged along the front of seaward facing scarps at Scots Bay. Backwearing by waves, probably assisted by frost, therefore operates, along with downwearing by weathering, on this platform. The laboratory experiments, which are supported, in part, by the TMEM data, suggest that downwearing rates on the basalt surface are fastest at the high tidal level. The upper portion of the platform, however, also experiences the strongest wave forces and, presumably, the most rapid rates of scarp erosion and backwearing (Trenhaile and Kanyaya, in press).

The laboratory experiments suggest that rates of platform downwearing on the sandstones of Burntcoat Head are much greater at the high than at the low tidal level. The TMEM data show that the fastest rates of downwearing by weathering are actually close to the mid-tidal level, however, in the vertical zone that experiences not only the greatest number of tidal wetting and drying cycles each year, but also the greatest frequency of wave action (Trenhaile, 2003; Trenhaile and Kanyaya, in press): lowering by wave abrasion is also important in shallow potholes and where there is a thin layer of sand. Several workers have proposed that weathering rather than wave erosion is responsible for platform downwearing, which has been found to be faster in summer, when air temperatures are higher and wave action is generally weaker, than in winter (Robinson, 1977; Mottershead, 1989; Stephenson and Kirk, 1998). Turbulent waves may facilitate removal of the loosened, weathered sand grains at Burntcoat Head, however, which would account for the mid-tidal downwearing maximum in the zone of most frequent wave action, and for the discrepancy between sandstone downwearing rates measured in the laboratory and in the field.

Micro-erosion meters allow precise measurement of the rate of surface downwearing on shore platforms. They cannot record the effects of wave quarrying or frost riving of large rock fragments and joint blocks, however, and therefore cannot be used to compare the relative importance of wave and weathering processes. Trenhaile and Kanyaya (in press) have demonstrated that wave generated forces on the coast of Gaspé and in the Bay of Fundy are strong enough to quarry large joint blocks, but because of the episodic and localised nature of block quarrying it has not been possible to quantify its absolute or relative importance in the development of shore platforms. Nevertheless, although one cannot measure directly the contribution of wave and frost quarrying (backwearing), it may be possible to estimate its historical importance in eastern Canada, and potentially elsewhere, by simply subtracting the amount of erosion accomplished by downwearing from the total amount of erosion required to produce a platform.

Most shore platforms are produced by the erosion and retreat of sea cliffs. Cliffs are generally undercut by waves and other marine processes, forming a surface that is initially at the height of the cliff-platform junction (the cliff foot or base). This surface is then gradually reduced in elevation by waves, weathering and biological agencies. The height of the cliff-platform junction, relative to platform elevation, is therefore an indication of the amount of lowering that has taken place at various points within the intertidal zone. The elevation of the cliff-platform junction varies according to rock strength and wave energy, but it is usually close to the high tidal level (Wright, 1970; Trenhaile, 1978, 1987). Although the junction is hidden under a coarse-grained beach at Mont Louis, it is generally close to the HHWMT level along this coast (Trenhaile, 1978). The base of the low cliff at Scots Bay is between the HHWMT and HHWLT levels, and the foot of the undercut, eroding cliff at Burntcoat Head is close to the HHWMT level.

In Gaspé, Holocene sea level has been within or very close to the present tidal range for the last 4000 years, and for only a couple of brief periods previously (Dionne, 2001). To have produced the Mont Louis platform over this time would have required a mean backwearing rate of about 4.5 cm/yr (given a platform width of 180 m), and a downwearing rate of about 0.30 mm/yr (to lower the platform 1.20 m from the HHWMT level to its present elevation). Waves and frost were probably quite capable of attaining cliff backwearing rates of this magnitude in friable argillites, particularly when the platform was much narrower during the earlier stages of development, and the required mean downwearing rate is compatible with measured rates in the field and those obtained in the laboratory (Fig. 8).

