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SHORE PLATFORM DOWNWEARING RATES AND PROCESSES IN THE
UPPER AND LOWER INTERTIDAL ZONES IN EASTERN CANADA

By
Kyle John Prestanski

A Thesis
Submitted to the Faculty of Graduate Studies and Research
through the Department of Earth and Environmental Sciences
in Partial Fulfillment of the Requirements for
the Degree of Master of Science at the
University of Windsor

Windsor, Ontario, Canada
2010
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ABSTRACT

This study examines weathering processes in the upper and lower intertidal zones of shore platforms in eastern Canada. Over 90 transverse micro-erosion meter stations were installed in six areas. Basalts, argillites, and sandstones from three areas were immersed or exposed in artificial sea water and de-ionized water to replicate tidal conditions at different elevations within the upper and lower intertidal zones. The results suggest that surface downwearing by salt weathering is important on some types of rock in the upper intertidal zone, but that wetting and drying is ineffective. Downwearing is very slow in the lower intertidal zone. A comparison of field and laboratory data indicates that weathering can account for much of the downwearing occurring in the upper intertidal zones of the study areas. Weathering-generated downwearing may have reduced the upper portions of shore platforms by one to several meters since sea level reached its present elevation.
I would like to take this opportunity to thank my advisor, Dr. Alan Trenhaile, for the support and guidance he has provided me over the past two years. I would also like to thank Neil Porter for helping me along the way and dealing with me for weeks on end out in the field. Without these two men I would have never been able to accomplish this!

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Finally, I would like to acknowledge the staff in the Department of Earth and Environmental Sciences: Melissa Price, Sharon Horne, and Denis Tetreault. Thank you for helping me along the way. I’m going to miss our lunchtime conversations!
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CHAPTER I: INTRODUCTION

1.0 Shore Platforms: A Brief Overview

Shore platforms are gently sloping to subhorizontal rock surfaces, extending a few metres up to hundreds of metres from the cliff foot. They are conspicuous elements of rocky coasts in environments ranging from the tropics to the poles. Gently sloping platforms, which have sometimes been called ramps, have gradients between 1° and 5°, and they extend from the cliff foot to below the low tidal level without any major break in slope (Figure 1.1a). Subhorizontal platforms (gradients less than 0.5°) generally terminate abruptly seawards in a low-tide cliff or ramp (Figure 1.1b). Much of the literature has emphasized the occurrence of subhorizontal platforms in Australasia and Hawaii, and sloping platforms in Britain, the northeastern United States, and elsewhere in the northern Atlantic (Trenhaile, 1987, 1999). Traditionally, much of the work on shore platforms was conducted by Australasian researchers, and their depictions and interpretations had a strong influence on the literature for nearly a century.

Figure 1.1: a) sloping limestone and shale platform in the Vale of Glamorgan, south Wales, UK; b) horizontal aeolianite platform with a low tide cliff near Lonsdale, southern Victoria, Australia.

2.0 Contesting Theories

Most of the debate over the origin of shore platforms has been concerned with the relative importance of wave and weathering processes. Some researchers proposed that
weathering, which includes wetting and drying and salt and chemical weathering, plays a dominant role in the development of sub-horizontal shore platforms in Australasia and in other swell- to low-wave energy environments (Wentworth, 1938, 1939; Hills, 1949, 1971; Gill, 1967, 1972; Bird, 1968; Davies, 1972; Stephenson and Kirk, 2000). Others have argued that waves are the main erosive mechanisms on these platforms (Bartrum, 1924, 1935, 1938; Johnson, 1933; Jutson, 1931, 1939; Edwards, 1941, 1951). There has been less debate over the origin of shore platforms in the mid-latitudes of the northern hemisphere, however, where most researchers have concluded that weathering plays a secondary role to wave erosion (Trenhaile, 2004).

Recent work has emphasized that shore platforms are the result of both marine and sub-aerial weathering processes (Trenhaile et al., 2006; Trenhaile, 2008 a,b). Trenhaile and Porter (2007) used their experimental downwearing (erosion in the vertical plane) data in a simple mathematical model to test the traditional, largely Australasian hypothesis, most recently proposed by Stephenson and Kirk (2000), that weathering can produce shore platforms, with the role of waves being restricted to washing away the fine-grained sediment. Trenhaile and Porter found that weathering and debris removal acting alone cannot produce shore platforms with gradients, widths, and profiles that are similar to those in the field. They concluded that although downwearing by weathering and debris removal plays an important, and possibly dominant, role on shore platforms in eastern Canada today, platform morphology is probably the result of mechanical wave erosion controlled by the tidally controlled expenditure of wave energy. Waves may be the dominant mechanism in some areas, or at some stage in the development of a platform, providing the energy to pluck material from cliffs and platforms (quarrying) and to move loose abrasives over the platform surface. However, weathering often plays an important supportive role in wave-dominated environments, weakening the rocks and making them more susceptible to wave erosion. Ultimately, both weathering and mechanical wave erosion operate on the shore platforms of eastern Canada today, although their relative and absolute importance varies across platform surfaces and has probably changed through time (Trenhaile and Porter, 2007; Trenhaile, 2008 a,b).
3.0 Platform Morphology and Tidal Range

Although some researchers briefly mentioned the possible relationship between platform gradient and tidal range (Edwards, 1941, 1958; King, 1959; Gill, 1967; Wright, 1967; Davies, 1972), the emphasis in the traditional shore platform literature has been on the relative importance of weathering and wave regimes, and it has been conducted in almost complete ignorance of the fundamental role of tidal range (Trenhaile, 1987). Trenhaile (1972, 1974, 1978, 1987, 2002) has shown that the mean regional gradient of shore platforms around the world varies in response to differences in tidal range. He found a moderately strong positive relationship between shore platform gradient and tidal range (Figure 1.2), which suggests that tidal range, rather than climate and wave conditions, is the main reason for the occurrence of horizontal platforms in the low tidal range environments of Australia and New Zealand, and sloping platforms in the high tidal range environments of the North Atlantic (Trenhaile, 1999). This relationship is

![Figure 1.2: The relationship between mean regional platform gradient and spring tidal range (Trenhaile and Porter, 2007)](image-url)}
illustrated in eastern Canada by the fact that there are horizontal platforms in Gaspé, Québec, where the tidal range is between 2.25 and 3.5 m (Trenhaile, 1987), and sloping platforms in the Bay of Fundy, where the tidal range is between 12 and 16 metres (Trenhaile, 2004).

4.0 Shore Platform Weathering Processes

There are a number of weathering processes that are responsible for shore platform downwearing. The two most important in regards to this study are wetting and drying, and salt and chemical weathering.

4.1 Wetting and Drying

Exposed rock surfaces in the intertidal zone are subjected to repeated wetting and drying cycles. Although the processes are not understood very well, it is generally assumed that alternate wetting and drying can cause rocks to weather through absorption and adsorption of water, expansion of the rocks, and their inability to return to their original size when they dry (Trenhaile and Kanyaya, 2004). High amounts of water in rocks can reduce their strength, and alternate wetting and drying can weaken the bonds between the constituent minerals (Pissart and Lautridou, 1984). The breakdown of rock by wetting and drying depends on its lithology and internal characteristics, specifically the presence of clay minerals, structural weaknesses such as cleavage planes, and pore size and distribution (Bland and Rolls, 1998). Cycles of wetting and drying will tend to give rise to expansion and contraction, with cracking and flaking of the rock. Shales and argillites containing clay minerals are especially susceptible to this process (Bland and Rolls, 1998), although other rock types that have little to no clay content (e.g. sandstone, limestone, granite, basalt and schist) can also be affected by the wetting and drying process (Nishioka and Harada, 1958; Nepper-Christensen, 1965; Goudie, 1974; Hudec and Sitar, 1975; Felix, 1983; Hamès et al., 1987; Hall and Hall, 1996; Kanyaya and Trenhaile, 2005).
Intertidal zones provide optimum conditions for wetting and drying processes and it is generally assumed that it plays an effective role in lowering some platform surfaces (Stephenson and Kirk, 2000; Trenhaile and Kanyaya, 2004). Stephenson and Kirk (2000) asserted that the mudstone platform at Kaikoura Peninsula in southern New Zealand is the product entirely of weathering, especially wetting and drying, and they suggested that the platform developed at the elevation which experiences the greatest number of tidal wetting and drying cycles. Trenhaile and Kanyaya (2004) set up a series of laboratory tidal experiments to closely imitate natural wetting and drying cycles in the intertidal zone. They found that wetting and drying is an effective downwearing agent on shore platforms on some types of rock, but is fairly ineffective on many other types, including igneous and metamorphic lithologies. Their experimental results suggest that wetting and drying is most effective at the high tide level and that its efficacy decreases with elevation within the intertidal zone, contrary to the findings of Stephenson and Kirk (2000) (Kanyaya and Trenhaile, 2005).

4.2 Salt and Chemical Weathering

For convenience, salt and chemical weathering will be considered separately, although they generally operate together in coastal regions, and are often difficult to distinguish in the field (Trenhaile, 1987). Although both mechanisms operate in the mid-latitudes, salt weathering is generally considered to be most important in the dry tropics, where there is high evaporation, whereas chemical weathering is most effective in the hot wet Tropics.

Salt weathering refers to the physical and/or chemical damage to rock or building stone resulting from salt accumulation (Tingstad, 2008). Over the last few decades, many field and laboratory studies have shown that salt weathering is one of the most important rock decay mechanisms in desert, urban, polar, and coastal environments (Evans, 1970; Pye and Sperling, 1983; Goudie, 1985; Trenhaile, 1987; Yatsu, 1988; Matsukura and Kanai, 1988; Cooke et al., 1993; Goudie and Viles, 1997). This has generated great interest in many fields, including engineering geology, geomorphology, environmental science, geotechnics, and materials science (Benevente et al., 2007). Salt weathering is
thought to play a role in the development of many geomorphologic features, including alveoles or honeycombs, and tafoni and other cavernous weathering forms (Bradley et al., 1978; Mustoe, 1982; Young, 1987; Trenhaile, 1987; Matsukura and Matsuoka, 1991; Mottershead and Pye, 1994; Turkington and Phillips, 2004). These geomorphological features may cause serious architectural problems when they appear in material used for building in coastal areas, especially in very porous sedimentary rocks (Rossi-Manaresi and Tucci, 1989; Ruedrich and Siegesmund, 2007). Indeed, salt weathering has been implicated as one of the primary agents in the loss of historic architecture and archaeological sites in coastal areas where salt and moisture are abundant (Evans, 1970; Goudie and Viles, 1997; Rodriguez-Navarro and Doehne, 1999; Cardell et al., 2003). Salt weathering may also result in contour scaling or flaking of rock layers (Smith and McGreevy 1988), crumbling or disintegration of rock (Cooke and Smalley 1968; Goudie and Watson 1994), and the observable presence of salt on the rock or stone surface (Turkington and Smith 2000).

Chemical weathering results from the chemical reaction of minerals with air and water. The main factor that controls the efficacy of chemical weathering is the presence and amount of water available for chemical reactions (Bland and Rolls, 1998). Coastal areas have an abundant source of saline water, and although the processes are complex, they generally involve the removal of the more soluble components of the rock minerals, and the addition of hydroxyl groups and atmospheric oxygen and carbon dioxide.

Chemical weathering may contribute to surface lowering in coastal environments and it has been accorded an important role in some classical models of shore platform development (Dana, 1849; Bartrum, 1916; Bartrum and Turner, 1928). Dana (1849) first proposed that marine cliffs are weathered down to the level at which the rocks are permanently saturated by sea water. Bartrum (1916; 1926; 1938) proposed that ‘Old Hat’ platforms develop in sheltered areas at the level of permanent saturation, through the removal of the fine-grained weathered material by weak waves. Other Australasian researchers argued that similar platforms can develop at the saturation level in more exposed areas by differential wave erosion. The suggestion that chemical weathering operates effectively only down to a well-defined intertidal level of permanent saturation, however, has been contested (Trenhaile and Mercan, 1984).
4.2.1 Salt and Chemical Weathering Mechanisms

Salts are chemical compounds formed from reactions between acids and bases, with water as a by-product (Bland and Rolls, 1998). Many salts are water soluble, and for salts to be effective weathering agents, they need to enter rock pores, typically from solution (Bland and Rolls, 1998). The rate at which a solution can penetrate a rock is determined by its lithological properties, including: porosity (volume of pore space), microporosity (proportion of micropores), water absorption capacity (amount of water absorbed in a specific time), and the saturation coefficient (amount of water absorbed in 24 hours when a sample is totally submersed) (Cooke, 1979; Bland and Rolls, 1998).

Cooke and Smalley (1968) identified three mechanisms by which salt causes physical weathering:

1) pressures exerted by crystals as they grow from solution (crystallization);
2) pressures from volume changes induced by hydration; and
3) pressures exerted by expanding salt crystals due to heating (thermal expansion).

Of the three mechanisms, the most cited cause of physical salt weathering is salt crystallization (Goudie and Viles, 1997). Experimental studies have suggested that crystal growth is the most significant in causing rock breakdown (Goudie, 1974; Cooke, 1979). Crystallization occurs in two ways: 1) by increasing the concentration of a solution through evaporation, and 2) by lowering the temperature of a solution that is close to being saturated, thereby decreasing its solubility (Bland and Rolls, 1998); the first case is the more common of the two (Cooke and Doorkamp, 1974). As a salt solution in a rock void begins to evaporate, for example, the concentration of the salt increases to the point where the salt is just maintained in solution (saturation); crystallization is not possible at this point. However, if the water content decreases further, the salt may crystallize slowly, or the solution may be maintained and become supersaturated, with crystallization occurring later – although when it does occur it is very rapid and the crystals are larger than those which form at lower concentrations (Trenhaile, 1987; Bland and Rolls, 1998). To cause rock disintegration, crystals must exert pressure on pore walls that exceed the cohesive forces (tensile strength) of the rock (Turkington and Paradise,
The nature and magnitude of the pressure exerted on rock pores depends on pore size and porosity, the degree of supersaturation of the saline solution (crystallization pressure is proportional to the degree of supersaturation), the crystallographic properties of the salt, and the strength of the rock (Bland and Rolls, 1998; Benevente et al., 2007). Crystallization pressure can be defined by the equation (from Cardell et al., 2003):

\[ p = \frac{2\gamma}{r} \]

where \( p \) is pressure in pascals (Pa), \( \gamma \) is interfacial tension of salt solution and \( r \) is the rock pore radius. Thus, crystallization pressure is inversely proportional to the pore radius, such that the pressure exerted by salt crystallization in micropores is greater than in macropores and is more likely to overcome the resistance of the rock (Rossi-Manaresi and Tucci, 1989; Cardell et al., 2003). For this reason, it is now widely accepted that salts cause extensive damage to rocks containing a large proportion of micropores connected to macropores (Rodriguez-Navarro and Doehne, 1999). Nevertheless, large salt crystals begin to grow in large pores/capillaries first at the expense of the small crystals in the small capillaries (Trenhaile, 1987).

Salt crystallization can occur on the surface of a porous material (efflorescence) and within the porous system (subflorescence). Efflorescence, typically visible to the naked eye, occurs when salts crystallize at the rock surface at the open ends of capillary systems where outward moving solutions evaporate (Ollier, 1984). Subflorescence is similar except that the salts crystallize before reaching the surface (Ollier, 1984). Subflorescence has been shown to be much more destructive than efflorescence (Cooling, 1930; Rodriguez-Navarro and Doehne, 1999). Environmental changes, especially relative humidity, dictate the location and/or the way salt crystallization and growth take place, promoting either the development of efflorescences or subflorescences (Rodriguez-Navarro and Doehne, 1999). Ultimately, salt crystallization in a porous rock causes a loss of coherence between the grain and the matrix, and may produce weight loss, a change in the size of the grains, splitting of the grains, a change in size of the pores, and visible surface deterioration (Benevente et al., 2001).
Mortensen (1933) first recognized that hydration can be an important weathering mechanism. When water molecules associate with a salt, the resulting compound is called a hydrate (e.g., the dihydrate gypsum is a compound of CaSO₄ • 2H₂O). When salts hydrate, they may increase considerably in volume, exerting pressures against the constraining walls of rock capillaries, and causing internal cracking (Cooke and Gibbs, 1995; Bland and Rolls, 1998). The greater the degree of hydration, the greater the pressure generated. The greatest pressures occur at low temperatures and high relative humidities, conditions normally experienced at nighttime (Trenhaile, 1987). The hydration and dehydration of salts can occur several times a day. The most potent salts are those which hydrate rapidly and expand by a significant amount when hydrated (Cooke, 1979; Trenhaile, 1987).

