Subannual Erosion and Retreat of Cohesive Till Bluffs, McNab’s Island, Nova Scotia

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ABSTRACT


The roles of variable geotechnical properties and meteorologic and oceanographic conditions in contributing to the subannual variance in erosion, failure and retreat of cohesive till bluffs have been investigated by comparison of results of 18 months of observations and measurements of bluff erosion, retreat, water content and shear strength with wind speed and direction, water level, wave height, precipitation and temperature. Shear strength of the unconsolidated cohesive till inversely depends on water content which is correlated to erosion and may be increased by precipitation and spray. In stepwise multiple regression, high winds from the direction of longest fetch, high water levels and high precipitation all significantly contribute to erosion. Failures and maximum rates of erosion tend to occur during storms when shear strength (resisting force) is low, and wave activity superimposed on elevated water levels results in increased incident energy (assailing force) at the bluff toe and over till exposures in the foreshore. The assailing and resisting forces are thus inversely related during storms such that thresholds of erosion can be easily exceeded. Erosion occurs at the bluff toe in response to both decreased resisting force and increased assailing force but, at the upper bluff edge, failures and retreat occur mainly due to decreased resisting force with only indirect impacts from increased wave activity. The relative importance of till properties and storms in contributing to subannual bluff erosion and retreat is therefore variable over the bluff profile which may contribute to longer term morphologic evolution of cohesive bluffs.

ADDITIONAL INDEX WORDS: Drumlin bluffs, coastal stability, vane shear strength, till water content, storm waves, storm surges, precipitation, spray, stepwise multiple regression.

INTRODUCTION

McNab’s Island lies at the entrance to Halifax Harbour (Figure 1) and is generally representative of the paraglacial Eastern Shore of the Atlantic Coast of Nova Scotia where distinctive patterns of morphology and evolution are related to late-Quaternary glacial sedimentation and Holocene glacioisostatic processes (FORBES and TAYLOR, 1987; FORBES and SVYITSKI, 1994). Relative sea level has been rising since approximately 11.2 ka (C14 years) (STEA et al., 1994) following deglaciation and the westward migration of a glacial forebulge (QUINLAN and BEAUMONT, 1981). The Halifax tide gauge record shows historical sea-level rise to be stepwise with rates ranging from 0.8 to 8 mm/a and a long-term rate of 3.0 mm/a since 1896 (SHAW et al., 1994). This has interacted with the faulted bedrock of the Cambro-Ordovician Meguma Group and overlying cohesive glacial sediments to form eroding drumlin headlands and deep marsh-fringed embayments partially enclosed by gravel barrier beaches (BOYD et al., 1987). Between 1992 and 1999, relative sea-level rise occurred at 8.0 mm/a (MANSON, 1999). The tidal range is approximately 2 m (CANADIAN HYDROGRAPHIC SERVICE, 1999).

Bluffs in the McNab’s Island area are similar to those on other paraglacial shorelines (e.g. MCGREAL, 1979; CARTER and ORFORD, 1988; PIPER et al., 1986; WANG and PIPER, 1982). They are formed in predominantly cohesive glacial sediments, often with drumlinoid morphology, and may be fronted by drift- or swash-aligned gravel beaches with a seaward outer boulder frame (cf. BLUCK, 1967; CARTER et al., 1990b) or have shore-parallel exposures of till in the foreshore between the frame and the landward beach toe (Figure 2).

Retreat occurs by mass wasting as failures at the bluff edge deliver colluvium to the bluff toe and upper beach where it can be subsequently removed by waves (WILCOCK et al., 1998) thus precluding the development of a stable colluvial slope. Retreat rates of bluffs on the Eastern Shore can reach rates of 9.5 m/a but are more commonly less than 0.5 m/a (TAYLOR et al., 1985; TAYLOR et al., 1995). CARTER et al. (1990a) show long-term bluff retreat may be controlled by longshore gradients in wave height and the wave breaking angle downdrift of drumlin headlands. At McNab’s Island, drift is to the northwest, corresponding to the direction of unlimited wave fetch and parallel to the drumlin trend, and the modal storm wind direction since 1953 is southwesterly (MANSON, 1999). Extratropical or tropical fall and winter storms are known to increase rates of barrier beach retreat when storm surge events coincide with high waves (TAYLOR et al., 1997; 1999; FORBES et al., 1997) but the short term effects of storms on the erosion of bluffs is less well known.
Figure 1. Maps showing location of the McNab's Island study area.