In the Bay of Fundy, Holocene mean sea level has also been within the present tidal range for about the last 4000 years (Amos, 2004). Platform formation during the Holocene would therefore have required cliff foot backwearing rates of about 10 to 12.5 cm/yr at Burntcoat Head (width from 400 to 500 m) and, assuming that the platform continues below the tidal flat to the low tidal level with approximately the same gradient, about 3.8 cm/yr at Scots Bay (estimated width of 150 m). For downwearing to have been entirely responsible for lowering platform surfaces in the Bay of Fundy from the elevation of the cliff foot, it would have had to operate at a mean rate of about 3.3 mm/yr at the seaward edge of the Scots Bay platform. The corresponding downwearing rate for the seaward edge of the platform at Burntcoat Head would be about 3.4 mm/yr. Measured rates of downwearing, in the field and the laboratory, are therefore too low to account for the amount of lowering that has occurred at the low tidal level in the Bay of Fundy. Assuming, given the lack of evidence to the contrary, that these platforms are entirely postglacial, other agents, particularly backwearing by waves and frost quarrying, must have been responsible for approximately one-half to two-thirds of the erosion that has occurred at Burntcoat Head, and from two-thirds (based on TMEM downwearing data) to over nine-tenths (based on laboratory downwearing data) of the erosion at Scots Bay (Fig. 8).

A SHORE PLATFORM PROCESS MODEL

There appear to be fundamental differences in the efficacy of the processes operating on the horizontal and sloping shore platforms of eastern Canada, and consequently in the mode of platform development:

(1) Mechanical wave erosion can operate at a variety of elevations on the sloping platforms in the macrotidal Bay of Fundy, although it is generally most effective in the middle to upper portions of the intertidal zone (Trenhaile and Kanyaya,

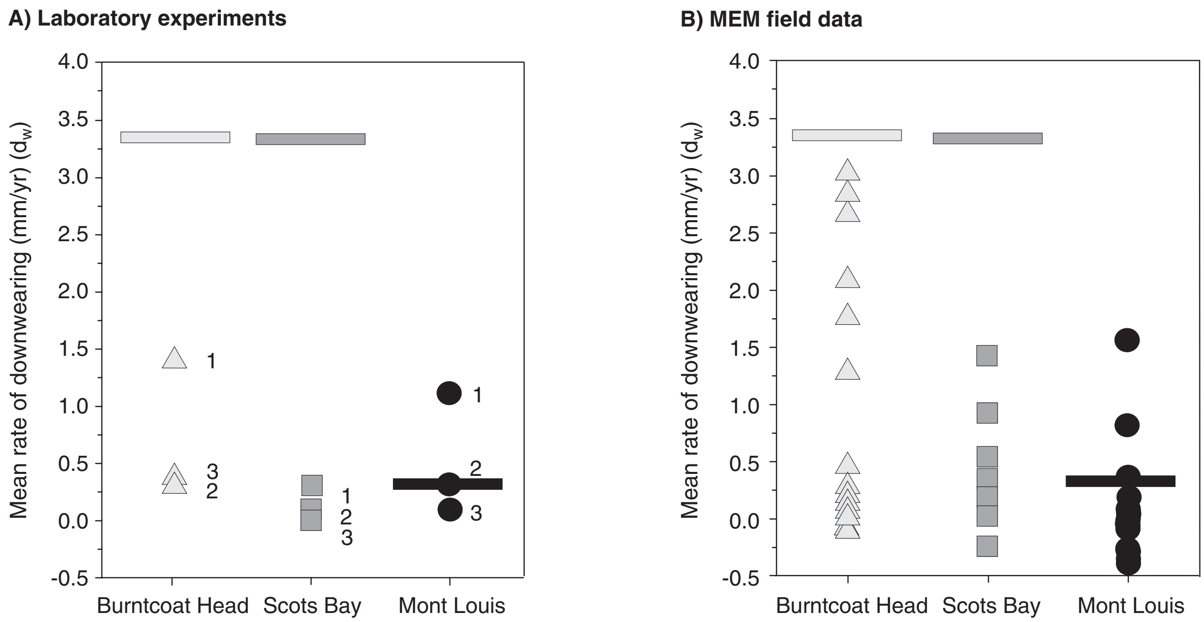

FIGURE 8. (A) Mean rates of laboratory downwearing by weathering in artificial sea water at the high, mid- and low tidal levels (numbered 1, 2 and 3, respectively). (B) Platform downwearing measured in the field with a TMEM. The shaded, horizontal bars represent the mean rates of downwearing, by all processes, that would have been required to reduce the seaward edge of the platforms in the study areas from the high to the low tidal level (LLWLT) (Table I) over the last 4000 years.