Thermal expansion is another possible salt weathering mechanism, although it is of less importance than hydration and crystallization pressures. For weathering to occur, the thermal expansion coefficient of a salt must exceed that of the surrounding rock (Bland and Rolls, 1998). As an example, sodium chloride (NaCl, or halite) produces a volumetric expansion of 0.5 percent when the temperature rises from near the freezing point to 60°C, whereas granites expand only by 0.2 percent (Cooke and Smalley, 1968; Trenhaile, 1987; Bland and Rolls, 1998). The expansion of entrapped salts causes pressures on the walls of the rock capillaries, which can result in granular disintegration or splitting (Trenhaile, 1987). While the process is theoretically reasonable, simulation studies have yet to demonstrate conclusively that thermal expansion of salts is an effective weathering mechanism (Turkington and Paradise, 2005). Nonetheless, Cooke and Smalley (1968) proposed that thermal expansion, and to a lesser degree hydration, are important weathering mechanisms in deserts where high temperatures and extreme diurnal changes are experienced.

There are a number of chemical reactions, often working together, that can produce rock weathering. Solution, which is the complete dissociation of a mineral in a solvent, is an important process, as a large proportion of weathering products are carried away in solution (Ollier, 1984). Oxidation, where a substance loses an electron and takes a positive charge, is common wherever minerals are in contact with air (Ollier, 1984). Iron is readily oxidized, which is evidenced by the presence of red and yellow iron oxide
and hydroxide (rust) stains. The opposite of oxidation, reduction, occurs in waterlogged, anaerobic conditions. Hydrolysis, the reaction between the $H^+$ and $OH^-$ ions of water and mineral ions, is important in the breakdown of silicate minerals, where the $H^+$ ions replace metal cations, and the $OH^-$ ions combine with these cations to form soluble products (Trenhaile, 1987). Other processes include carbonation, hydration and chelation; detailed analyses of these, and the processes mentioned above, however, is beyond the scope of this discussion.

4.2.2 Field and Laboratory Investigations Exploring the Role of Salt

Extensive field and laboratory experiments, especially by French geomorphologists in the 1950s and 1960s, illustrated the effects of various salts on different rock types (Birot, 1954; Pedro, 1957; Tricart, 1960). In the late 1960s and into the 1970s, a methodological shift in rock weathering studies was evident, with the focus of attention shifting from the field toward the laboratory (Nordberg and Turkington, 2004). Experiments on the mechanisms of salt weathering (crystallization, hydration, and thermal expansion) were driven in part by continued emphasis on landform development under desert conditions (Cooke, 1979; Goudie et al., 1979; Nordberg and Turkington, 2004). Much of the interest in experimental simulations of salt weathering, however, originated from materials science due to the weathering of construction stone by salt. Nevertheless, recent geomorphological laboratory simulations have been conducted on a variety of lithologies to assess rock degradation produced by salt weathering (Goudie, 1999 a,b; Rodriguez-Navarro and Doehne, 1999; Warke and Smith, 2000; Robinson and Williams, 2000; Chabas and Jeanette, 2000; Benevente et al., 2001; Cardell et al., 2003; Rivas et al., 2003; Gómez-Pujol et al, 2006; Trenhaile et al., 2006; Wells et al., 2006; Benevente et al., 2007; McCabe et al., 2007; Ruedrich and Siegesmund, 2007; Wells et al., 2007).

Laboratory experiments on salt weathering have been used to study the relative destructiveness of various salt solutions, the ideal environmental conditions under which it takes place, and its relative efficacy on different types of rock (Tingstad, 2008). Several laboratory experiments have studied the weathering behaviour of sodium chloride and
demonstrated that, while it is responsible for salt damage in many locations and in many rock types (Evans, 1970; Chapman, 1980; Winkler, 1994), it is much less effective than some other salts, including alkali metal sulphates, carbonates and nitrates (Pedro, 1957; Kwaad, 1970; Goudie et al., 1970; Goudie, 1974; Smith and McGreevy, 1982, 1988; Goudie, 1986; 1993; Warke, 2007). In nature, however, it is rare for only a single salt to occur on, or within, the surface of the rock. More commonly, two or more salts occur together at a particular site (Goudie and Viles, 1997). This has driven recent studies to explore how two or more salts interact to increase or decrease rock breakdown. Studies have shown that combined salt solutions are more effective in breaking down rock than single solutions alone, and that it is difficult to predict the weathering behaviour of combined salt solutions from the weathering behavior of the salts individually (Goudie, 1986; Williams and Robinson, 2001). Other experiments have explored the role of salts in frost weathering, concluding that frost damage can be greatly increased by the presence of certain salts (sodium chloride and sodium sulphate), although in some circumstances salts may reduce weathering by delaying the onset or completeness of freezing (Trenhaile and Rudakas, 1981; McGreevy, 1982; Jerwood et al., 1990 a,b; Williams and Robinson, 2001).

Despite the abundance of salt weathering studies, few experiments have satisfactorily simulated natural conditions (McGreevy and Whalley, 1984; Bland and Rolls, 1998; Tingstad, 2008). McGreevy and Smith (1982) and Bland and Rolls (1998) identified a number of issues that may limit the applicability of many salt weathering experiments, including: the inability to reproduce the complexity of natural climatic conditions, the use of unrealistic environmental conditions in order to maximize the effectiveness of a specific salt solution, the use of salts which may not be present under natural conditions, testing salts in isolation when mixtures are the most common in nature, accelerating the weather process to produce results rapidly, and the extent to which the experimental rock samples are representative of those in the field. In response, recent simulations (Trenhaile et al., 2006; Wells et al., 2006; McCabe et al., 2007) have sought to more closely simulate natural conditions in the laboratory.
4.2.3 The Role of Salt in Rocky Coastal Environments

It has been assumed that marine salts accelerate rock weathering in coastal environments (Mottershead et al., 2003). The salts deposited in coastal areas are mainly sodium chloride, but sulphates, carbonates, potassium, calcium, magnesium and other salts are present in smaller quantities (Trenhaile, 1987) (Table 1.1). The crystallization of sea salts in between rock lattices or in pore spaces via sea spray and alternate phases of salt water inundation and exposure in coastal areas can generate stresses and lead to serious deterioration of porous sedimentary rocks (Coussy, 2006). Researchers in Australia (Dunn, 1915; Coleman et al., 1966) concluded that a combination of sea spray, wetting by high tides, and high rates of evaporation provide ideal conditions for salt crystallization to occur, and attributed the occurrence of disaggregated rocks on high tidal flats in Queensland to these factors. Tricart (1962) stressed the importance of salt weathering on coastlines with long dry seasons or high levels of solar insolation such as those in the tropics and in the Mediterranean. However, coastal salt weathering forms are also important in moist temperate environments (Mottershead, 1982; Johannessen et al., 1982). Nevertheless, from a study of volcanic rocks in a range of climatic environments along the Atlantic Ocean, Guilcher and Bodéré (1975) concluded that the efficacy of

<table>
<thead>
<tr>
<th>Ions in solution in sea water</th>
<th>Salts crystallizing out of sea water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion g/kg</td>
<td>Salt g/kg</td>
</tr>
<tr>
<td>Cl⁻  18.98</td>
<td>NaCl 27.21</td>
</tr>
<tr>
<td>Br⁻  0.065</td>
<td>MgCl₂ 3.81</td>
</tr>
<tr>
<td>SO₄²⁻  2.65</td>
<td>MgSO₄ 1.66</td>
</tr>
<tr>
<td>HCO₃⁻  0.14</td>
<td>CaSO₄ 1.26</td>
</tr>
<tr>
<td>Mg²⁺  1.27</td>
<td>K₂SO₄ 0.86</td>
</tr>
<tr>
<td>Ca²⁺  0.4</td>
<td>CaCO₃ 0.12</td>
</tr>
<tr>
<td>K⁺   0.38</td>
<td>MgBr₂ 0.08</td>
</tr>
<tr>
<td>Na⁺   10.56</td>
<td></td>
</tr>
</tbody>
</table>

Table 1.1: The ions and salts of sea water (after Mottershead, 1982).
coastal salt weathering declines with increasing latitude and decreasing temperature and evaporation. In studying coastal landform development in Oregon, Johannessen et al. (1982) concluded that sunny, south-facing coastal cliffs experienced ten times more weathering than shaded, north-facing cliffs, and they attributed this to the drying and thermal expansion of salts in the sunny areas.

More recently, studies conducted by Mottershead (1994; 1997; 2000) provide evidence for rapid rates of rock weathering in the supratidal zone, with values commonly in the range of 0.05-0.25 mm yr\(^{-1}\), and extreme values of up to 0.6 mm yr\(^{-1}\) for greenschist and 1.05 mm yr\(^{-1}\) for sandstone. These findings echo those of Goudie et al. (1970), who found that low porosity igneous and metamorphic rocks were little affected by salts, whereas porous stones, such as chalk, limestone, and sandstone, were particularly vulnerable to salt weathering, as they broke down rapidly after repeated immersion in saline solutions. In comparing sandstone weathering rates between coastal and inland locations, Mottershead et al. (2003) found that weathering occurred 59 percent more rapidly in the coastal environment, which he attributed primarily to the acceleration of weathering by coastal salts. Mottershead (1989) measured the rate of coastal denudation of greenschist in the supratidal zone by salt spray weathering in southwestern England. Over a seven year period, he observed a mean rate of surface lowering of 0.625 mm yr\(^{-1}\), with a marked summer maximum which was strongly correlated with monthly air temperature. The rapid denudation was attributed to crystallization and thermal expansion of sodium chloride, both of which are enhanced by high summer temperatures.

Although there is a moderately large body of literature on the role of salt in coastal environments, few researchers have considered its role in the development of shore platforms (Williams and Robinson, 1981). Mottershead (1982) examined the role of salts on shore platforms consisting of greenschist in southwestern England. By calculating the pressure of crystal growth within the pores, he determined that salt concentrations of 1.5 percent above that of sea water were sufficient to cause rock failure. Moses and Smith (1994) suggested that salt weathering plays a dominant role in the supratidal zone of a limestone platform in southern Mallorca. Stephenson and Kirk (2000) observed salt weathering on mudstone platforms at Kaikoura, New Zealand during the summer months. Salt crystals formed around the edges of pools of water left behind
after the tide had receded, and as the sea water evaporated from the pools, a “bath tub ring” of salt crystals was left behind. The surfaces of platforms where salt crystal growth was observed were friable, exhibiting evidence of flaking and pitting, which the authors attributed to mechanical salt weathering.

Stephenson and Kirk (2001) observed surface swelling on shore platforms at Kaikoura, and proposed that swelling is caused by salt crystal growth in the lattice of rocks (and to a lesser extent wetting and drying causing expansion and shrinking). The erosion produced by swelling occurs where the growth and re-growth of salt crystals in the lattice of the rock pushes the surface of the rock up where particles then flake away or are dislodged over time. This process is often repeated, resulting in a net lowering effect of the platform surface. Similarly, Porter and Trenhaile (2007) measured short-term rock surface expansion and contraction in the intertidal zone. It was demonstrated that intertidal rocks in eastern Canada contract, and occasionally expand, over short periods of time in response to tidal immersion and exposure, which may generate stresses that contribute to surface downwearing. Trenhaile et al. (2006) conducted a series of synthetic sea water experiments to measure intertidal platform downwearing rates in eastern Canada. Rates of argillite breakdown ranged from 0 to 2.3 mm yr\(^{-1}\), although these values were generally lower than those experienced in similar de-ionized (fresh water) wetting and drying experiments, suggesting that the presence of salts in some way inhibits the effect of wetting and drying in this type of rock. Rates of sandstone breakdown ranged from 0 to 2.65 mm yr\(^{-1}\), which were significantly higher than in de-ionized water. Rates of basalt downwearing were also higher in synthetic sea water than in de-ionized water, with rates ranging from 0 to 0.73 mm yr\(^{-1}\). In all cases, downwearing increased with elevation within the intertidal zone.

5.0 The Problem

Of particular importance to this study is the conclusion by Trenhaile and Mercan (1984) and Kanyaya and Trenhaile (2005) that the amount of water absorbed by rocks in the intertidal zone attains its maximum level after about 1 to 1.5 hrs of inundation. Consequently, the efficacy of wetting and drying is much more dependent on the length
of period of exposure than on the length of the period of inundation. For example, the sandstones, basalts, and argillites used by Kanyaya and Trenhaile (2005) required approximately one hour to attain their maximum water content, but they continued to lose water after eleven hours of exposure. This means that the period of inundation experienced in the upper intertidal zone is sufficient to allow the rocks to attain a high degree of saturation, but the period of exposure in the lower intertidal zone is insufficient to allow the rocks to completely dry. Kanyaya and Trenhaile (2005) concluded that the wetting and drying cycles experienced at the high tidal level provide optimum conditions for rock breakdown, which supported their laboratory data which suggested that the efficacy of this process decreases with elevation within the intertidal zone. The authors also suggested that long periods of inundation in the lower intertidal zone must decrease the efficacy of wetting and drying (and therefore salt weathering), because of the less frequent and shorter periods of exposure. However, they lacked experimental evidence to support this contention, as their rock cores and cubes and were inundated every twelve hours (representing the zone of maximum wetting and drying frequency, i.e. the zone between the lowest high and highest low tidal levels, Figure 1.3).

Figure 1.3: Conceptual diagram indicating the presence of field and laboratory data within the zone of maximum wetting and drying frequency on shore platforms, and the absence of data above and below this zone.
6.0 Purpose and Objectives of the Research

The research described in this thesis was conducted to contribute to an ongoing investigation of sloping and sub-horizontal shore platforms in macro- to microtidal environments in eastern Canada; additional, ongoing work which applies the techniques described in this paper to a tropical environment in Mexico is discussed at the end of this thesis. The study was primarily concerned with rates and processes of surface downwearing (erosion in the vertical plane) in the upper and lower intertidal zones, which were not considered in Trenhaile et al.'s (2006) experiments. The upper intertidal zone is defined as the area above the lowest high tide (LHT) level, and the lower intertidal zone is defined as the area below the highest low tide (HLT) level. The term ‘wetting and drying’ refers to the erosional effect of alternate immersion and exposure of the rock owing to such factors as tides, wave run-up, and splash; downwearing by wetting and drying may be accomplished by the expansion and contraction of the rock as it absorbs and desorbs water, and by chemical and salt weathering. Although weathering is not an erosional mechanism, it is accompanied in the field by rapid debris removal by waves and in the laboratory by gravity, resulting in the lowering of the rock surface.

The specific objectives of the study were to:

a) measure the effect of wetting and drying in the laboratory under controlled laboratory conditions that simulated conditions in the upper and lower portions of the intertidal zone, and;

b) measure rates of rock breakdown and downwearing in the field within these zones in temperate eastern Canada.

The investigation had three main components: (a) laboratory experiments to measure wetting and drying induced downwearing rates; (b) the measurement of platform downwearing rates at existing and newly established transverse micro-erosion meter (TMEM) stations in the field; and (c) the utilization of relevant platform downwearing rates obtained by Trenhaile, Kanyaya, and Porter over the last four years to supplement the data obtained from this study.
7.0 Hypotheses

There were several hypotheses:

1) Downwearing rates increase with elevation within the upper intertidal zone up to an optimum elevation, based on the frequency of wetting by tides, spray or splash, and the corresponding length of the period of exposure and drying. Rates then decline with increasing elevation above the optimum level;

2) Because of the effect of pore size distributions, tensile strength, and other factors, the elevation of the optimum level varies according to the type of rock;

3) Downwearing rates are very slow in the lower intertidal zone because of infrequent periods of exposure and short periods of drying;

4) Rates of downwearing in the upper intertidal zone are primarily the result of salt weathering rather than wetting and drying; and

5) Downwearing is faster in coarse-grained than in fine-grained rocks.
1.0 Study Areas

The wide variety of tidal environments in eastern Canada has produced regionally
dominant horizontal shore platforms in some areas, and sloping platforms in others.
There are seven study areas, four in the macro-to mega-tidal Bay of Fundy and three in
the meso-to micro-tidal St. Lawrence Estuary and Gulf of St. Lawrence (Figure 2.1).