Figure 2. Generalised cross-section of morphology and processes affecting retreat and erosion of a bluff in the McNab's Island area. Retreat at the bluff edge occurs due to decreased resisting force while erosion at the bluff toe occurs due to reduced resisting and increased assailing forces. Not all features are necessarily present. Uncertainty in higher high water (HHW) is contributed by rising sea level and storm surges.
Table 1. Comparisons of the erosion monitoring sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>Cumul. Erosion (m)</th>
<th>Erosion Rate (m/a)</th>
<th>Mean w (%)</th>
<th>Mean S_n (kPa)</th>
<th>Beach Elevation (m)</th>
<th>Wave Angle (deg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M14</td>
<td>2.08</td>
<td>3.42</td>
<td>10.37</td>
<td>123.75</td>
<td>1.39</td>
<td>111</td>
</tr>
<tr>
<td>M15A-25</td>
<td>1.10</td>
<td>1.39</td>
<td>10.04</td>
<td>139.28</td>
<td>1.86</td>
<td>90</td>
</tr>
<tr>
<td>M5</td>
<td>1.74</td>
<td>2.45</td>
<td>11.42</td>
<td>87.45</td>
<td>2.02</td>
<td>110</td>
</tr>
<tr>
<td>L4+40</td>
<td>1.32</td>
<td>1.74</td>
<td>10.09</td>
<td>136.51</td>
<td>2.46</td>
<td>69</td>
</tr>
</tbody>
</table>

Erosion of the bluff toe may be caused by an imbalance between an assaulting force proportional to wave height at the bluff toe and a resisting force proportional to the compressive or shear strength of the bluff-forming material whereby erosion occurs when the assaulting force exceeds the resisting force (Sunamura, 1977; 1992). Material properties that contribute to the resisting force of cohesive bluffs in glacial materials have been considered to be till shear strength (Kamp-Huis, 1987), till sedimentology and stratigraphy (Eyles et al., 1986; Jibson et al., 1994) and groundwater flow (Leatherman, 1986). Previous measurements that define the resisting force of hills near McNab’s Island are grain sizes and Atterberg Limits (Neilson, 1976; Stea and Fowler, 1979; Podolak and Shilts, 1978).

This paper investigates the assaulting and resisting forces and the subannual erosion of till bluffs to determine the relative importance of till properties versus environmental forcing by storm events in contributing to bluff erosion. Grain size, shear strength and water content analyses and results from 18 months of observations and measurements of bluff retreat and erosion, till water content, and environmental indicators of storms are presented and discussed.

METHODS

To investigate the resisting side of the erosion force balance, 14 samples were taken from the various facies of hills in the study area for analysis of grain size and remolded vane shear strength. Grain sizes were determined by wet-seieving to mud, sand, and gravel fractions, each of which were dried and weighed. The mud fraction was further differentiated to clay and silt by hydrometer analysis. The coarse fraction percentage was determined by superimposing a grid on a ground level photograph of the sample site, estimating percent coverage of each square by particles coarser than 64 mm and averaging to give percent by weight (Kellerhals and Bray, 1971).

Undrained remolded shear strength was measured using a laboratory vane shear device that digitally encodes peak torque. Clasts that would interfere with testing (>~ 4 mm) were removed and water was added in small increments until the sample was just moldable. Peak shear strength was calculated by:

\[ S_u = \frac{\tau_{\text{max}}}{C} \]  

(1)

where \( \tau_{\text{max}} \) is peak torque and \( C \) is a constant depending on the shape and dimensions of the vane given by Lu and Bryant (1997) as:

\[ C = \pi D^2 (1 + D/3H) \times 10^{-6} \]

(2)

where \( D \) and \( H \) are the width and height of the vane, in this case each 12.5 mm. After peak shear strength was reached the water content of the sample was determined following standard methods (e.g. Holtz and Kovacs, 1981), another small amount of water remolded into the remaining bulk sample and the shear test repeated. An average of eight tests were performed for each sample, the results from samples of the same facies combined and the relationship of shear strength to water content determined by regression.