(A) Moyenne des taux d'usure verticale en laboratoire obtenus par haloclastie avec de l'eau de mer artificielle pour les niveaux de haute, moyenne et basse marée (numéros 1, 2 et 3). (B) Usure verticale mesurée sur le terrain avec un appareil de mesure de micro-érosion. Les barres horizontales grises représentent les taux moyens de l'usure horizontale qui auraient été nécessaires pour la réduction du rebord des plates-formes des régions étudiées par les marées (LLWLT) (Tableau I) sur une période de 4000 ans.

in press). The experimental data suggest that downwearing by weathering is normally most effective in the higher parts of the intertidal zone. In the sandstones of Burntcoat Head and in other weak rocks that granularly disintegrate, however, waves may accelerate the process by removing loosened, weathered grains. In such cases, the fastest rates of downwearing may be around the mid-tidal level, which experiences most frequent wave action (Fig. 9A).

(2) Waves break on or over the low tide cliff, the abrupt seaward terminus of the horizontal shore platforms that characterize the low mesotidal coast of Gaspé. Several subtypes may be identified which vary according to the relative importance of the backwearing and downwearing agents which, in turn, reflect the mechanical strength of the rock, its susceptibility to wetting and drying and other weathering processes, the tidal range and the strength of the waves. Waves become increasingly less effective erosional agents at the cliff foot as horizontal platforms widen. Weathering can lower the platform surface and increase the depth of the water during high tidal periods, however, thereby allowing the waves to either retain or regain their ability to erode the cliff foot.

Wave erosion at the cliff foot and downwearing by weathering on the platform can produce a more steeply sloping ramp at the foot of the cliff (Fig. 9B) although, as at Mont Louis, the ramp may be concealed under, or replaced by, a beach. Rapid cliff erosion and slow downwearing may produce a horizontal platform near the high tidal level (Fig. 9C). Shallow water over the platform would eventually prevent effective wave action, however, and this condition is therefore likely to exist only in the early stages of platform development when the platform is still very narrow. It is also possible that cliff erosion could essentially cease as a platform became very wide. More rapid downwearing in the upper portion of the intertidal zone would remove any ramp that had previously formed (Fig. 9D). Assuming that mechanical wave erosion, rather than frost, shore ice, wetting and drying or salt weathering, is responsible for cliff backwearing, this is also likely to be a temporary condition, as deeper water over the platform, as it is reduced by downwearing, would gradually restore the ability of the waves to attack and erode the cliff foot.

CONCLUSIONS

The absolute and relative efficacy of the wide variety of processes that operate on shore platforms vary temporally and spatially according to such factors as wave regime, tidal range, air temperature and other climatic factors, rock structure, hardness, mineralogy and other geological characteristics, and the elevation, gradient and other aspects of platform morphology. Although a particular process suite may be dominant at a particular time or in a particular place on a platform surface, the traditional, simplistic assumption that horizontal platforms are formed by weathering and sloping platforms by wave action must be rejected.

Although the various components of this research need to be continued for some time, preliminary field and laboratory data suggest that:

(1) Despite the occurrence of some loose quarried blocks along the scarps of ridges of more resistant rock, wave action