1.1 Bay of Fundy

The shore platform at Salmon River lies along the southern shore at the mouth of the
Bay of Fundy. The rocks belong to the early Cambrian Goldenville Formation, consisting
of sandstone turbidites and slates, which have been metamorphosed in places to schist
and gneiss (Nova Scotia Department of Natural Resources, 2009b). The exposed portion
of the platform is 70 to 80 m in width, and continues down below the low tide level. It
has a convex profile with gradients of 5.5 to 6.5° up to 30 m from the cliff, and 2 to 3° further seawards. Overall, the platform gradients range from about 3.5 to 5.7°.

Figure 2.2: (a) sandstone and turbidite platform at Salmon River; (b) basaltic platform at Scots Bay; (c) argillaceous platform at Bramber; (d) red sandstone platform at Burntcoat Head; (e) horizontal argillite platform at Mont Louis, Quebec; (f) sandstone cliffs and ledges at East Point, Prince Edward Island; and (f) sloping siltstone platform at Arisaig, Nova Scotia.
There is an abundance of abrasive pebbles, rounded cobbles, and boulders on the platform, producing smooth rock surfaces and troughs, running at high angles to the shore, between the steeply dipping strata.

The rocks at Scots Bay are part of the North Mountain Basalts, which were formed during a period of increased volcanic activity during the early Jurassic (Crosby, 1962; De Wet and Hubert, 1989). Plagioclase and pyroxene are the most abundant minerals found throughout the platform, with smaller quantities of chalcedony, pyrite, and clorite. The platform is concave upwards, 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 (Trenhaile et al., 2006). The platform is approximately 100 to 120 m in width. The upper portion above the neap high tide level is discoloured and extremely weathered, with visible salt accretion on its surface. Small boulders are found on lower potions of the platform, which is covered, in large part, by seaweed and small barnacles. The platform 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.

In the Minas Basin, the argillaceous rocks at Bramber belong to the Horton Bluff Formation, consisting of late Devonian to Early Carboniferous shales, siltstones, and mudstones (Nova Scotia Department of Natural Resources, 2009a). The mudstones are olive grey to green, and non-laminated and bioturbated. The siltstone is crudely laminated with dolostone, and all rock units are separated by intervals of dark grey to black shale. The platform at Bramber has a linear to slightly convex profile, with gradients from 2° up to more than 5°. The lower portions are covered by seaweed, and loose rock fragments litter the surface in most places. A muddy tidal flat covers the platform below the mean low tide level.

The red clastic sandstones at Burntcoat Head belong to the Triassic Wolfville Formation, and are thought to have originated as alluvial fans, braided streams and eolian sand dunes (Klein, 1962). Large angular clasts of quartz and alkali feldspar are the principal minerals in the sandstone. The Triassic sandstones in this area contain an iron-rich cement (hematite) that gives them their characteristic red colour. The platform at Burntcoat Head is between 375 and 450 m in width, although it can be more than 600 m in width during exceptionally low tides. The platform is slightly concave upwards, with a
gradient of 2.5° in the upper portion and between 1° and 1.5° in the lower portion (Kanyaya and Trenhaile, 2005). There are undulating strata of more resistant, lighter coloured sandstone throughout the platform. Stratified layers of cemented, rounded pebbles deposited by ancient streams have also been observed. There are large numbers of sandstone blocks lying on the surface in the upper portions of the platform as a result of ongoing cliff erosion. There are also numerous glacial erratics on the platform, many of which are large; these erratics probably fell into the intertidal zone as the cliff was undermined by erosion. There are some gastropods and patches of seaweed in places in the upper foreshore, while barnacles form an almost continuous cover on the rock surface near the low tidal level. The platform is backed by a steep, active rock cliff about 20 m in height.

Wave direction is most frequently southwesterly, westerly, and northwesterly in the Bay of Fundy. The Minas Basin is quite sheltered, however, and the majority of waves (78%) are less than 1 m in height (Eid et al., 1991). 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. The tidal regime in the Bay of Fundy is semi-diurnal, with maximum tidal ranges varying from 16 m at Burntcoat Head, which has the highest tidal range in the world, down to 5.7 m at Salmon River, at the mouth of the Bay (Figure 2.1) (Canadian Hydrographic Service, 2008).

1.2 St. Lawrence Estuary and the Gulf of St. Lawrence

The Canadian Appalachian-Acadian region, which includes Gaspé, has experienced numerous rifting, faulting, and fusing events associated with the Paleozoic Appalachian orogen. The rocks in this region have been subjected to extreme faulting, folding, metamorphism, and plutonism (Williams, 1995). The parautochthonous flysch in the Mont Louis region belongs to the Middle Ordovician Cloridorme Formation and is characterized by extreme folding and low-grade tectonic metamorphism (Enos, 1969; Williams, 1995). Horizontal shore platforms are found along approximately 600 km of the southern shore of the St. Lawrence River, between Québec City and Cap-des-Rosiers
(Trenhaile, 1978). The shore platform at Mont Louis consists of siltstones, mudstones, and finely-laminated, interbedded shale with calcite intrusions. The general term ‘argillite will’ will be used in this thesis to represent the rocks in the platform at Mont Louis. The mineral and chemical composition of the argillites is similar to shale, mainly containing clay minerals, with some quartz and opaques (Kanyaya and Trenhaile, 2005).

The Mont Louis platform is subhorizontal and is elevated about 1 m above the mid-tidal level. The platform terminates abruptly seawards at a low tide cliff of unknown height that is only exposed during very low tidal periods (Trenhaile, 1987). The platform is 170-200 m wide and is backed by a 3-4 m high cliff composed of the same lithology as the platform. There is a steep coarse-grained beach at the cliff foot. The platform surface is characterized by outcrops of steeply-dipping strata with pools between the scarps. The pools persist during low tide and host a variety of flora and fauna. Eroded material from the platform accumulates in the pools where it cannot be washed away by tides or waves. The tidal regime at Mont Louis is semi-diurnal, with a tidal range of 3 m, although there is some inequality in the height of the two daily high tides.

The characteristic ‘redbed’ sandstones of Prince Edward Island, underlying an estimated 60 percent of its surface area, have been assigned to the Pictou Group, which varies in age from Upper Pennsylvanian to Lower Permian (van de Poll, 1984). The redbeds are slightly tilted to the northeast (1-3°) such that the older Upper Pennsylvanian strata are exposed along the southern and western coasts of the Island, and the younger Lower Permian strata are exposed along the central, northern and northeastern coasts; the latter are found at East Point (van de Poll, 1984). The grain size of the sandstone ranges from very fine to very coarse, and depending on this, the sandstone can vary in colour from pale orange (very fine) through dark-purplish red (very coarse). The sandstone is arkosic in composition, consisting mainly of quartz and feldspar grains in a hematite matrix (van de Poll, 1984). Crossbedding is evident, as are irregular white and green patches of sandstone, which can be attributed to reduction (or non-oxidation) of the hematitic matrix (Crowl, 1969). The redbeds of Prince Edward Island are entirely continental in origin, and probably formed in a warm, seasonally dry climate where soils were strongly leached and oxidized (Crowl, 1969; van de Poll, 1984).
The structural ledges at East Point are narrower than the platforms at the other sites, ranging in width from approximately 2 to 10 m along the shoreline. The ledges are backed by a sandstone cliff approximately 6-7 m in height. Large blocks of sandstone eroded from the cliff lie along the upper foreshore. Salt accretion is evident on the surface of the ledges above the high tidal zone, presumably due to the combined effects of wave splash and spray (Figure 2.3a). Numerous depressions litter the surface of the sandstones above the high tidal level, and in many cases, visible salt crystals can be seen on their floors (Figure 2.3b). The tidal regime is mixed semi-diurnal, with a tidal range of approximately 1.7 m (Giles, 2002).

The rocks at Arisaig consist largely of landward-dipping Silurian siltstones, and to a lesser extent, shales and mudstones interbedded with sandstones and limestones. The platform is quite narrow, extending only a few tens of meters from the cliff foot, and it is covered by an abundance of abrasive rock fragments in the upper foreshore. The platform surface is irregular, with deeply inclined strata and quarried joint blocks covering the surface. The profile has an inconsistent shape, with an overall gradient between 1.7 and 2°.
Annual tidal data (Fisheries and Oceans Canada, 2006) were analyzed to determine the heights of the LHT and the HLT at each of the study areas (Table 2.1). The data showed that much of the intertidal zone lies above the LHT, where immersion frequency decreases and exposure duration increases with increasing elevation, or below the HLT, where the exposure frequency decreases and the immersion duration increases with decreasing elevation. The proportion of the extreme tidal range above the LHT and below the HLT increases with decreasing tidal range, and it includes all of the tidal range in the microtidal Gulf of St. Lawrence.

<table>
<thead>
<tr>
<th>Site</th>
<th>Highest high tide</th>
<th>Lowest high tide (LHT)</th>
<th>Highest low tide (HLT)</th>
<th>Lowest low tide</th>
<th>% in extreme tidal zones</th>
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</thead>
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<tr>
<td>Salmon River</td>
<td>5.9</td>
<td>4</td>
<td>2</td>
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<tr>
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<td>3.4</td>
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</tr>
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<td>11.2</td>
<td>3.9</td>
<td>-0.2</td>
<td>52.6</td>
</tr>
<tr>
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<td>1.6</td>
<td>1.2</td>
<td>0.2</td>
<td>86.7</td>
</tr>
<tr>
<td>East Point</td>
<td>1.4</td>
<td>0.9</td>
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<td>0.3</td>
<td>100</td>
</tr>
<tr>
<td>Arisaig</td>
<td>1.8</td>
<td>1.2</td>
<td>1.2</td>
<td>0.1</td>
<td>100</td>
</tr>
</tbody>
</table>

*Table 2.1*: Elevation of the tidal extremes (above the LHT level and below the HLT level) in eastern Canada. Note: As there was no tidal data for Bramber, Burntcoat Head tidal data were used.

It is more difficult to determine the proportion of the platform surfaces in each area within these zones, particularly in the lower portions of the lower intertidal zone, which can only be observed and accessed occasionally, during neap tides. In some other areas, such as Scots Bay, the lower portion of the platform is covered by a tidal flat or by less continuous deposits. About 25 to 35 m of the exposed section at Scots Bay lies within the upper intertidal zone, while at Burntcoat Head, roughly 300 m of the platform surface falls within the lower intertidal zone, and only about 66 m is within the upper intertidal zone. Owing to the inequality of the twice daily high tides and horizontal nature of the platform at Mont Louis, the LHT is at the mid-tidal level, and almost the entire platform surface therefore falls within the upper intertidal zone. All of the rock ledges at East Point are also within the upper intertidal zone, and at Arisaig, the HLT and LHT are at the same elevation.
2.0 Methods

The methods outlined below describe the analytical components of this study, both in the laboratory and in the field.

2.1 Laboratory Experiments

Typical periods of exposure and immersion frequency and duration were identified for Scots Bay, Burntcoat Head, and Mont Louis, based on the analysis of 2006 tidal data (Fisheries and Oceans Canada, 2006). The analysis showed that there is a wide range in the number of consecutive high tides that immerse sites in the upper intertidal zone, and conversely, in the number of low tides that expose sites in the lower intertidal zone. There is also enormous variation in the length of the periods of exposure in the upper intertidal zone and of immersion in the lower intertidal zone. It would be impossible to represent this range of exposure-immersion events in the laboratory, but, as previously noted, Kanyaya and Trenhaile (2005) found that water absorbed by rocks from these three areas does not increase after 1 to 1.5 hours of immersion. The amount of absorbed water varied neither with immersion duration (after 1.5 hours) nor with the number of consecutive immersions by high tides. Therefore, the only variable that had to be considered in determining the experimental setup was the duration of exposure.

One set of experiments used de-ionized water to measure the effect of rock expansion and contraction owing to the absorption and desorption of water, and another set used synthetic sea water to determine the additional effect of salt (salt and chemical weathering). The experimental conditions were also designed to measure the effect of salt weathering in the upper portions of the intertidal zone, which are wetted infrequently, and the lower portions of the intertidal zone, which are dried infrequently (Table 2.2). Rock samples were inundated in plastic basins once for 1.5 hours every one, two, or three weeks to represent areas of increasing elevation in the upper intertidal zone, and were exposed for the same duration and at the same frequencies to represent areas in the lower intertidal zone. Each set of experiments used a series of 18 plastic basins to represent
<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Samples Per Basin</th>
<th>Location</th>
<th>Submergence Period (Time in water)</th>
<th>Emergence Period (Time out of water)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>25</td>
<td>Upper Intertidal Zone</td>
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<td>1 week</td>
</tr>
<tr>
<td>Sandstone</td>
<td>25</td>
<td></td>
<td>1 week</td>
<td>2 weeks</td>
</tr>
<tr>
<td>Argillite</td>
<td>20</td>
<td>Lower Intertidal Zone</td>
<td>2 weeks</td>
<td>3 weeks</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3 weeks</td>
<td>90 minutes</td>
</tr>
</tbody>
</table>

Table 2.2: The experimental conditions used in this study.

specific environments. Rock samples were placed in the basins and elevated on a plastic screen so that the debris could accumulate at the bottom of the basins (Figure 2.4). The samples were exposed to experimental conditions that simulated tidal cycles and did not accelerate the weathering processes. If rock fragments separated from the cores or cubes, the larger fragment was retained in the experiments, as the smaller fragments were considered eroded fragments that would have been washed away by the waves.

Figure 2.4: Rock samples being exposed to experimental conditions

The rock samples were prepared following the procedure of Kanyaya and Trenhaile (2005) and Trenhaile et al., (2006). Rock cores were extracted from the basalts of Scots Bay, Nova Scotia and the argillitic rocks of Mont Louis, Québec, using a diamond-
studded drill bit, 1.9 cm in diameter, to produce a core 2 cm in length. The surface on the top and bottom of each core was removed with a rock saw in order to minimize the effects of pre-experimental weathering. Sandstones from Burntcoat Head in the Bay of Fundy, which were too friable to be cored, were cut into 2 cm cubes. A total of 300 basalt cores from Scots Bay, 240 argillite cores from Mont Louis, and 300 sandstone cubes from Burntcoat Head were utilized for the experiments (Figure 2.5). Each core (and cube) was numbered and oven dried for 12 hours and then weighed. The samples were then submerged in either salt- or freshwater for two weeks in order to obtain their maximum wet weight prior to commencement of the experiments.

![Figure 2.5: Rock samples utilized for this study. From left to right: Basalt, Sandstone, and Argillite](image)

Commercial synthetic sea water, produced by Aquarium Systems Inc., was used in the experiments. This water has an approximate salinity of 35 parts per thousand and contains 28 ions and elements in concentrations that are similar to their occurrence in natural sea water. The term fresh water will be used subsequently to refer to the de-ionized water and salt water to refer to the synthetic sea water. Fresh and salt water were replaced every three weeks in order to ensure the pH, and specifically the salinity in the saltwater experiments, were consistent. Due to evaporation, fresh water was added to the saltwater basins as necessary in order to maintain an approximate salinity of 35 parts per thousand. The experiments commenced on 14 July 2008 and ran for one year. Each month, the amount of rock material that had become detached from the samples and had accumulated at the bottom of the basins was collected on filter paper, dried, and weighed. These measurements provided group data on the mean rates of downwearing of each rock type under each of the experimental conditions without having to oven-dry the rocks, which could have contributed to their deterioration. Upon completion of the experiments
in July 2009, the individual samples were oven dried and weighed in order to determine the individual sample breakdown rate experienced during the year.

The following equation was used to convert rates of rock breakdown in the laboratory experiments into equivalent rates of surface downwearing ($D_r$) (mm yr$^{-1}$), a format that allowed comparison with downwearing data from the field (Kanyaya and Trenhaile, 2005):

\[
D_r = \frac{(W_1 - W_2)}{\rho A} \times 10
\]

where: $W_1$ and $W_2$ are the initial and final dry weights of the rock samples (g), $\rho$ is the rock density (g cm$^{-3}$), $A$ is the surface area of either the core or cube (cm$^2$), and 10 is to convert centimeters to millimeters.