Samples of Lawrence Towl Till facies were collected at weekly to monthly intervals from November 1997 to May 1999 to determine the facies variability of natural water contents at 12 locations. Approximately 30 g samples were taken from depths of 2 cm and 10 cm, wrapped in plastic kitchen wrap, sealed in small sample bags and processed following standard methods within 2 days of sampling. Shear strength of natural water content samples was calculated using the appropriate facies-specific relationship of shear strength to water content.

Bluff erosion and natural water content were best monitored at steep bluffs with high retreat rates formed in the clay facies (Table 1; Figures 3 and 4). Three 0.5 to 1.0 m long rebar rods were hammered horizontally into the bluff toe at approximately 0.5 m, 1.0 m, and 1.5 m above the top of the beach (cf. Amin and Davidson-Arnott, 1995). Measurements were taken at weekly to monthly intervals, as logistically feasible, from the exposed end of the rebar rod to the bluff face using a steel ruler. Accuracy of measurement may be ±0.1 cm, but error was contributed by loss of rods as the bluff eroded rapidly during storms, particularly during the winter of 1997/1998, the more stormy of the two monitored winters, when 0.5 m rods were used. As rods were observed...
Figure 4. Photographs of the study area. A) The bluff at M14 showing the 1999 slump and location of erosion monitoring station M14 (circles represent rebar rods). B) A 0.5 m high oblique foreshore scarp located 4 m to the right of rods in panel A. C) The bluff at M2. D) The bluff at M15A with rods of erosion monitoring station M15A-25. E) Tension crack at M11 which formed during heavy precipitation in July 1998. 1.55 m Emery pole for scale. F) A typical bluff-edge failure caused by precipitation without direct contribution from wave attack. Erosion monitoring station L4+40 is located 10 m to the right. G) The bluff at M5 with erosion monitoring station. H) The bluff at M10 in winter. Note ice in leved channel. See also Fig. 7 for profiles.
after some storm events to be loosely in place when one half the length protruded from the bluff, erosion of one half the rod length was assumed when rods were lost. Erosion rates during storms in the winter of 1997/1998 are therefore likely underestimated and not considered in further quantitative analyses.

Retreat and repeat bluff and beach profile measurements were collected annually using Emery poles (EMERY, 1961) or, where and when possible, real time kinematic or dual-phase differential GPS.

To represent the assailing force, records of daily maximum and minimum temperature and precipitation and hourly wind speeds recorded at CFB Shearwater were obtained from the Meteorological Service of Canada (MSC). Hourly water level elevations recorded at the Halifax Harbour tide gauge and deep-water significant wave heights measured at Shear-
water wave-ride buoy (46 m water depth) were obtained from the Marine Environmental Data Service (MEDS) (instrument locations in Figure 1). The wave-ride was in operational for 49% of the monitoring period. Correlation and multiple regression analyses were conducted on 97 positive measurements of the dependent variable erosion and independent variables representing water content, southeasterly to southwesterly storm winds, water level, precipitation and temperature.

RESULTS

Based on mapping, grain size, shear strength and water content, four sedimentologic facies are recognised in the study area (Tables 2 and 3). Exposures of the lowermost, silt-rich Hartlen Till are found at the toes of 2 large southwest-facing bluffs. The overlying Lawrencetown Till consists of an abundant clay facies with sand and gravel lenses which, in turn, is overlain by a 0.5–2 m thick sandy facies veneer (cf. STEA and FOWLER, 1979) which may grade into a third stony facies occupying channels incised into the clay facies. Meguma Group bedrock is exposed only in one embayment on McNab's Island.

Different grain-size facies show different failure styles and shear strength responses to increased water content. Shear strength and water content in the cohesive facies share an inverse power relationship which becomes linear in the non-cohesive stony facies (Figure 5). In the clay and sandy facies the decrease in shear strength occurs over a critical range of water contents corresponding to 10.0–14.0% in the clay facies and 4.0–8.5% in the sandy facies. Lying between the end-members, the sand lens has a different model best represented by three straight lines with some cohesion attributable to the presence of silt; shear strength is maintained to 13.5% water content and then falls.