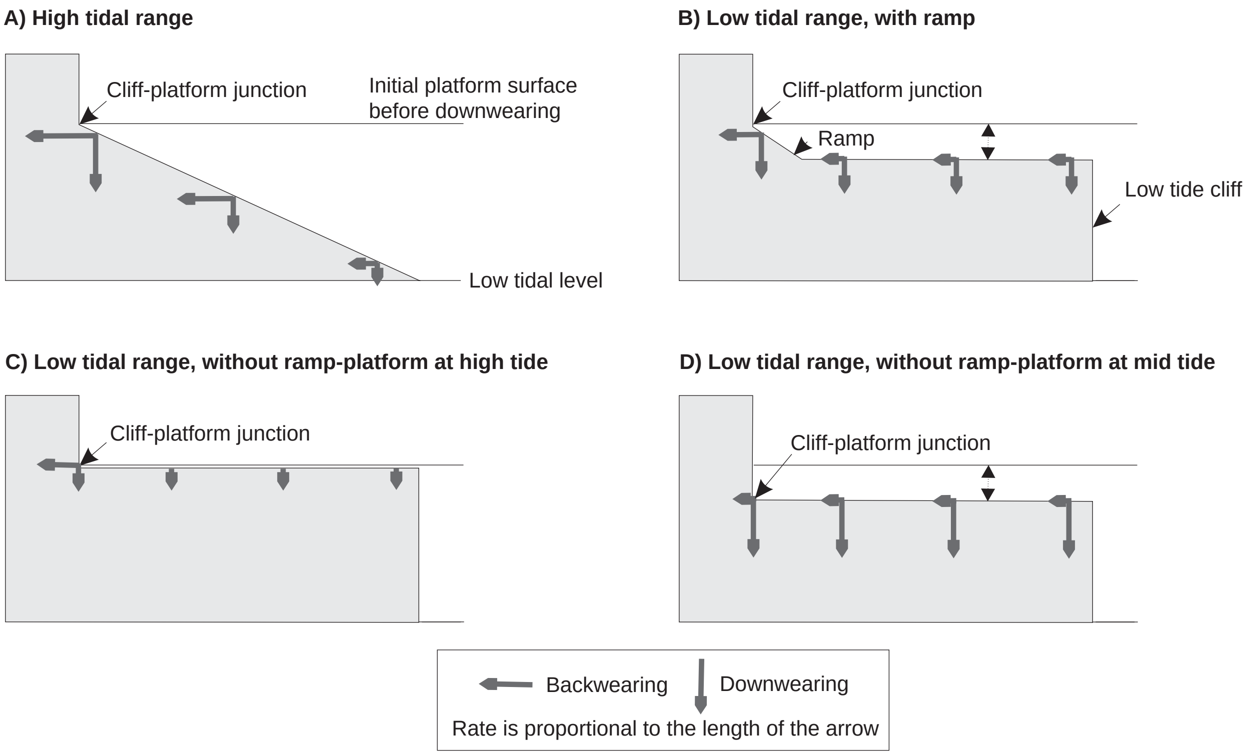

FIGURE 9. A generalized process model for sloping, macrotidal and horizontal mesotidal shore platforms in eastern Canada. Rates of backwearing relative to downwearing will vary from place to place according to such factors as wave regime, tidal range, climate and geology.

Modèle général fondé sur les processus qui génèrent les plates-formes inclinées dans les endroits soumis à des très hautes marées et des plates-formes soumises à des marées modérées dans l'est du Canada. Les taux d'usure horizontale par rapport à l'usure verticale varie d'un endroit à l'autre en fonction de facteurs tels le régime des vagues, la variation du niveau des marées, le climat et la géologie.

is presently largely ineffective on the horizontal, mesotidal platform at Mont Louis. Although the argillaceous platform may have been cut initially by waves at the high tidal level, it is being lowered by weathering today.

(2) The sloping, macrotidal platform at Scots Bay is the product of wave and weathering process. Although backwearing by mechanical wave erosion and frost has probably been more important than downwearing by weathering in the past, backwearing is limited today to the undercutting of a few basaltic scarps and, in the absence of much abrasive material, slow downwearing by weathering dominates over most of the platform surface.

(3) The friable sandstones in the macrotidal, sloping platform at Burntcoat Head are much weaker than the basalts of Scots Bay. Therefore wave action probably plays an important role in removing loosened weathered material, thereby contributing to platform downwearing. Abrasion is significant where there are pockets of loose sand. Although scarps are generally less prominent here than at Scots Bay, the data suggest that backwearing by wave quarrying and probably by frost has been at least as important as downwearing on this platform in the Holocene.

In summary, the results of this study suggest that waves and weathering are both important on sloping shore platforms, which is contrary to recent statements by Stephenson and Kirk (2000b) regarding the inability of waves to erode coastal rocks. Conversely, the results generally support Stephenson and Kirk's (2000a) conclusion that weathering may be dominant today on some horizontal platforms, although the Mont Louis platform may have been cut originally by waves.

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