### 2.2 Field Measurements

Micro-erosion meter stations were installed to measure downwearing rates in the upper intertidal and lower intertidal zones at each study area. Micro-erosion meters use an engineer’s dial gauge, which sits on a low, triangular frame, to measure the downward extension of a needle-like probe (Figure 2.6). In use, this assembly is mounted upon three metal bolts (a MEM station) that have been permanently embedded in the rock, allowing for repeated measurements to be made at precisely the same place on a rock surface (High and Hanna, 1970). However, the traditional MEM only allows three measurements to be made at each station, whereas traversing micro-erosion meter (TMEM) permits numerous measurements to be made within the triangular frame of the instrument with the aid of ball bearings that are fixed along each side of the base of the instrument (Trudgill et al., 1981; Stephenson, 1997; Stephenson et al., 2004). The TMEM used in this study allowed rates of rock surface downwearing to be measured within 0.01 mm. Several researchers have used the MEM/TMEM to measure slow rock downwearing in the intertidal zones of rocky coasts (Kirk, 1977; Robinson, 1977; Gill and Lang, 1983; Mottershead, 1989; Stephenson and Kirk, 1996, 1998; Foote et al., 2001; Andrade et al., 2002; Foote et al., 2006; Trenhaile et al., 2006; Stephenson and Finlayson, 2009).
An industrial heavy duty, battery-powered drill was used to cut three holes, 65 to 70 mm deep and 20 mm diameter, at each station. Three stainless steel bolts were then permanently embedded in the holes using industrial strength epoxy (Epcon A7, produced by Red Head Adhesive Anchoring Systems). The bolts were 8 mm in diameter and 65 mm in length. The top of each bolt was set below the rock surface, in order to protect it from abrasion and other damage by moving sand, boulders, and ice (Figure 2.6). Once installed, and after the measurements had been made with the TMEM, the bolts were covered with silicone for protective purposes. In June 2008, 67 TMEM stations were installed in the upper intertidal zone in eastern Canada (25 at Burntcoat Head, Nova Scotia; 20 at Scots Bay, Nova Scotia; 22 at East Point, Prince Edward Island) (Figure 2.7). Additionally, 32 TMEM stations were installed throughout the entire intertidal zone at Salmon River (18 stations) and Arisaig (14 stations) (Figure 2.7). It was difficult to set TMEM stations in the lower intertidal zone for a variety of reasons, including limited exposure time, the presence of barnacles, seaweed, and other organisms that attach themselves to the platform surface, and the presence of tidal flats, which may cover the lower portions of the platform. The elevation of seven points on the rock surface at each TMEM station were initially measured, and upon returning to the sites in the summer of 2009, the same seven points were remeasured; these data were used to calculate mean annual downwearing rates at each point, based on the change in elevation from the initial measurement. Because of the distance to the study sites and the occurrence of thick sea ice in the winter, it was only possible to take measurements during the summer months. The downwearing data from the newly installed stations supplemented data obtained over the last five years from stations previously installed in these zones by Kanyaya, Porter, and Trenhaile. The stations at Mont Louis, Scots Bay, and Burntcoat Head were installed from 2004 to 2007, providing the longest records of downwearing. The stations at Bramber were installed in 2007. All stations were surveyed to determine their position relative to the average high tide elevation at each station.
A Schmidt N-Type Rock Test Hammer was used to determine the local hardness of the rock. The Schmidt Hammer was first used by geomorphologists to assess the compressive strength of rock (Hucka, 1965; Yaalon and Singer, 1974; Day, 1980; Day and Goudie, 1977) and has since been implemented in a number of rock coast studies as a means of assessing the resistance/compressive strength of the rock, or the effect of weathering in reducing rock strength (Stephenson and Kirk, 2000; Kennedy and Beban, 2005; Gómez-Pujol et al., 2006; Kennedy and Dickson, 2006; Trenhaile et al., 2006; Kennedy, 2010). Thirty measurements were made adjacent to each station and a mean of the rebound values was used, without the elimination of outlier values, to represent each site.
Figure 2.7: Location of the TMEM stations in the study areas, including stations previously installed by Kanyaya, Porter, and Trenhaile in the central portions of the intertidal zone.
CHAPTER III: RESULTS

1.0 Laboratory Results

There were substantial differences in downwearing rates among the three rock types in both the salt weathering and wetting and drying experiments, and in the susceptibility of each rock type to different tidal levels. The breakdown patterns experienced during the course of these experiments were similar to those of Kanyaya and Trenhaile (2005). Granular disintegration of the sandstones resulted in a gradual reduction in weight of the cubes over the experimental period. In the simulated upper intertidal zone, this ultimately led to a number of cubes’ complete destruction. The basalts were much more resistant, with only a very small number of cores experiencing erosion. The erosion that did occur was through detachment of small fragments, with very little granular disintegration. Breakdown of the fissile argillites was dominated by splitting and flaking along discontinuities and bedding planes, producing shards of loose material similar to those that are found on the platform. Erosion was much more abrupt and episodic than in the basalts and sandstones, producing a step-like reduction in weight over time.

Mean downwearing rates in the laboratory were much greater in salt water than in fresh water in the upper intertidal zone and rates were uniformly low in the lower intertidal zone, irrespective of immersion or exposure frequency (Table 3.1). Rates above the LHT level were highest in the sandstones and lowest in the basalts. There was a general tendency for downwearing rates in the sandstones and basalts to decrease with increasing elevation above the LHT level. The data does suggest, however, that despite infrequent wetting events, downwearing rates may continue to be significant in the highest portions of the platform up to the lower supratidal zone, especially in the sandstones, and to a lesser extent, in the argillites.
<table>
<thead>
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<th>De-ionized Water</th>
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</thead>
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<tr>
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<td>Sandstone Basalt</td>
</tr>
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<td>Upper Intertidal</td>
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<td></td>
</tr>
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</tr>
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<td></td>
</tr>
<tr>
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<td>0.015 0.012 0.003</td>
</tr>
<tr>
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<td>0.017 0.009 0.001</td>
</tr>
<tr>
<td>3 Week Immersion</td>
<td>0.027 0.016 0.015</td>
<td>0.010 0.008 0.001</td>
</tr>
</tbody>
</table>

Table 3.1: Summary of the mean rates of downwearing (mm yr\(^{-1}\)) in the lower and upper intertidal zones.

1.1 Basalt

The experiments suggest that salt water immersion and exposure in the basalts is less effective in the upper intertidal zone than in the sandstones and argillites. Only 12% of the basaltic cores experienced breakdown in the 1 week exposure treatment, and the proportion of cores that experienced breakdown rapidly decreased with elevation up the platform (Table 3.4). In all other salt and freshwater treatments, basalt downwearing was uniformly low, irrespective of immersion and exposure frequency. Typically, only 1 or 2 cores out of 25 in each basin experienced any downwearing.

1.2 Argillite

Salt weathering was much more effective on the Mont Louis argillites than the Scots Bay basalts. Two week exposure appears to be optimal for argillites to break down in the upper intertidal zone. The rate of downwearing in this zone in saltwater was 83 times greater than similar cores in freshwater (mean of 0.997 mm yr\(^{-1}\) compared to 0.012 mm yr\(^{-1}\)). The argillites experienced considerably greater downwearing in the 1 and 3 week exposure periods in saltwater compared to the basalts, where 40% of the cores in
both these treatments experienced breakdown; much fewer of the basalt cores experienced breakdown in either of these zones in salt water. Two weeks also appeared to be the optimal exposure duration for argillite breakdown in the upper intertidal and supratidal zone in freshwater, although very little material was eroded from the samples. As in the basalts, argillite downwearing was consistently low in all the freshwater experiments, regardless of the time of immersion or exposure.

1.3 Sandstone

There were marked differences in the rock slabs used to produce the cubes for the sandstones at Burntcoat Head. In general, the cubes derived from the dark orange slabs were friable and particularly susceptible to granular breakdown, whereas the cubes derived from the light orange slabs contained rounded grains and much stronger cement, and were more resistant to breakdown. To compensate for this, equal numbers of cubes from each slab were used in each basin. This produced breakdown distributions that were highly skewed, with a number of samples experiencing fairly rapid breakdown and others very slow breakdown (Figure 3.1). In almost all cases, sandstone downwearing

![Figure 3.1: Five number summary box plots of surface downwearing rates (mm yr⁻¹) in the sea water experiments. Each column shows the median and maximum and minimum values for each experimental treatment. The shaded boxes extend from the 25th to the 75th percentiles and therefore contain 50 % of the data. A) The labels 1, 2, and 3 refer to increasingly higher elevations in the upper intertidal zone, corresponding to 1, 2, and 3 weeks of exposure between wetting events, respectively; B) The labels 1, 2, and 3 refer to decreasing elevations in the lower intertidal zone, corresponding to 1, 2, and 3 weeks of submergence between drying events, respectively.](image)
was greater than that of the basalts and argillites. As hypothesized, the greatest rates of downwearing were experienced in the sandstones in the salt water experiments, especially in the upper intertidal zone, where between 52% and 85% of the cubes experienced breakdown. As an example, the downwearing rates of sandstones in the 1 week upper intertidal treatments were nearly 25 times greater than those cubes exposed to similar conditions in freshwater (mean of 1.754 mm yr$^{-1}$ compared to 0.075 mm yr$^{-1}$). Similar to the basalts, the mean downwearing values in the saltwater upper intertidal zones declined after 1 week of exposure (from 1.754 to 0.980 and 0.912 mm yr$^{-1}$, respectively). The upper intertidal freshwater experiments produced similar results, with 1 week exposure being optimal for breakdown to occur. As in the basalts and argillites, downwearing in the freshwater and saltwater low tidal zones was uniformly low and lacked any discernable elevational pattern.

1.4 Patterns of Breakdown

A number of patterns become evident when analyzing rock sample breakdown over time (Tables 3.2 and 3.3). In most cases, the basalt cores eroded quickly during the first several months of the experiments, then slowed down, and began eroding again near the eight month mark. A possible explanation of the erosion at the beginning may be that the particles that were already loose or prone to removal by physical means (i.e. salt weathering, wetting and drying) were quickly removed, and only after 8 months of experimentation do we begin to see progressive chemical deterioration and the cumulative effects of the stresses generated by repeated expansion and contraction.

The sandstones exhibited the same decay patterns in the salt and fresh water experiments in the low tidal zone. Much of the friable material on the cubes cut from the dark orange slabs detached in the first few months of experimentation, with little to no erosion occurring after this. In saltwater, in the upper intertidal zone, the sandstones began eroding fairly rapidly after about four months, including the complete disintegration of some samples. As hypothesized, breakdown was most effective in the 1 week exposure treatments, as the repeated saltwater immersion and exposure destroyed the weaker samples. By the end of the 12 months of experimentation, only the harder
samples were left, resulting in very little material accumulating in the bottom of the basin. Significant amounts of erosion of the samples in the 2 and 3 week exposure period experiments began much later than in the 1 week exposure experiments, approximately 7 to 8 months into the experimentation cycle; this may be attributed to less frequent episodes of salt crystallization in the beginning.

The argillites in the saltwater upper intertidal treatments began to fracture approximately 7 to 8 months into the experiments, with little or no erosion before this. A likely explanation is that the relative humidity in the laboratory began to rise at this time (March-April) as spring approached. These fine-grained rocks containing clay can be damaged by wetting and drying resulting from the additional adsorption of water from the air during periods of high relative humidity (Kanyaya and Trenhaile, 2005); minimal argillite erosion was experienced during the winter months, possibly owing to the lower air temperatures and humidity. Kanyaya and Trenhaile (2005) came to similar conclusions, most argillite breakdown occurring in their 3 year experiments during the late spring and summer where temperatures and relative humidity were higher. This pattern was similar in the basalts, with higher erosion rates at the beginning and end of the experimental period, corresponding to warmer and moister conditions in July and August. The porous, coarse-grained sandstones are not adsorption-sensitive, and they broke down in the winter irrespective of the lower temperature and relative humidity.

The breakdown patterns reported in this study are contrary to those of Kanyaya and Trenhaile (2005), who observed almost no erosion on most cores from eastern Canada for the first several months of their wetting and drying experiments, irrespective of rock type. In part, the authors attributed this to partial sealing of the surface voids of the cores and cubes during the cutting process, as small fragments of detached material and dirt block pore spaces. In contrast, in the present study, there were several instances of fairly high rates of downwearing in the saltwater experiments over the first 21 days in the sandstones and basalts, and over the first 77 and 78 days in the argillaceous rocks (Tables 3.2 and 3.3). The difference between the two experiments is likely attributed to salt weathering, as Trenhaile and Kanyaya (2005) only considered the role of wetting and drying in fresh water.
<table>
<thead>
<tr>
<th>Tidal level</th>
<th>Elapsed time (days)</th>
<th>0-21</th>
<th>21-78</th>
<th>78-136</th>
<th>136-197</th>
<th>197-260</th>
<th>260-316</th>
<th>316-358</th>
</tr>
</thead>
<tbody>
<tr>
<td>HT3</td>
<td>0-21</td>
<td>0.166</td>
<td>0.006</td>
<td>0.066</td>
<td>0.082</td>
<td>0.311</td>
<td>0.651</td>
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<td>0.636</td>
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<th>197-260</th>
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<td>0.019</td>
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<td>0.020</td>
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Table 3.2: Changes in the mean rate of downwearing (mm yr\(^{-1}\)) over 1 year in the salt water experiments. HT 1 to HT 3 represents increasingly higher elevations in the upper intertidal zone and LT 1 to LT 3 represents increasing lower elevations within the lower intertidal zone. The downwearing means are non-cumulative.
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<th>Tidal level</th>
<th>Elapsed time (days)</th>
<th>Tidal level</th>
<th>Elapsed time (days)</th>
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<td>0.000</td>
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<th>Tidal level</th>
<th>Elapsed time (days)</th>
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<th>Elapsed time (days)</th>
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<td>0.043</td>
<td>0.019</td>
<td>0.014</td>
<td>0.013</td>
<td>0.002</td>
</tr>
<tr>
<td>LT2</td>
<td>0.067</td>
<td>0.013</td>
<td>0.007</td>
<td>0.010</td>
<td>0.002</td>
</tr>
<tr>
<td>LT3</td>
<td>0.064</td>
<td>0.013</td>
<td>0.007</td>
<td>0.000</td>
<td>0.003</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tidal level</th>
<th>Elapsed time (days)</th>
<th>Tidal level</th>
<th>Elapsed time (days)</th>
<th>Tidal level</th>
<th>Elapsed time (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HT3</td>
<td>0.002</td>
<td>0.003</td>
<td>0.007</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>HT2</td>
<td>0.006</td>
<td>0.000</td>
<td>0.000</td>
<td>0.105</td>
<td>0.000</td>
</tr>
<tr>
<td>HT1</td>
<td>0.002</td>
<td>0.005</td>
<td>0.000</td>
<td>0.011</td>
<td>0.007</td>
</tr>
<tr>
<td>LT1</td>
<td>0.003</td>
<td>0.002</td>
<td>0.000</td>
<td>0.000</td>
<td>0.004</td>
</tr>
<tr>
<td>LT2</td>
<td>0.006</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>LT3</td>
<td>0.001</td>
<td>0.009</td>
<td>0.000</td>
<td>0.000</td>
<td>0.001</td>
</tr>
</tbody>
</table>

**Table 3.3:** Changes in the mean rate of downwearing (mm yr⁻¹) over 1 year in the fresh water experiments. HT 1 to HT 3 represents increasingly higher elevations in the upper intertidal zone and LT 1 to LT 3 represents increasing lower elevations within the lower intertidal zone. The downwearing means are non-cumulative.

1.5 **Statistical Analysis: Analysis of Variance**

Analysis of variance (ANOVA) was used to analyze the relationships between downwearing rates, rock types, and tidal immersion and exposure frequencies. ANOVA is commonly used to compare the means of three or more groups of observations based
on a single variable that has been measured at the interval/ratio level, in this case, downwearing. It determines whether there is more variation between groups than within groups and is preferable to running multiple T tests, which may increase the probability of making a Type I error (rejection of the null hypothesis when it is true). While ANOVA shows that there are significant differences between means, however, it does not identify which means are different from each other; there are several post hoc testing procedures that can be used to determine the significance of differences between pairs of means.