Measured natural water contents were more variable at 2 cm than 10 cm depth and were found to lie within or above the critical ranges of water contents of each facies (Table 3). Shear strength at each station is plotted in Figure 6 with
erosion. While not well measured at some stations before day 170, in the winter of 1998/1999 shear strength minima and erosion maxima appear to coincide. Water contents of till foreshores were found to be higher than bluff water contents.

Most bluffs in the study area erode too slowly to be measured with horizontal rods and are better characterised by measurements and observations of retreat (Figure 4). Where the sandy facies is thick and where well-developed gravel beaches reduce the frequency of toe erosion (e.g., M10, Figure 4H), a gently sloping, relatively stable colluvial slope may form. Failures on these slopes originate over 1-2 m lengths of bluff scarp during periods of thaw as fluidised flows confined to leved channels that deposit muddy sediment on the upper beach. Usually less than 0.2 m of retreat occurs due to these failures. Leved channels may be occupied by persistent winter ice that forms from groundwater flow from the sandy facies; surface flows and creep are ubiquitous on the semi-vegetated bluff face upon thaw.

Where slump blocks are present, episodic movement along deep-seated rotational failure planes may occur. Repeat bluff profiles (Figure 7) show that the surface of the slump block at M11 increased in elevation due to deposition of material from the landward scarp. Loading of slump blocks by sediment eroded from a landward scarp may contribute to episodic rotational failure, likely assisted by reduced shear strength along failure planes and tension cracks (Figure 4E).

A final style of failure is unique to the stony facies. This facies is a clast-supported glaciofluvial deposit with little silt and clay that forms near-vertical bluffs that fail by toppling of individual boulders. Its failure style in outcrop is controlled by coarse particle arrangement rather than the shear strength of the relatively sparse and non-cohesive matrix (cf. Nasit, 1987). Only 0.1 m of retreat was measured at this site.

Also shown in Figure 6 are time series of precipitation, temperature, wind speed, wave height and water level. Erosion peaks appear to correspond to wind events coincident with increased wave heights, water levels and precipitation and decreased shear strength.

Variables representing wind speed and direction, water level, precipitation, temperature and interior and exterior water content (Table 4) were included in a correlation analysis (Table 5) which shows that erosion is significantly positively correlated with high wind, water level, precipitation and interior water content and that high wind is significantly correlated with all variables (α = 0.05). Precipitation is correlated with neither exterior nor interior water content but both of these correlate positively with each other and negatively with the absolute value of temperature.

In multiple regression, high onshore winds, elevated water levels and precipitation were found to significantly contribute to erosion while till water content was not (Table 6). Stepwise, with the first addition of wind, 25% of the variance in measured erosion was explained (model $R^2 \times 100$); with the second and third additions of precipitation and water level, model explanation increased to 30% and 35% respectively, but did not increase with the addition of water content. The amount of variance in erosion left unexplained is 65%.

**DISCUSSION**

Although the regression model does not explain most of the variance in erosion, high winds from the direction of longest fetch, high water levels and precipitation all contribute significantly. Wind is correlated to both high water levels and precipitation indicating that these tend to occur together during storms, but water level and precipitation are not significantly correlated. As precipitation was generally observed to occur during storms, the lack of correlation is most likely a result of storms occurring at low tide, thus not raising water levels over the chosen 2.0 m threshold.

Despite strong correlation of laboratory water content and shear strength, shear strength calculated from natural water content did not significantly correlate with any other variable. Additionally, measured natural water content was not significantly correlated with precipitation, indicating water content and shear strength were too infrequently monitored to capture the sudden changes in water content that can occur during storms.