The first set of ANOVA tests were run on samples of similar lithology for the various tidal immersion and exposure frequencies in both the salt and fresh water treatments. The p: 0.05 level of significance was used throughout this thesis. The results indicated that there are significant differences between breakdown rates in both the upper and lower intertidal zones, although no pattern is readily discernable (see Appendix A for the full analyses; table 3.4 is presented as a summary). The null hypothesis, which stated that there are no significant differences between mean downwearing rates, was rejected 3 out of 4 times in the argillites, with the exception coming from samples in the fresh water upper intertidal zone. This suggests that breakdown rates among the samples in the 1, 2, and 3 week exposure period treatments are significantly different. The opposite is true of the basalts, where only the sample means from the fresh water upper intertidal zone were significantly different. Mean sandstone breakdown rates were statistically similar, aside from those found in the fresh water lower intertidal zone.

<table>
<thead>
<tr>
<th></th>
<th>Salt Water</th>
<th>Fresh Water</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Σx²</td>
<td>df</td>
</tr>
<tr>
<td>Above LHT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between Groups</td>
<td>67.2</td>
<td>8</td>
</tr>
<tr>
<td>Within Groups</td>
<td>189.9</td>
<td>200</td>
</tr>
<tr>
<td>Total</td>
<td>257.1</td>
<td>208</td>
</tr>
<tr>
<td>Below HLT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between Groups</td>
<td>0.01</td>
<td>8</td>
</tr>
<tr>
<td>Within Groups</td>
<td>0.03</td>
<td>201</td>
</tr>
<tr>
<td>Total</td>
<td>0.04</td>
<td>209</td>
</tr>
</tbody>
</table>

Table 3.4: Sample ANOVA for the salt and fresh water experiments. Σx² = sum of the squares, mean X² = mean square, df = degrees of freedom, F is the F-test statistic and Sig. is its significance. The F critical value in each case is 1.99.
The second set of ANOVA tests compared the mean breakdown rates of the three rock types at each tidal elevation (see Appendix B for the full analyses). All of the null hypotheses were rejected for the samples in the salt water treatments. The low P values indicated that there were significant differences between mean downwearing rates for the argillites, basalts, and sandstones. In the fresh water experiments, breakdown rates for the three rock types are similar for the 1 and 2 week submergence periods experienced in the upper intertidal zone; the other treatments were significantly different.

1.6 Post Hoc Comparisons: Tukey’s Honestly Significant Difference

Post hoc comparisons are typically performed after obtaining a significant F value (or a P value of less than 0.05) in the ANOVA analysis. Tukey’s Honestly Significant Difference (HSD) can be used to determine which differences in the means were responsible for the significant P value obtained through the ANOVA test. Tukey’s HSD test is quite similar to a t-test. However, Tukey’s HSD is preferable when multiple comparisons are being made, as the formula corrects for the experiment-wise error rate (decreases the probability of making a Type 1 error). The P value obtained through Tukey’s HSD is low if the difference in downwearing rates between a pair of means is significant, and high (above 0.05) if it is not significant. Tukey’s HSD was used to compare similar rock types in the upper intertidal zone between 1 week to 2 week exposure, 1 week to 3 week exposure, and 2 week to 3 week exposure in both fresh and salt water experiments (Table 3.5); a similar procedure was conducted for lithologies in the lower intertidal zone. Typically, only one or two out of the three mean downwearing comparisons would account for the significant P value obtained in the ANOVA tests.
Table 3.5: Tukey’s HSD comparisons between pairs of laboratory downwearing rates in the upper and lower intertidal zones (● signifies that differences are significant at the 0.05 level). HT 1 to HT 3 represents increasingly higher elevations in the upper intertidal zone and LT 1 to LT 3 represents increasing lower elevations within the lower intertidal zone.

### 1.7 Statistical Analyses: The T Test

A simple t-test was employed to compare downwearing rates at different tidal elevations in order to determine if fresh and salt water means were statistically different from each other. There were significant differences in downwearing rates between salt and fresh water at all elevations within the upper and lower intertidal zones (Table 3.6), with the exception occurring in two of the basalt treatments (1 week submergence (LT1) and 1 week exposure (HT1)). The low P values (typically less than 0.005) amongst the pairs that were significant indicate a very strong probability that that the difference in downwearing between samples in fresh and salt water were different.

<table>
<thead>
<tr>
<th>Sandstone</th>
<th>Basalt</th>
<th>Argillite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal Level Comparison</td>
<td>Sig. diff.</td>
<td>Tidal Level Comparison</td>
</tr>
<tr>
<td>HT1</td>
<td>HT2</td>
<td>HT1</td>
</tr>
<tr>
<td>HT1</td>
<td>HT3</td>
<td>HT1</td>
</tr>
<tr>
<td>Salt Water</td>
<td>LT1</td>
<td>LT2</td>
</tr>
<tr>
<td>LT1</td>
<td>LT3</td>
<td>LT1</td>
</tr>
<tr>
<td>LT2</td>
<td>LT3</td>
<td>LT2</td>
</tr>
<tr>
<td>HT1</td>
<td>HT2</td>
<td>HT1</td>
</tr>
<tr>
<td>HT1</td>
<td>HT3</td>
<td>HT1</td>
</tr>
<tr>
<td>Fresh Water</td>
<td>LT1</td>
<td>LT2</td>
</tr>
<tr>
<td>LT1</td>
<td>LT3</td>
<td>●</td>
</tr>
<tr>
<td>LT2</td>
<td>LT3</td>
<td>●</td>
</tr>
</tbody>
</table>

Table 3.6: T-test results comparing samples in salt and fresh water at the same tidal levels (● signifies that differences are significant at the 0.05 level). HT 1 to HT 3 represents increasingly higher elevations in the upper intertidal zone and LT 1 to LT 3 represents increasing lower elevations within the lower intertidal zone.

<table>
<thead>
<tr>
<th>Tidal level</th>
<th>P value</th>
<th>Sig. diff.</th>
<th>Tidal level</th>
<th>P value</th>
<th>Sig. diff.</th>
<th>Tidal level</th>
<th>P value</th>
<th>Sig. diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>HT3</td>
<td>0.004</td>
<td>●</td>
<td>HT3</td>
<td>0.000</td>
<td>●</td>
<td>HT3</td>
<td>0.016</td>
<td>●</td>
</tr>
<tr>
<td>HT2</td>
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<td>●</td>
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<td>HT2</td>
<td>0.000</td>
<td>●</td>
</tr>
<tr>
<td>HT1</td>
<td>0.000</td>
<td>●</td>
<td>HT1</td>
<td>0.063</td>
<td>●</td>
<td>HT1</td>
<td>0.011</td>
<td>●</td>
</tr>
<tr>
<td>LT1</td>
<td>0.003</td>
<td>●</td>
<td>LT1</td>
<td>0.404</td>
<td>●</td>
<td>LT1</td>
<td>0.000</td>
<td>●</td>
</tr>
<tr>
<td>LT2</td>
<td>0.000</td>
<td>●</td>
<td>LT2</td>
<td>0.002</td>
<td>●</td>
<td>LT2</td>
<td>0.001</td>
<td>●</td>
</tr>
<tr>
<td>LT3</td>
<td>0.000</td>
<td>●</td>
<td>LT3</td>
<td>0.000</td>
<td>●</td>
<td>LT3</td>
<td>0.000</td>
<td>●</td>
</tr>
</tbody>
</table>

41
1.8 The Effect of Sample Shape

A small scale experiment was conducted to determine if sample shape was an important factor controlling the rate of rock breakdown. Previous studies suggest that the weathering behaviour of rock samples is partly controlled by their shape (Goudie, 1974; Robinson and Williams, 1982). It is believed that angular samples break down more rapidly than rounded samples of the same lithology because the edges and corners on a cube, for example, are vulnerable to weathering from multiple directions, and cubes possess greater lengths of edges and have larger surface area to volume ratios than do cores/cylinders (Robinson and Williams, 1982).

A sandstone block from Burntcoat Head was used to prepare 10 cubes and 10 cores/cylinders that were of the same size and dimension as the samples prepared for the main laboratory investigation. The cores were hand prepared using a lathe, and were later smoothed using sand paper. The sandstones were then subjected to salt water inundation and exposure frequencies experienced in the upper intertidal zone (1 week exposure), and the eroded material was measured using methods that are outlined in Chapter 2.

The results, after 8 months of experimentation, demonstrated that the cores experienced higher rates of breakdown, with a mean downwearing rate of 1.09 mm yr\(^{-1}\), as compared to 0.59 mm yr\(^{-1}\) for the cubes. This result is contrary to Robinson and Williams (1982), who found that sandstone cubes were more susceptible than cores to salt weathering, owing to the increased length of edge exposed to weathering. A possible explanation could be that the method in which the cores were prepared (by hand) may have increased surface roughness and loosened quartz fragments in the samples, allowing the samples to become readily detached upon inundation and exposure cycles. It has been shown that polished and smoothed surfaces, such as those on the cubes that were prepared with a rock saw, disintegrate less rapidly than rough surfaces (Kwaad 1970). The results suggest that the shape of the samples does influence the results, and that rates of sandstone downwearing may be even greater, relative to the basalts and argillites, than indicated in the experiments; further work is required, however, to reliably gauge the effect of variable sample shape on rates of surface downwearing.
2.0 Field Results

Swelling or expansion/elevation (as opposed to downwearing) of the rock surface was recorded above the LHT in most of the study areas. At Burntcoat Head, a swelling of 0.03 mm yr\(^{-1}\) was observed at MEM1 (Figure 3.4). At Scots Bay, a mean of 0.99 mm yr\(^{-1}\) was derived from two stations (Old MEM 1 and KC, Figure 3.3), and at East Point, a mean of 0.09 mm yr\(^{-1}\) was recorded from three stations (14, 15, and 20, Figure 3.2). Swelling was particularly common in the argillaceous rocks at Mont Louis, where 21 of the 37 TMEM stations exhibited swelling generally less than 1 mm but occasionally ranging up to 8 mm at individual points within the TMEM stations. The mean for all stations was for swelling of 0.005 mm yr\(^{-1}\), but when the swelling data were removed, there was a mean downwearing rate of 0.242 mm yr\(^{-1}\). Swelling has been reported in a wide range of rock types, over different time scales, in a variety of tidal environments (Stephenson and Finlayson, 2009), although it appears to be particularly common in argillaceous rocks (Trenhaile, 2006). While swelling has been attributed to a number of mechanisms, including wetting and drying, salt crystallization, changes in temperature and humidity, endolithic and epilithic algae growth, and operator error (Stephenson and Finlayson, 2009), it appears likely that the adsorption of water by the chlorite and illite clay minerals in the rocks accounted for the swelling observed at Mont Louis. This phenomenon is not uncommon, as Porter and Trenhaile (2007) recorded surface contraction up to 0.04 mm over a few hours at Mont Louis as the rocks dried during low tidal stages, implying that swelling by an equal amount occurred when the rocks were immersed. However, there is no evidence that swelling promotes downwearing in this area (Porter et al., in press, a). Given that swelling events are temporary phenomena and that platform surfaces can only be lowered over the long-term, those stations that experienced swelling were excluded when calculating mean downwearing rates.

Despite marked differences in tidal range and rock type, mean rates of downwearing in the upper portions of the intertidal zone were fairly high (≥ 1 mm yr\(^{-1}\)) in most of the study areas (Figures 3.2, 3.3, 3.4). The fastest rates occurred in the coarse grained sandstones at East Point and Burntcoat Head. Downwearing rates were also quite rapid in the argillaceous rocks at Bramber, but they were much lower in the argillaceous
rocks at Mont Louis (Table 3.7). Mean downwearing rates in the upper intertidal zone at Burntcoat Head and Scots Bay were similar or higher than the means for the entire intertidal zones. The downwearing data from all study areas were positively skewed, reflecting the occurrence of rapid downwearing at a smaller number of TMEM stations, and slower downwearing at a greater number of stations. Overall, the sandstones at Burntcoat Head and East Point had the highest range of downwearing rates, owing to one TMEM experiencing over 10 mm yr\(^{-1}\) in one year at each location (Station 10 at East Point (11.03 mm yr\(^{-1}\); Figure 3.2) and Station K9 at Burntcoat Head (12.08 mm yr\(^{-1}\); Figure 3.4)). The high kurtosis values indicated that the downwearing rates were leptokurtic, with most rates centered about the mean.

There were few TMEM stations installed below the HLT level, and it is therefore difficult to compare the available field data with the experimental data, or with measured downwearing rates above the LHT or in the more central portions of the intertidal zone. The data that do exist come from 13 stations at Arisaig, 4 at Salmon River, and 3 at Burntcoat Head. The mean downwearing rate at Arisaig was slightly higher than for the platform as a whole. It was also quite high at Salmon River, and a mean rate of 0.50 mm yr\(^{-1}\) from the stations at Burntcoat Head was much greater than was obtained for this elevation in the laboratory experiments (0.026 mm yr\(^{-1}\)).
<table>
<thead>
<tr>
<th></th>
<th>Above the LHT</th>
<th>Below the HLT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Scots Bay</td>
<td>Burntcoat Head</td>
</tr>
<tr>
<td>Mean Station Number</td>
<td>0.99</td>
<td>1.27</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>28</td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.19</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>0.80</td>
<td>0.44</td>
</tr>
<tr>
<td>Median</td>
<td>1.06</td>
<td>2.36</td>
</tr>
<tr>
<td></td>
<td>1.13</td>
<td>5.59</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>11.99</td>
<td>17.00</td>
</tr>
<tr>
<td></td>
<td>3.19</td>
<td>3.85</td>
</tr>
<tr>
<td>Sample Variance</td>
<td>5.39</td>
<td>12.04</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>5.54</td>
<td>12.08</td>
</tr>
<tr>
<td>Skewness</td>
<td>0.15</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Table 3.7: Summary statistics for mean TMEM downwearing rates (mm yr\(^{-1}\)) in the upper and lower intertidal zone in eastern Canada. Swelling values were omitted from the analyses.
Figure 3.2: Platform profiles and mean TMEM downwearing rates at Mont Louis, Quebec, East Point, Prince Edward Island, and Arisaig, Nova Scotia.
Figure 3.3: Platform profiles and mean TMEM downwearing rates at Scots Bay and Salmon River, Nova Scotia.
2.1 Correlation Analyses: Pearson's $r$ and Correlation of Determination

Correlation coefficients were calculated to determine the strength of the relationships between downwearing rates and TMEM elevation, downwearing rates and rock hardness (Schmidt rock hammer rebound value), and TMEM station elevation and rock hardness (Figures 3.5 and 3.6). This was completed on the TMEM stations above the
LHT from six of the study areas; the limited number of stations installed above the LHT and below the HLT at Salmon River prevented statistical analyses at this site. Stations that experienced swelling were omitted from the analyses. Data from all TMEM stations at Mont Louis were included in this analysis, as none of the stations lie below the HLT. Because of the number of suitable stations that were available, correlation analyses were only conducted for Arisaig below the HLT.

There were no significant correlations between downwearing and rock hardness in any of the study areas (Table 3.8). Much the same can be said for correlation coefficients between downwearing and elevation of the TMEM stations (Table 3.9). There was a positive, statistically significant relationship at Bramber, indicating that downwearing rates tended to increase with increasing elevation above the LHT. There was no relationship in any of the other study areas.

<table>
<thead>
<tr>
<th>Location</th>
<th>Number of MEMs</th>
<th>Degrees of Freedom</th>
<th>Pearson's r</th>
<th>R2</th>
<th>r Critical</th>
<th>Significant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scots Bay</td>
<td>30</td>
<td>28</td>
<td>-0.271</td>
<td>0.073</td>
<td>0.361</td>
<td>No</td>
</tr>
<tr>
<td>Burntcoat Head</td>
<td>28</td>
<td>26</td>
<td>-0.078</td>
<td>0.006</td>
<td>0.374</td>
<td>No</td>
</tr>
<tr>
<td>Mont Louis</td>
<td>17</td>
<td>15</td>
<td>-0.443</td>
<td>0.196</td>
<td>0.482</td>
<td>No</td>
</tr>
<tr>
<td>East Point</td>
<td>18</td>
<td>16</td>
<td>0.254</td>
<td>0.064</td>
<td>0.468</td>
<td>No</td>
</tr>
<tr>
<td>Bramber</td>
<td>6</td>
<td>4</td>
<td>0.521</td>
<td>0.271</td>
<td>0.881</td>
<td>No</td>
</tr>
<tr>
<td>Arisaig¹</td>
<td>13</td>
<td>11</td>
<td>0.482</td>
<td>0.232</td>
<td>0.553</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 3.8: Correlation analysis of downwearing and rock hardness (Schmidt rock hammer rebound value) amongst TMEMs installed above the LHT (upper intertidal zone). ¹Stations are below the HLT level.

<table>
<thead>
<tr>
<th>Location</th>
<th>Number of MEMs</th>
<th>Degrees of Freedom</th>
<th>Pearson's r</th>
<th>R2</th>
<th>r Critical</th>
<th>Significant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scots Bay</td>
<td>30</td>
<td>28</td>
<td>0.275</td>
<td>0.076</td>
<td>0.361</td>
<td>No</td>
</tr>
<tr>
<td>Burntcoat Head</td>
<td>28</td>
<td>26</td>
<td>-0.138</td>
<td>0.019</td>
<td>0.374</td>
<td>No</td>
</tr>
<tr>
<td>Mont Louis</td>
<td>17</td>
<td>15</td>
<td>0.101</td>
<td>0.01</td>
<td>0.482</td>
<td>No</td>
</tr>
<tr>
<td>East Point</td>
<td>18</td>
<td>16</td>
<td>-0.017</td>
<td>0</td>
<td>0.468</td>
<td>No</td>
</tr>
<tr>
<td>Bramber</td>
<td>6</td>
<td>4</td>
<td>0.842</td>
<td>0.709</td>
<td>0.881</td>
<td>Yes</td>
</tr>
<tr>
<td>Arisaig¹</td>
<td>13</td>
<td>11</td>
<td>0.48</td>
<td>0.231</td>
<td>0.553</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 3.9: Correlation analysis of downwearing and elevation amongst TMEMs installed above the LHT (upper intertidal zone). ¹Stations are below the HLT level.
Stronger correlations were found between elevation and rock hardness, although most were again insignificant (Table 3.10). Rock strength increases with increasing elevation at Scots Bay and Mont Louis, a relationship that is evident in the field at Mont Louis, where higher, harder siltstone and mudstone ridges run between weaker shale and mudstone depressions that are filled with water. This relationship can explain some of the discrepancies between laboratory and field data. In the laboratory, elevation only determined the period of tidal immersion and exposure, whereas in the field, the height-downwearing relationship is obscured by the opposing effect of elevational variations in rock type and hardness.

<table>
<thead>
<tr>
<th>Location</th>
<th>Number of MEMs</th>
<th>Degrees of Freedom</th>
<th>Pearson's r</th>
<th>R2</th>
<th>r Critical</th>
<th>Significant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scots Bay</td>
<td>32</td>
<td>30</td>
<td>0.428</td>
<td>0.183</td>
<td>0.349</td>
<td>Yes</td>
</tr>
<tr>
<td>Burntcoat Head</td>
<td>28</td>
<td>26</td>
<td>-0.296</td>
<td>0.088</td>
<td>0.374</td>
<td>No</td>
</tr>
<tr>
<td>Mont Louis</td>
<td>37</td>
<td>35</td>
<td>0.587</td>
<td>0.344</td>
<td>0.325</td>
<td>Yes</td>
</tr>
<tr>
<td>East Point</td>
<td>21</td>
<td>19</td>
<td>0.447</td>
<td>0.2</td>
<td>0.468</td>
<td>No</td>
</tr>
<tr>
<td>Bramber</td>
<td>6</td>
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<td>-0.33</td>
<td>0.109</td>
<td>0.881</td>
<td>No</td>
</tr>
<tr>
<td>Arisaig¹</td>
<td>13</td>
<td>11</td>
<td>-0.114</td>
<td>0.013</td>
<td>0.553</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 3.10: Correlation analysis of elevation and rock hardness (Schmidt rock hammer rebound value) amongst TMEMs installed above the LHT (upper intertidal zone). ¹Stations are below the HLT level.
Figure 3.5: The relationship between elevation and downwearing at all study sites in eastern Canada.
Figure 3.6: The relationship between rock hardness and downwearing at all study sites in eastern Canada.
CHAPTER IV: DISCUSSION

Large differences in downwearing rates in the salt and fresh water experiments suggest that salt or possibly chemical weathering is much more important than wetting and drying in the upper intertidal zone. In the upper intertidal zone, above the LHT level, downwearing rates in the sandstones, argillites, and to a lesser extent in the basalts, were much higher in salt water than in fresh water, which suggests that the long exposure periods at these elevations promote salt crystallization and other salt weathering processes, and possibly chemical weathering. The experimental data also suggest that downwearing is related, in part, to elevation, as rates generally decrease with elevation and with decreasing wetting frequency above the LHT level (Figure 4.1); there are differences in the nature and strength of this relationship between the three sampled rock types, however, which probably reflect differences in their physical and chemical properties, including void size and number, and the effect of these differences on the weathering processes. With the basalts, samples in the 1 week salt water exposure treatment experienced more than four times the amount of downwearing than all other treatments in the upper intertidal zone. This suggests that 1 week of exposure was sufficient to facilitate salt crystallization within rock voids, while at the same time, providing greater crystallization expansion and contraction frequency than at higher elevations. Similarly, the results suggest that 1 week of exposure is optimum for salt crystallization and disintegration of the sandstone in the upper intertidal zone. The

Figure 4.1: Summary of the relationship between downwearing rates and elevation within the intertidal zone in the Burncoat Head sandstones and the Scots Bay basalts. Data obtained from the intertidal zone between the HLT and the LHT are reported in Porter et al. (in press, c). The values are means from the experimental data using salt water.
bimodal nature of the downwearing rates in the salt water experiments for the upper intertidal zone indicates that the sandstones either completely disintegrated or lost very little material, owing to differences in the nature of the slabs used to extract the samples; downwearing rates ranged from over 3.33 mm yr\(^{-1}\) in the softer sandstone to 0 mm yr\(^{-1}\) in the harder samples. In contrast, the optimum exposure interval for argillite breakdown in the upper intertidal zone was 2 weeks, both in salt and fresh water.

The evidence is less clear in the lower part of the intertidal zone, which experienced only very slow rates of breakdown, presumably because the brief and infrequent periods of exposure inhibited both wetting and drying and salt and chemical weathering. However, some salt or chemical weathering may be occurring, as the samples in the salt water experiments produced approximately double the amount of eroded material than their fresh water counterparts. Downwearing was consistently low at the 3 elevations in the lower intertidal zone, and showed no relationship to the frequency of the exposure periods.

In the field, TMEM measured downwearing rates on the sloping shore platforms in the Bay of Fundy tend to be higher in the upper intertidal zone than in the lower intertidal zone. It is difficult, however, to draw conclusions from the limited number of stations installed in the lower intertidal zone. There is some limited, although not statistically significant, evidence to suggest that rates may decrease within the central portion of the intertidal zone (Trenhaile et al., 2006; Porter et al., in press, b;c) and attain a minimum in the lower intertidal zone. Positive, albeit statistically insignificant, correlations between elevation and downwearing at most of the study sites may also suggest that downwearing increases with elevation in the upper intertidal zone. This is contrary to the laboratory data at Scots Bay, which showed downwearing decreasing with increasing elevation above the LHT. Conversely, the field data at Burntcoat Head supports the experimental results, which suggested that downwearing rates decrease with increasing elevation above the LHT. The platform at Mont Louis and the rock ledges at East Point are subhorizontal and entirely within the upper intertidal zone, and there were no significant relationships between the small changes in elevation found on these surfaces and the rate of downwearing. Distance from the low tide cliff may have a greater influence on the downwearing rates than elevation, as wave splash may provide more
wetting and drying cycles. However, the effect of splash on wetting and drying is likely restricted to a fairly narrow area along the outer edge of the platform surface at Mont Louis, and as such, is probably not an effective erosional mechanism on the entire platform surface. At East Point, downwearing rates were generally higher near the seaward edge of the structural ledges, although the number of stations was fairly low.

The relationship between downwearing rates and elevation is more complex in the field than in the experiments. In the field, downwearing is a product of not only the processes simulated in the experiments (wetting and drying, salt weathering, etc), but also of the additional contributions made by other erosive mechanisms. Whereas the experiments suggested that the efficacy of the simulated weathering processes was related to elevation, the elevational pattern in the field is the combined product of the different elevation-efficacy patterns of each mechanism. Additionally, the dominance of one mechanism over another may vary considerably between platforms in both a spatial and temporal context and any downwearing pattern that may be produced may be obscured or eliminated by the effects of variations in the chemical and physical characteristics of the rocks on the platform surface.

The experimental data were only concerned with the effect of some weathering processes. Other mechanisms must be considered in order to account for differences between the laboratory and field data, and consequently, to obtain a better understanding of how shore platforms reached their present level. Wave quarrying is effective in the upper intertidal zone in most of the study areas. The frequent stormy conditions experienced in the North Atlantic can produce waves that exert high pressures as they impact rock surfaces (water hammer), or where air is compressed within joints and other structural discontinuities (hydraulic quarrying); breaking waves can also generate high shock pressures against steep surfaces. The evidence on the platforms includes debris consisting of large, angular rock fragments, detached joint blocks, fresh rock scars, and in a couple of cases, at Bramber (Figure 4.2) and East Point, the bending or removal of the steel studs (8 mm thick and 65 mm long) at the TMEM stations. At Scots Bay, an entire station (F4) was lost through the removal of a large joint block. Wave quarrying is probably ineffective today at Mont Louis, however, where the waves usually break in front of, or over, the abrupt low tide cliff at its seaward edge during most tidal stages.
(Trenhaile and Kanyaya, 2007). This is common on subhorizontal platforms - Stephenson and Kirk (2000) found that only 5 to 7% of the wave energy at the seaward edge of the platform at Kaikoura, New Zealand, reaches the cliff foot.

**Figure 4.2**: Damaged TMEM station (SR1) at Bramber. A large rock fragment was removed (quarried) from the surface, exposing the two studs furthest from the camera, and bending the stud closest to the camera (adapted from Porter et al. (in press, b)).

Abrasion is also an important process in the upper and lower intertidal zones in some areas. Potentially abrasive materials are common at Mont Louis (shale fragments), Bramber (shaly fragments), and Arisaig (small stones); the latter two platform surfaces are polished and are covered by an abundance of abrasive materials, which form an almost continuous cover on the upper portions of the platforms. However, the gravel generally consists of the same type of rock as in the platform and may therefore have only limited abrasional potential. Such is the case at Mont Louis, where stations 5 and 6 on Line 5 (Figure 3.2) are covered by approximately 50 cm of beach materials; downwearing has not been recorded at these stations which therefore appear to be protected from erosion. Abrasion is the dominant erosive mechanism at Salmon River, where rolling boulders have carved out smooth-sided shore-normal troughs, destroying a number of TMEM studs that were initially installed at insufficient depths. Abrasion may
also provide an explanation for the high rates of downwearing below the HLT at Arisaig and Salmon River, which were much greater than the very low values, albeit from different types of rock, measured in the laboratory at this elevation. Conversely, the high rates of downwearing above the LHT at Bramber and Salmon River, which were similar to, or greater than, those rates at other study sites, may be attributed to the abundance of abrasive materials found in the upper intertidal zone.

The role of frost and ice must be considered in eastern Canada and other cold regions (Trenhaile, 1983, 1987, 1997; Allard and Tremblay, 1983; Hansom, 1983; Dionne and Brodeur, 1988). Previous work by Trenhaile and Rudakas (1981) demonstrated that frost operates effectively on the shore platforms of Gaspé, Québec, particularly in the lower portions of the cliff and on the platform in the upper intertidal zone. The upper intertidal zone receives a supply of freshwater from melting snow, the melting ice foot, rain, and cliff seepage. Coupled with below freezing temperatures, freshwater can freeze on the platform surface and cause erosion through continuous freeze-thaw cycles, especially in the early and late winter months, when midday temperatures are above freezing. Robinson and Jerwood (1987 a,b) found that frost cracking and surface spalling on chalk platforms in southern England was much more effective in the upper intertidal zone than in the lower zone which has only limited exposure to freezing temperatures. Drift ice can damage platform surfaces as well, plucking loose rock fragments and cutting grooves and striations from rock fragments frozen into the base of the ice (Allard and Tremblay, 1983; Hansom, 1983; Dionne, 1985; Hansom and Kirk, 1989). This type of abrasion from ice has been shown to be effective on the weak shale and slate platforms along the upper St. Lawrence (Dionne, 1985; Dionne and Brodeur, 1988). While ice erosion/frost likely operates through the entire suite of intertidal elevations to varying degrees, the relationship between the two factors is not well known, nor is the optimum elevation at which ice erodes platform surfaces. However, Fournier and Allard (1992) have shown that the greatest erosion of frost loosened rocks by waves and ice in Ungava Bay, Canada, corresponds to the tidal maximum at the mean neap high water level.

The previously discussed mechanisms typically operate most effectively in the mid to upper intertidal zones and may therefore help to account for the higher
downwearing rates recorded in the field near the cliff foot. Conversely, bioerosion is most effective in the subtidal and lower intertidal zones, particularly in calcareous substrates in the Tropics (Trudgill, 1976; Trenhaile, 1987; Spencer, 1988; Spencer and Viles, 2002). The climate and rock types in eastern Canada are not conducive to rapid bioerosion, although the platforms at Burntcoat Head and Mont Louis host a variety of borers, gastropods, and burrowers in small, isolated pools that remain on the surface of the platform at low tide. Barnacles are also present near the low tidal level at Burntcoat Head, forming a near continuous cover near station 10 (Figure 3.4). There are few bioerosional organisms on the other platforms and there is little evidence to suggest that they play an important role in this area.

A comparison between downwearing rates in the experiments and in the same rocks in the field may provide some indication of the possible role of other mechanisms. The mean downwearing rate in the upper intertidal zone at Burntcoat Head is broadly consistent with the experimental data for this zone above the LHT (Table 3.4). This suggests that the weathering processes that operated in the laboratory (wetting and drying, salt and chemical weathering) can account for most of the downwearing that occurred in the field.

Measured downwearing rates in the upper intertidal zone at Mont Louis are considerably lower than rates observed in the laboratory. The opposite is true for the basalts at Scots Bay, where the downwearing rates in the field are greater than those in the laboratory. There are three possible explanations at Mont Louis. The first is that the steeply-inclined argillite strata and fractured nature of the platform surface prohibited the placement of TMEM stations at preferred locations. As a result, they were generally installed on smoother and harder mudstone or siltstone surfaces, rather than on the more friable and faster eroding shales and softer mudstones that provided most of the slabs used to cut the argillaceous rock cores. The use of less resistant argillite samples in the laboratory may have contributed to greater downwearing rates than those experienced in the field. The second possibility is that the tidal conditions at Mont Louis are quite different than those experienced in the Bay of Fundy in that the twice daily high tides at Mont Louis are often markedly unequal. The platform surface at Mont Louis may be covered by one high tide but not by the other, such that exposure periods may be much
longer than those experienced in the Bay of Fundy. As such, the Mont Louis platform may not experience the exposure periods that were represented in the laboratory experiments. A third, albeit untested, possibility is that due to the estuarine environment in the St. Lawrence, the salinity of the water at Mont Louis is likely much less than the 35 parts per thousand that was tested in the laboratory. Elevated salinity may, in part, account for the greater rates of downwearing experienced in the laboratory as compared to those in the field.

It is more difficult to account for differences between the experimental and field data for the Scots Bay basalts. Not only were the mean rates of downwearing in the field above the LHT level much higher than in the salt and fresh water experiments, but they were also much higher than in previous salt water experiments from the mid-tide to the LHT level (Trenhaile et al., 2006). Additionally, laboratory experiments by Porter et al. (in press, b) have shown that Scots Bay basalts break down rapidly when they are wetted and then exposed for fairly long periods in fresh water in the upper part of the middle intertidal zone (just below the LHT level). For that reason, a possible explanation for the greater rates of downwearing experienced in the upper intertidal zone is that there is a steady supply of freshwater to the higher parts of the platform, from heavy rainfall (mean about 1200 mm yr⁻¹), spring snowmelt from the mountain slopes behind, and particularly from the frequent dense morning fogs that are characteristic of this area. Tidal immersion and exposure, combined with wetting and drying in fresh water, may accelerate the weathering process in the upper portions of the platform. Nevertheless, it remains to be determined whether the frequency and duration of these atmospherically induced cycles of wetting and drying can account for the fairly rapid downwearing that takes place on the upper platform surface at Scots Bay.