Prior to a storm, the bluff face is alternately subjected to wetting and drying and a hard, brittle outer layer can form to a few cm depth (cf. Williams and Jones, 1991). During a storm, with precipitation and spray, water content rapidly increases and erosion thresholds are easily reached by wave energy superimposed on high water levels. Continual wetting, droplet and wave impact, shear strength loss and erosion occur exposing lower water content till. After a storm,

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**Table 2. Results of grain size analyses.**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Facies</th>
<th>Coarse</th>
<th>Gravel</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>97-M1</td>
<td>clay</td>
<td>5.9</td>
<td>10.8</td>
<td>32.3</td>
<td>32.5</td>
<td>17.7</td>
</tr>
<tr>
<td>97-M2</td>
<td>sand lens</td>
<td>0.0</td>
<td>0.0</td>
<td>79.7</td>
<td>16.6</td>
<td>3.0</td>
</tr>
<tr>
<td>97-M3</td>
<td>sandy</td>
<td>1.8</td>
<td>12.4</td>
<td>44.3</td>
<td>31.7</td>
<td>9.8</td>
</tr>
<tr>
<td>97-M4</td>
<td>sandy</td>
<td>2.2</td>
<td>23.7</td>
<td>38.3</td>
<td>29.2</td>
<td>6.4</td>
</tr>
<tr>
<td>97-M5</td>
<td>clay</td>
<td>5.5</td>
<td>15.0</td>
<td>32.8</td>
<td>31.2</td>
<td>14.7</td>
</tr>
<tr>
<td>97-M6</td>
<td>clay</td>
<td>4.0</td>
<td>12.8</td>
<td>25.2</td>
<td>36.7</td>
<td>21.3</td>
</tr>
<tr>
<td>97-M6b</td>
<td>clay</td>
<td>14.0</td>
<td>11.5</td>
<td>22.6</td>
<td>32.9</td>
<td>19.1</td>
</tr>
<tr>
<td>98-M7</td>
<td>clay</td>
<td>4.2</td>
<td>8.5</td>
<td>33.1</td>
<td>32.9</td>
<td>20.8</td>
</tr>
<tr>
<td>97-L1</td>
<td>clay</td>
<td>5.3</td>
<td>10.8</td>
<td>31.9</td>
<td>32.1</td>
<td>19.4</td>
</tr>
<tr>
<td>97-L2</td>
<td>stony</td>
<td>46.4</td>
<td>27.7</td>
<td>19.4</td>
<td>5.1</td>
<td>1.2</td>
</tr>
<tr>
<td>98-L3</td>
<td>sandy</td>
<td>1.4</td>
<td>15.6</td>
<td>48.0</td>
<td>28.0</td>
<td>7.0</td>
</tr>
<tr>
<td>97-H1</td>
<td>clay</td>
<td>3.9</td>
<td>6.9</td>
<td>25.2</td>
<td>35.8</td>
<td>27.8</td>
</tr>
<tr>
<td>97-H2</td>
<td>Hartlen</td>
<td>9.9</td>
<td>17.2</td>
<td>23.7</td>
<td>34.2</td>
<td>14.8</td>
</tr>
<tr>
<td>97-H3</td>
<td>Hartlen</td>
<td>9.4</td>
<td>15.5</td>
<td>24.3</td>
<td>36.5</td>
<td>13.5</td>
</tr>
</tbody>
</table>

**Table 3. Mean internal and external natural water contents and shear strengths in the various facies.**

<table>
<thead>
<tr>
<th>Facies</th>
<th>Internal w (%)</th>
<th>Internal $S_c$ (kPa)</th>
<th>External w (%)</th>
<th>External $S_c$ (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>10.5</td>
<td>119.2</td>
<td>12.2</td>
<td>68.6</td>
</tr>
<tr>
<td>Sandy</td>
<td>13.0</td>
<td>18.7</td>
<td>14.6</td>
<td>12.8</td>
</tr>
<tr>
<td>Sand lens</td>
<td>25.1</td>
<td>1.5</td>
<td>no data</td>
<td>no data</td>
</tr>
<tr>
<td>Till foreshore</td>
<td>12.1</td>
<td>70.5</td>
<td>12.5</td>
<td>63.7</td>
</tr>
</tbody>
</table>

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the remaining exterior over a certain water content threshold is eroded by runoff and gravity flows, bringing low water content material closer to the surface. Dynamic water content gradients may exist to a depth that varies in the presence of infiltration and seepage near failure planes and concentrations of permeable sand and gravel (Figure 2).