It is useful to evaluate whether the downwearing rates obtained from this study were high enough to produce the sloping and horizontal platforms in eastern Canada. Much of the traditional literature on shore platform formation emphasized the competing merits of mechanical wave erosion and weathering, including salt weathering and wetting and drying (Trenhaile, 1980, 1987; Stephenson, 2000). Recent work has recognized that both wave erosion and weathering are important on the horizontal and sloping shore platforms of eastern Canada, although their absolute importance varies across platform
surfaces and has likely changed though time (Trenhaile et al., 2006; Trenhaile and Porter, 2007). Although surface downwearing rates obtained from the laboratory experiments were quite high in the upper intertidal zone, the rates generated from weathering alone are much too low to produce platforms observed in the field in the 4,000 years since the sea has been at its present level (Dionne, 2001; Amos, 2004) or, if the platforms were inherited, over the total 10,000 to 20,000 years of several interglacial stages. Recent modeling by Trenhaile and Porter (2007) and Trenhaile (2008a) has demonstrated that downwearing by weathering and debris removal acting alone cannot produce shore platforms with gradients, widths, and profiles that are similar to those in the field, and that these two processes are only of secondary importance in the long-term evolution of platform surfaces. Backwearing (erosion on the horizontal plane) by waves is more rapid than downwearing in most coastal environments (Trenhaile, 2008a). However, waves become increasingly attenuated as platforms become wider and more gently sloping. As well, scarps and irregular, upstanding rock formations on the platform surfaces are removed by waves. Therefore, it appears probable that rates of wave erosion are much lower today than they were in the past. Modeling suggests that platforms in eastern Canada were initially cut by waves when the sea was above its present elevation during the Holocene, and as the sea fell towards its present level, weathering and the removal of debris by weak, attenuated waves assumed important roles in lowering and widening platform surfaces (Trenhaile, 2008a). The platforms in eastern Canada likely developed quickly when sea levels were higher, but as the sea fell to its present level, their development became progressively slower under an increasingly weathering and debris removal regime (Trenhaile, 2010), although the role of tidal range, rock resistance, and site-specific factors cannot be discounted.

TMEM measurements suggest that downwearing by weathering and debris removal is important, and possibly dominant, today on the subhorizontal platform at Mont Louis, and possibly on the sloping platforms at Scots Bay and Burntcoat Head. Surface downwearing rates, which were commonly between 0.5 and 2 mm yr$^{-1}$ in the upper intertidal zone, will continue to play a direct role in the future development and evolution of the platforms. Weathering will also promote mechanical wave erosion by reducing rock strength and, through increases in water depth, reducing rates of wave
attenuation (energy depletion) (Trenhaile, 2008; Porter et al., in press b). The data from this study, in augmenting previously accrued field and laboratory data from the more central portions of the intertidal zone, will assist in assessing future models of long-term platform development in eastern Canada, and the effect of rising sea level, and possibly increased storminess, on cliff coasts.
CHAPTER V: CONCLUSION

The five hypotheses proposed at the beginning of this study were, at least in part, confirmed by the field and laboratory experiments:

1) **Downwearing rates will increase with elevation within the upper intertidal zone up to an optimum elevation, based on the frequency of wetting by tides, spray or splash, and the corresponding length of the period of exposure and drying. Rates then decline with increasing elevation above the optimum level.** A comparison of experimental downwearing rates measured in this study in the upper and lower intertidal zones with other work conducted in the central intertidal zone (Porter et al., a; b; c) shows that the fastest rates are at the LHT level, as downwearing rates generally tended to decrease with increasing elevation above this level. This pattern was not evident in the field, as the downwearing/elevation relationship is obscured by additional contributions made by other erosive mechanisms;

2) **Because of the effect of pore size distributions, tensile strength, and other factors, the elevation of the optimum level varies according to the type of rock.** The experiments suggested that 1 week exposure was the optimal timeframe for breakdown to occur with the sandstones and basalts in the upper intertidal zone, and 2 weeks exposure for the argillites;

3) **Downwearing rates are very slow in the lower intertidal zone because of infrequent periods of exposure and short periods of drying.** The experiments demonstrated that downwearing rates were significantly greater in the upper intertidal zone than in the lower intertidal zone, owing to the prolonged and frequent periods of exposure and drying experienced at higher platform elevations; downwearing was uniformly low beneath the HLT for all lithologies, regardless of exposure duration. The field data generally supports this contention, although it is difficult to draw conclusions from the limited number of stations installed in the lower intertidal zone;

4) **Rates of downwearing in the upper intertidal zone are primarily the result of salt weathering rather than wetting and drying.** The majority of the laboratory data
demonstrated that the rates of downwearing in the upper intertidal zone were significantly greater amongst samples immersed in salt water than in fresh water, suggesting that salt weathering can be an effective erosive mechanism on the shore platforms of eastern Canada, although the role of chemical weathering cannot be discounted;

5) **Downwearing is faster in coarse-grained than in fine grained rocks.** Experimental downwearing rates were greatest amongst the sandstones compared to the argillites and basalts. Field downwearing patterns were similar, although mean downwearing rates were high amongst argillaceous rocks at Bramber and Arisaig, albeit from a limited number of stations.

The laboratory data indicate that weathering and debris removal can account for much of the downwearing that is presently occurring in the upper intertidal zone, although maximum downwearing rates in this zone cannot be solely attributed to the weathering processes simulated in the laboratory. The differences between the field and laboratory data must reflect additional contributions by other mechanisms, including wave quarrying, abrasion, frost, and ice, especially in the lower intertidal zone, where field downwearing rates were considerably greater than the values obtained in the laboratory experiments. This study provides evidence that weathering rates are high enough to have reduced the upper portions of shore platforms from one to several metres since the sea reached its present elevation, whereas erosion in the lower sections must be by other mechanisms, including abrasion, where there is suitable loose material, wave quarrying, where there are seaward-facing rock scarps or steeply dipping strata, and bioerison.

This work has contributed to three papers in international journals:


3) Porter, N.J., Trenhaile, A.S., **Prestanski, K.J.**, and Kanyaya, J.I. Patterns of

This work has also been presented at four conferences:


CHAPTER VI: THE MARINE NOTCHES AND SHORE PLATFORMS OF BAJA CALIFORNIA SUR, MEXICO

1.0 Introduction

Salt weathering and wetting and drying are also potentially important processes in the formation of shore platforms and marine notches in rocky coastal regions of the tropics. The coastline along Baja California Sur, México, in the vicinity of the capital city of La Paz, was chosen to apply the techniques developed in eastern Canada to explore the development of notches and shore platforms in a tropical to subtropical environment. The following is an introduction and review of current literature on marine notches - much of the introductory material on shore platforms having been covered in Chapter 1. As well, this chapter provides 9 months of experimental data from samples extracted from the study area, and also provides preliminary observations and measurements of notch morphology along the coast.

2.0 Marine Notches: A Brief Overview

Marine notches are conspicuous elements of rocky coasts around the world. They are groove like features, often assuming a recumbent U or V shape, which can be found at a variety of elevations (Rust and Kershaw, 2000; Benac et al., 2004; Ramirez-Herrera et al., 2004). Notches develop through erosion of the foot of steep littoral slopes in rocks that are strong enough to remain unsupported for some time. Notches do not develop in weak rocks or in rocks that are densely jointed or otherwise structurally weak; these rocks erode through very frequent and small rockfalls. Notches vary greatly in their size, shape, and external appearance and develop through a variety of physical, biological, and chemical processes (Pirazzoli, 1986; Kershaw and Guo, 2001; Masselink and Hughes, 2003; Benac et al., 2004; Moura et al., 2006); the relative importance of any one of these
processes differs from one locality to the next with variations in coastal exposure, tidal regime, and wave exposure (Spencer, 1985).

Notches can develop at a variety of tidal elevations, and there is no consensus over the level, or levels, at which abandoned or emerged notches, especially in low tidal range environments, have developed in the past (Ternhaile, 1987; 1997). Some notches developed at the high tidal level (Wentworth, 1939; Guilcher, 1953; Newell, 1956; Verstappen, 1960; Christiansen, 1963; Takenaga, 1968; Hills, 1971; Tricart, 1972; Nicod, 1972; Ternhaile et al., 1998), others at the mid-tidal level (Gisenberg, 1953; Guilcher, 1958; Hodgkin, 1964; Teichert, 1947, 1950; Fairbridge, 1948; Sweeting, 1973; Debrat, 1974; Trudgill, 1976; Woodroffe et al., 1983), and yet others in the low tidal zone which experiences complete immersion (Schneider, 1976; Torunski, 1979; Pirazzoli, 1986; Antonioli et al., 2006). As tidal range increases, notches may even form at the high and low tide levels simultaneously at one location (Taillefer, 1957; Flemming, 1965; Hills, 1971; Battistini, 1980; 1981). The problem of determining the optimum elevation for their development has historically been compounded by a number of issues, including the effect of variable tidal range, the lack of precise measurement, and the poor reliability of bench-mark data in many areas (Ternhaile, 1987; 1997). Laser distance finders have been used recently to measure notch profiles more precisely (Kogure et al., 2006).

3.0 Notch Classification and Formative Processes

As previously mentioned, the erosional processes that result in notch formation may be physical, biological, and/or chemical depending on the environment in which they occur. Notches formed by mechanical wave erosion develop in relatively resistant rock formations, typically in the high energy storm wave environments of the temperate latitudes, where the hydraulic pressure of wave impact and the abrasive action of water armed with sand or other loose material scours the base of the cliff in the surf zone (Vita-Finzi and Cornelius, 1973; Davies, 1980; Tjia, 1985; Pirazzoli, 1986; Bird, 2008). Abrasion notches (Figure 6.1) are typically 1-2 m high and about 3 m deep (Bird, 2008), and are readily distinguishable from biologically or chemically formed notches by the
Figure 6.1: Abrasional notches in (a) Galicia, northwest Spain, and (b) along the Maya Riviera, Mexico (Trenhaile)

development of smoothed and polished interior face (Pirazzoli, 1986; Rust and Kershaw, 2000; Bhatt and Bhonde, 2006). Their formation is favoured in shale or similar lithologies with vertical stratification (Pirazzoli, 1986), or in horizontally bedded rocks where the weaker members are exposed and exploited by erosive wave action. Wave-cut notches may occur in continuous or very short segments. Continuous notches are typically found in cliffs fronted by platforms at the level of the highest tides. Conversely, localized abrasion notches (those that fail to maintain their profile for more than a few meters) typically occur near beaches where sediment supply is abundant (Pirazzoli, 1986).

It is now recognized that a combination of chemical and biological processes are the most important mechanisms in the formation of the prominent notches that characterize many tropical regions, especially on calcareous substrates (Pirazzoli, 1986; Spencer, 1988, 1992; Trenhaile, 1997). Notches formed in this manner are termed solutional or corrosional notches (Figure 6.2). They are the result of a combination of chemical and biological breakdown of the rock, forming notches with rough, rugged, and pitted surfaces (Pirazzoli, 1986). Biological erosion may occur though microbial action from algae, and from the grazing, boring, and encrustation of certain types of organisms (Davies, 1980; Ramirez-Herrera et al., 2004). Biological erosion often operates in unison with chemical dissolution on limestone coasts. The principal constituent of limestone, calcium carbonate, is highly soluble in seawater (Rust and Kershaw, 2000; Woodroffe, 2003). Consequently, notches are prominent in limestone lithologies throughout the
tropics, where warm tropical seas, coupled with microtidal regimes, weak waves, and large and varied biomasses produce deeply undercut cliffs (Pirazzoli, 1986; Trenhaile, 1987; 1997; Benac et al., 2004; Antonioli et al., 2006; Moura et al., 2006). The erosive processes are concentrated within a narrow range of elevations, allowing deep notches to form. In contrast, higher waves, coupled with a macrotidal regime, can produce broad, shallow indentations along coasts, where the difference in elevation between the notch floor and roof is much greater (Newell, 1961; Butzer, 1962; Christiansen, 1963; Neumann, 1966; Hodgkin, 1970; Torunski, 1979; Trenhaile et al., 1998).

Figure 6.2: Solutional/Corrosional notches in (a) southern Curacao, Netherlands Antilles, and (b) Phuket, Thailand (Trenhaile)

As an example, Takenaga (1968), working in the Ryukyu Islands of Japan, found that the height of the notch roof corresponds to the upper limit of sea spray, and is therefore greatest on open coasts. Verstappen (1960) and Russell (1963) concluded that notches on exposed coasts have flat floors and steeply inclined roofs produced by surf and sea spray.

Focke (1978) is often cited in the literature for his work on limestone cliff morphology in Curacao and elsewhere in the Netherlands Antilles (Figure 6.3). He surmised that cliff profiles on limestone coasts depend on the degree of exposure, which affects water turbulence, duration of inundation, and biological action. In sheltered areas, notches predominate without significant organic accumulations. In exposed areas, organic accretions (corniche) dominate, but are restricted to a narrow zone in the middle of the cliff notch at about mid-tide level. As a result, a double notch may form within the mid-intertidal zone. In the most exposed settings, the role of biota is accentuated, such that coralline algae and Vermetid (worm snail) accretions become thicker and better lithified,
having a major protective role in the intertidal zone, giving rise to protruding surf benches (trottoirs) up to 10m wide and as much as 2m above sea level (Trenhaile, 1987).

In these highly exposed areas, the spray zone reaches up to the top of the cliff, and the upper notch is generally replaced by a corroded slope or platform scattered with small pools and lapies, or karren (small ridge-like structures that develop as a result of the solution of rock by running or standing water).

Abrasion may also play an important role in tropical regions. On Aldabra Atoll in the Indian Ocean, Trudgill (1976) found that where sand is absent, grazing organisms account for between one-third and one-half of the erosion. Conversely, abrasion accounts for about one-third of the notch erosion where sand is present at the foot of the notch. Notches that are abraded at the base of the cliff have much flatter floors and less concave profiles than in areas where it is absent. Trudgill (1976) concluded while chemical solution by sea water is possible in this area, it is of minor significance; physical processes such as abrasion and other mechanisms such as wave action account for a large portion of the erosion of limestone notches at Aldabra.
4.0 Notch Erosion Rates and Applications

Notch erosion rates have been estimated by several researchers. A compilation of published data by Pirazzoli (1986) suggested that 0.2–5.0 mm yr\(^{-1}\) is typical of limestones, with the most frequent values being in the range of 1.0–1.5 mm yr\(^{-1}\). Erosion rates on non-carbonate lithologies are virtually absent in the literature.

The employment of steel rods (Bird et al., 1979; Hodgkin, 1964) and microerosion meters (Trudgill, 1976; Spencer, 1985) have been used to measure erosion rates in the field. On Aldabra Atoll, Trudgill (1976) obtained reef limestone erosion rates of 0.6-4.0, 1.0-3.0, and 0.5-2.0 mm yr\(^{-1}\) working in the upper, mid, and lower intertidal zones, respectively. Spencer (1985) obtained mean erosion rates of 1.12 mm yr\(^{-1}\) in the subtidal and 0.88 mm yr\(^{-1}\) in the intertidal zones of reef limestones in the Grand Cayman. From the published data, Pirazzoli (1986) surmised that erosion rates may exceed 1.0 to 1.5 mm yr\(^{-1}\) on exposed coasts, where surf and spray shift the maximum wear zone from the mid-littoral to the supra-littoral zone.

Notches can be used as indicators of rates and patterns of tectonic activity (Trenhaile, 1987; Rust and Kershaw, 2000; Ramirez-Herrera et al., 2004; Antonioli et al., 2006; Bhatt and Bhonde, 2006; Ramirez-Herrera et al., 2004; Benac et al., 2008), and they have been used to identify palaeo-sea levels around the world (Pirazzoli, 1986; 1996; Pirazzoli et al., 1996; Sartoretto et al., 1996; Kershaw and Guo, 2001; Rust and Kershaw, 2000; Kershaw and Antonioli, 2004; Antonioli et al, 2006).