Overall low regression model explanation may be contributed by widely spaced water content and shear strength measurements and the effects of interacting process time scales. For instance, accelerated erosion events may result in the exposure of drier material which may retain high shear strength thus resulting in decreased erosion in subsequent measurements. Additionally, the importance attributed to wave energy in causing coastal erosion requires it to be explicitly considered as a separate independent variable (AMIN and DAVIDSON-ARNOTT, 1995). Unfortunately wave data were unavailable for much of the study.

Interior and exterior water content are negatively correlated with the absolute value of temperature such that temperatures both well above and below freezing contribute to low water contents and temperatures near freezing increase water contents. While not statistically significant in contrib-

Figure 5. Facies-specific shear strength to water content relationships. Relationships were determined from remolded vane shear strength measured at known water contents and used to calculate shear strength from till natural water content.
Bluff Erosion in Nova Scotia

Figure 6. Comparisons of shear strength (dashed lines) and erosion rate (solid lines) measured at the four monitoring sites with daily precipitation, mean daily wind speed, mean daily wave height and maximum daily water level between November 1997 and May 1999. In the four upper graphs, grey and black lines represent daily means and 5 day running means respectively. Shear strength measurements greater than 1000 kPa are not plotted.

utating to erosion, temperature and water content relationships were observed to be important to bluff-edge retreat by mass wasting. For example, a series of flows at site M2 occurred in late January 1999 after groundwater accumulated in the sandy facies during a 6 day period of below-freezing temperatures; following increased temperatures and thaw, water content rapidly increased and approximately 0.5 m of retreat resulted. A similar process occurred near M5 where a sand lens accumulated water as ice in November 1997. When temperatures rose, water content reached 35%, shear strength dropped to near zero, and 1.6 m of retreat occurred.

Precipitation was also observed to be important as a contributor to retreat. An example occurred near M11; where a 10 m wide and 75 m long slump block is present in the clay facies, a shallow flow originating at the edge of the seaward scarp was triggered by a 76.6 mm precipitation event on July 11, 1998. No high winds were recorded and a 3 m wide cobble terrace fronted the toe of the slump block, protecting it from wave attack.

Beach elevations were collected at several locations at annual intervals (Figure 7). Change in beach elevation was only notable at M5 and L4+40 where gravel accumulated covering shore-parallel gaps between the beach toe and outer frame. At M5 the beach elevation increased by up to 0.5 m and caused both bluff-edge retreat and bluff-face erosion rates to decrease. The bluff toe at M14 was not protected by significant beach sediment during the study.

In the longer term, foreshore erosion has been considered to occur as an equilibrium shoreline profile is translated upwards and landwards by rising sea level (Bruun, 1988; Davidson-Arnott and Oliverhead, 1995). In the McNab’s Island area, present shoreline morphology is controlled largely by antecedent geomorphology and alongshore sediment movement is common, indicating the equilibrium profile hypothesis is not applicable (Pilkington et al., 1993). Foreshore erosion, similar to bluff erosion, occurs physically due to softening of till across dynamic water content gradients, wave attack and abrasion by mobile sediment rather than to maintain an equilibrium profile.

Foreshore lowering is not necessarily a gradual process but can occur over a single storm. For example, during the winter of 1998/1999, a 0.5 m high oblique foreshore scarp migrated downdrift at M14. Following this, a slump occurred resulting in the highest retreat and erosion rates measured at M14. A thin sandy gravel layer (cf. Skaffel and Bishop, 1994; Devries, 1992) may have contributed to the initial formation of the foreshore scarp (Figure 4b). Exposures of high water content till seaward of the bluff toe allow erosion and lowering of the foreshore and increased incident wave energy at the bluff toe.

The above discussion has treated erosion and retreat as separate processes when, in reality, they are not independent. Erosion and retreat occur over different time scales and portions of the bluff profile and are measured differently but together contribute to the response of cohesive shorelines to storms and relative sea-level rise. Retreat, taken here as mass wasting by failure at the bluff edge, is contributed to by erosion at the bluff toe which precludes the development of a stable slope and removes support. Erosion, taken here as the wearing away of bluff toe material by various physical impacts, is contributed by retreat because colluvium descending the bluff face can remove the high water content surface material, briefly causing high erosion, but then accumulate at the bluff toe slowing erosion. Rates of retreat and erosion varying out of phase with each other contribute to changes in bluff slope and profile leading to longer-term behaviour such as cyclic retreat (cf. Quickley et al., 1977) which has occurred at M14 and M5 (Figure 7) since the 1980s (Manson, 1999).

CONCLUSIONS

Bluffs on McNab’s Island are formed in cohesive tills for which shear strength and water content are inversely power
related. The area is open to the Atlantic Ocean and extra-tropical wind storms with accompanying precipitation, spray, waves and elevated water levels occur in winter. Erosion maxima also occur in winter while erosion minima generally occur in summer and fall.

In correlation analysis of erosion, geotechnical and oceanographic data, high till water content, precipitation, water levels and wind speeds from the direction of longest fetch were all found to positively correlate with bluff toe erosion. Precipitation and spray may decrease the resisting force of bluffs while high winds generate waves superimposed on elevated water levels and increase the assaulting force. During storms, the resisting and assaulting forces are thus inversely related and thresholds of erosion may be easily exceeded indicating the importance of storms in causing bluff erosion.

Table 4. Definitions of variables in the correlation and multiple regression analyses.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erosion</td>
<td>Amount of erosion during a measurement period</td>
</tr>
<tr>
<td>Wind</td>
<td>Frequency of hourly winds ( \geq 25 ) km/h from directions between 120 and 240°</td>
</tr>
<tr>
<td>Water level</td>
<td>Frequency of hourly water level ( \geq 2.0 ) m</td>
</tr>
<tr>
<td>Precipitation</td>
<td>Cumulative daily precipitation during a measurement period</td>
</tr>
<tr>
<td>Temperature</td>
<td>Cumulative absolute value of temperature during a measurement period</td>
</tr>
<tr>
<td>Water content</td>
<td>Interior or exterior water content measured at the beginning of a measurement period</td>
</tr>
</tbody>
</table>

were all found to positively correlate with bluff toe erosion. Precipitation and spray may decrease the resisting force of bluffs while high winds generate waves superimposed on elevated water levels and increase the assaulting force. During storms, the resisting and assaulting forces are thus inversely related and thresholds of erosion may be easily exceeded indicating the importance of storms in causing bluff erosion.

In multiple regression, 35% of variance in subannual erosion is explained by high winds from the direction of longest fetch, elevated water levels (increased assault force) and high precipitation (decreased resisting force). Retreat, in contrast, occurs mainly in response to decreased resisting force caused by temperature- and precipitation-induced elevated water contents with lesser indirect influence from the assaulting force as slopes are steepened due to erosion at the bluff toe. The relative importance of the assaulting and resisting forces therefore changes over the bluff profile. As relative rates of retreat and erosion vary, changes in bluff profiles and cyclic retreat can occur.

Beach sediment may be present resulting in slow erosion and retreat rates or may be absent exposing till in shore-parallel gaps in the boulder frame and increasing rates of
erosion and retreat. Exposed till foreshores are eroded by the impact of waves and mobile sediment on softened till which allows waves to reach and erode the bluff toe, removing support and promoting gravitational failure and retreat at the bluff edge. Similar to bluff erosion, foreshore erosion can occur rapidly during storm events.

Much of the variance in erosion is left unexplained. Some of the unexplained portion of the regression model may be contributed by dynamic morphologic change at various time scales influencing subsequent erosional response and some because water content and shear strength were too infrequently measured to capture their shortest-term variance during storms.

ACKNOWLEDGEMENTS

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Table 5. Results of correlation analysis. Insignificant correlations are in italics.

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<th>n = 97</th>
<th>Water Level</th>
<th>Precipitation</th>
<th>Temperature</th>
<th>Interior Water Content</th>
<th>Exterior Water Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha</td>
<td>Erosion</td>
<td>Wind</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>0.05</td>
<td>1.00</td>
<td>-0.13</td>
<td>-0.28</td>
<td>0.16</td>
<td>0.00</td>
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</tbody>
</table>

Table 6. Results of stepwise multiple regression analysis. Insignificant contributions are shown in italics.

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<th>n = 97</th>
<th>p-level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha</td>
<td>0.05</td>
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LITERATURE CITED