5.0 The Problem

Notches in the La Paz area are not formed in any of the ways that have been previously discussed. They are not abrasional, because there is a lack of erosive material at their base, nor are they bioerosional, because they are above mean sea level and lack marine organisms. Solution is not likely to be the formative mechanism because the rocks are volcanic. Mechanical wave erosion is unlikely to play an important role because notches are present only in the more sheltered areas of the western La Paz Peninsula, which are subject to weak wave attack; they are replaced in more exposed areas by shore
platforms. Consequently, it appears likely that the notches in the La Paz area formed by wetting or drying (including the effects of salt and chemical weathering).

6.0 Purposes and Objectives of the Research

An investigation is being conducted on the processes operating on sloping shore platforms and marine notches in the microtidal environment of the La Paz Peninsula, Baja California Sur, Mexico. Similar to the work conducted in eastern Canada, this investigation has three main components: (a) laboratory experiments to measure wetting and drying and salt weathering breakdown and downwearing rates for marine notches; (b) measurements of platform and notch downwearing rates at TMEM stations in the field; (c) the use of wear pins to measure rates of erosion in the notches and laser distance meters to measure notch profiles; and (d) comparison of relevant platform downwearing rates obtained by Trenhaile, Porter, Kanyaya, and myself over the last five years to compare the data obtained from this study.

7.0 Hypotheses

There are two hypotheses:
1) Notches in Baja are the product of wetting and drying cycles (wetting and drying and salt and chemical weathering processes); and
2) Notches of various types and shore platforms of variable width are distributed along the peninsula according to variations in exposure to wave attack.

8.0 Study Areas

The study area is located along the western and northern coasts of the La Paz Peninsula, in the arid, subtropical region of Baja California Sur, Mexico (Figure 6.4). The geologic evolution of Baja California Sur is dominated by the interaction of lithospheric
plates, principally the subduction of the southern portion of the Farallon plate, called the Guadalupe plate, beneath the North American plate, and the volcanism that ensued (Figure 6.5) (Mammerickx and Klitgord, 1982; Atwater and Stock, 1988; Atwater, 1989; Lonsdale, 1991; Stock and Lee, 1994; Bellon et al., 2006).

The widespread Comondú Formation dominates the geology of the Bahía de La Paz region. The Formation, previously referred to as Mesa Sandstone (Gabb, 1882, Darton, 1921), has been used to describe the Miocene sequence of volcanic and
volcaniclastic rocks of the Sierra de la Giganta, the northwest-trending mountain chain that dissects Baja California Sur (Heim, 1922; Beal, 1948; Mina, 1957). The Comondú Formation is composed of rhyolitic ash-flow tuffs, interbedded volcanic sandstones and conglomerates, and along the Bahía coast north from La Paz towards Playa El Tecolote, andesitic lahars and lava flows (Hausback, 1984; McLean et al., 1987; Bellon et al., 2006). The lahars, which are up to 40m thick in some areas, largely consist of breccias of andesite with angular clasts of up to 1m or more in diameter (Hausback, 1984). The clasts float in a groundmass, or matrix, of grey to brown, poorly-sorted, poorly-stratified, sand-sized andesitic detritus (Hausback, 1984; Aranda-Gomez and Perez-Venzor, 1988). The andesitic breccias found in the La Paz area were likely formed by hot volcanic debris flows from strato-volcanic eruptions along the western flank of the Comondú volcanic chain. After deposition, these dense, blocky flows became lithified and very resistant (Hausback, 1984). Erosion of weaker sandstones that were subsequently deposited on top of the lahars has left the lahars as caps to many of the mesas in the La Paz area. The Comondú Formation was deposited during the early to middle Miocene with dates ranging from 25.0 to 14.5 mya (Hausback, 1984; Aranda-Gomez and Perez-Venzor, 1988). K-Ar dates from andesite lahar and lava samples collected near Playa Pichilingue.
(approximately 6 km south of Balandra Bay) yielded dates of 18.6 ± 2.4 and 20.3 ± 0.4 mya, respectively (Hausback, 1984).

Tides are mixed semidiurnal, with a maximum range of approximately 1.71m (tide-forecast.com, 2009).

9.0 Methodology

The methods outlined in this chapter are for the laboratory experiments and field measurements that are currently being conducted.

9.1 Field Measurements – Shore Platforms

In December 2008, 36 TMEM stations were installed on three shore platforms along the exposed northern tip of the La Paz Peninsula (13 stations on Platform 1, 10 on Platform 2, and 13 on Platform 3) (Figure 6.4) along lines perpendicular to the shore (see Chapter 1 for more information regarding the TMEM and its installation). As this study is still ongoing, upon returning to the sites in the next few years, each station will be surveyed to determine their position relative to the average high tide elevation and tested for rock hardness using an N-Type Rock Test Hammer.

9.2 Field Measurements – Notches

In addition to the work completed on the platforms, cross-sectional profiles of 24 notches were measured at 18 sites located along the La Paz Peninsula (Figure 6.4). There were three profiles at sites 1, 2, and 3, and only one profile at the remaining sites. Extensive notches were observed between sites 12 and 18. However, much of this area was either private property or was inaccessible for various reasons.

The notches were profiled using a Leica DISTO D3 laser distance meter, a technique that has been used for a similar purpose in Japan (Kogure et al. 2006). At each site, a measuring tape was extended along the floor of the notch from the apex to the point at which the roof no longer covers the inside of the notch. Depending on the size of
the notch, the distance from the floor to the roof was measured every 5, 10, or 20 cm to produce a cross-sectional profile. In addition, the angle of the floor of each notch and the height of the cliff on top of the notch (where applicable) were determined using the laser distance meter (Figure 6.6).

Figure 6.6: Using the laser distance meter to profile a notch at Site 1

At all 24 profiled notch locations, a wear pin was installed at the apex of the notch where erosion is at its maximum. A wear pin is a stainless steel bolt that is permanently embedded in the notch face. An industrial heavy duty drill was used to drill a hole 65 to 70 mm deep with a 20 mm diameter at sites 1, 2, and 3. The steel bolts were then embedded in the holes using premixed concrete. The bolts were 8 mm in diameter and 65 mm in length. The top of each bolt was flush with the rock surface (Figure 6.7). At the remaining 15 sites, 8 mm diameter and 70 mm long holes were drilled into the faces of the notches, and the bolts were hammered into place until they were flush with the surface. Subsequent measurement of the difference in the elevation of the end of each bolt and the surrounding rock surface will provide a general indication of the rate of notch erosion.
Figure 6.7: A wear pin flush with the notch face at Site 2.

TMEM stations were also installed at the base of notches at Sites 2, 3, 6, 13, and 15 (see Chapter 1 for more information regarding the TMEM and its installation) (Figure 6.8). These Sites were chosen for TMEM installation owing to the representative nature of the notches in the surrounding area. The use of TMEMs will allow repeated measurements to be made at precisely the same place on the notch surface, and will supplement the data obtained using the wear pins installed at each Site.

Figure 6.8: TMEM installation at the base of a notch at Site 6.
9.3 Laboratory Experiments

A series of experiments were conducted to determine the efficacy of both salt weathering and wetting and drying in the formation of the notches, and also to supplement field measurements that will be obtained in the next few years. The deepest part of most notches is between the maximum high and mean high tidal levels, which is wetted infrequently, and at elevations where long periods of exposure may promote salt crystallization. To simulate conditions at these elevations, rock samples were immersed in either salt or fresh water for 1.5 hrs every one or two weeks to represent areas of increasing elevation in the upper intertidal zone. As in the eastern Canadian experiments, de-ionized water was used to determine the effect of wetting and drying acting alone, and synthetic sea water to evaluate the additional effect of salt, and possibly chemical, weathering.

Seventy-eight samples of varying size were extracted from notches along the La Paz Peninsula. The samples consisted of clumps of andesitic matrix material that were extracted from the inside the notches; it is the erosion and breakdown of this material, rather than of the clasts, that controls notch development. The matrix material was too friable to be cored or cubed, so the samples were grouped into small, medium, and large sample sizes, with average sample weights of 9.5g, 36g, and 700g, respectively (Table 6.1). Each set of experiments use a series of 6 plastic basins to represent specific environments. Rock samples were placed in the basins and elevated on a plastic screen so

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Sample Size</th>
<th>Samples Per Basin</th>
<th>Location</th>
<th>Submergence Period (Time in water)</th>
<th>Emergence Period (Time out of water)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andesitic Detritus</td>
<td>Small</td>
<td>10</td>
<td>Upper Intertidal</td>
<td>90 Minutes</td>
<td>1 or 2 Weeks</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>8</td>
<td>and Supratidal Zone</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>1 or 2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.1: The experimental conditions utilized to measure notch breakdown patterns.
that the weathered debris could fall away and accumulate at the bottom of the basins (in
the field, debris removal is accomplished by the waves). The samples were exposed to
experimental conditions that simulated tidal cycles and do not accelerate the weathering
process. Commercial synthetic sea water, produced by Aquarium Systems Inc., was used
in the laboratory experiments. This water has an approximate salinity of 35 parts per
thousand and contains 28 ions and elements in concentrations that are similar to their
occurrence in natural sea water. Both the salt and fresh water were replaced every three
weeks in order to ensure the pH, and specifically the salinity in the saltwater experiments,
were consistent. Owing to evaporation, fresh water was added to the saltwater basins as
necessary in order to maintain a salinity of 35 parts per thousand. The experiments
commenced in January 2009 and will continue for at least one year. Each month, the
amount of rock material that has become detached from the samples and has accumulated
at the bottom of the basins has been collected on filter paper, dried, and weighed. These
measurements will provide group data on the mean rates of breakdown of each rock type
under each of the experimental conditions without having to oven-dry the rocks, which
could contribute to their deterioration. Upon completion of the experiments, the
individual samples will be oven dried and weighed in order to determine the individual
sample breakdown rate experienced during the year. Owing to the irregular nature of the
sample shapes and sizes, rates of breakdown were related to the percentage loss in the
original weight of the samples. The data obtained from these laboratory experiments will
supplement and help interpret the erosional data obtained in the field from wear pins and
TMEM stations.

10.0 Preliminary Results

This study is still ongoing and the following comments are based on preliminary
field reconnaissance, measured notch morphology, and 9 months data from the laboratory
experiments.
10.1 Field Observations

In the following discussion, a small notch is defined as having a height and depth measurement of less than 2 m (maximum height from the top of the visor to the floor, and maximum depth from the mouth to the most concave portion of the notch); a large notch is defined has having dimensions greater than 2 m.

Marine notches are common in sheltered areas along the western coast, and they are gradually replaced by sloping shore platforms towards the more exposed tip of the La Paz Peninsula, which is subject to increasing wave exposure from the Gulf of California. As well, the notches generally increase in size moving north from the city of La Paz to the tip of the Peninsula (Figure 6.9); this pattern is consistent at Balandra Bay (Figure 6.10), where small notches are present in the sheltered portions of the Bay, and become

![Figure 6.9: a) small notch in a sheltered bay, Site 14; b) larger notch at Site 16; c) large notch at Balandra Bay, Site 6; and d) shore platform at the exposed northern tip of the peninsula facing the Gulf of California. Note Isla Espiritu Santo and large waves in the background.](image-url)
larger towards the mouth of the Bay where exposure increases. This is consistent with Trudgill’s (1976) observation that coastal profiles around Aldabra Atoll change from notch to cliff to ramp (platform) as the degree of exposure increases. Similarly, Spencer (1985) noted that the reef-protected deep and narrow notches found on Grand Cayman Island in the West Indies are replaced by broader notches and vertical cliffs on exposed coasts. Additionally, it was observed that cliffs experiencing large waves, particularly at Site 2, have larger, shallower notches (Figure 6.10 and 6.11) than the smaller, deeper notches found in calmer waters inside the Bahia. The notches immediately west of Playa El Tecolote, which face Isla Espiritu Santo, are exposed to wave action from the Gulf of California.
California and are wetted by sea spray, especially during windy conditions. The notches in this area have flat floors approximately 4-5 m wide and steeply inclined roofs. These findings are consistent with those of Verstappen (1960) and Russell (1963), who noted that notches on exposed coasts have flat floors and steeply inclined roofs produced by surf and sea spray. Increasing exposure to the Gulf of California to the east of Playa El Tecolote yields a change in coastal profiles, from notch to platform, consistent with the observations of Trudgill (1976) and Focke (1978).

Figure 6.11: Large, broad notch indentations at Site 2.

Collapsed notches were found at several locations along the coast. Notch collapse (or failure) occurs when the notch has attained its maximum depth and the weight of the cliff above the notch is no longer capable of being supported (Trenhaile et al., 1998; Kogure et al., 2006). The point at which a notch collapses is determined by the supporting rock's lithological properties. Froget (1963) and Debrat (1974) concluded that notches eroded by waves and abrasives attained their best development on headlands. This may be explained by headlands being exposed to much more wave energy than bays, which will ultimately lead to cliff failure given enough time. While this may be the case for wave and erosional notches, it is not necessarily true for those formed by solutional, bioerosional, wetting and drying, or salt weathering processes, at least in Baja where there are a number of collapsed notches in the sheltered areas of Balandra Bay. (Figure 6.12). It also appears likely that, since the sea reached its present level, the number of
episodes of notch formation and collapse has increased to the north with exposure. There are deep notches in the sheltered bays and less exposed coastal areas where erosion is slow, and collapse is infrequent. On the more exposed northern coasts, erosion is fast, inhibiting the formation of deep notches and allowing for collapses and rock falls to occur more frequently, thus providing the opportunity for shore platforms to develop.

Figure 6.12:Collapsed notch at Balandra Bay, near Sites 5 and 6.

Finally, it was noticed that the size of the notches generally decreased towards the inside of bays and sheltered areas in the La Paz area; other researchers have noticed a similar pattern (Stearns, 1935; Wentworth, 1939; Hills, 1971).

12.2 Laboratory Results

The following data are from the first nine months of the salt weathering and wetting and drying experiments being conducted on the andesitic detritus material in which the notches in the La Paz area form. These experiments have run for nine months and will be completed in early 2010, at which time the individual samples will be reweighed, statistics calculated, and a more accurate determination of the rates of breakdown will be determined. While the following data are preliminary, some patterns are becoming evident.

Small Sample Size

Very little material (less than 5% of the original weight) has eroded and accumulated at the bottom of the basins thus far. Both the saltwater and freshwater (wetting and drying) experiments demonstrate the same pattern, with greater amounts of
eroded material accumulating in the 1 week exposure basins than in the 2 week exposure basins. Salt water appears to be more effective in the 2 week exposure treatments.

![Percentage of Original Weight Eroded After 9 Months - Small Sample Size](image)

**Medium Sample Size**

The medium size samples demonstrate similar patterns, again with greater amounts of eroded material accumulating in the 1 week exposure basins. However, salt appears to be much more effective in this case, with over 7% of the original sample weight eroding as opposed to approximately 1% for those samples in freshwater.
Large Sample Size

The large samples show the same pattern as the medium sized samples. The experiments suggest that 1 week of exposure (and possibly less) is sufficient for salt crystallization or other responsible processes to break down the rock, and that more erosion occurs with shorter periods of emergence because of the correspondingly greater frequency of the wetting and drying cycles. These preliminary conclusions are consistent with field observations that suggest that the deepest part of the notch is located at about the mean high tidal level, between the lowest and highest high tidal levels.
13.0 Discussion

Thus far, these laboratory experiments suggest that saltwater is more effective than freshwater in eroding the andesitic detritus material. As well, the efficacy of salt weathering decreases with increasing elevation within the notch, above the level of the mean high tide; this is consistent with field observations. These preliminary conclusions also support the conclusion, from the Canadian east coast experiments, that surface downwearing decreases with increasing elevation in the upper intertidal zone. However, it is still too early to draw conclusions from this preliminary laboratory data as the sample size is small and only simplistic analyses have thus far been completed. More thorough analyses will be conducted in the future, upon completion of the experiments. Additionally, little can be said about the processes operating on shore platforms in the La Paz area, given that field measurements have yet to be made. A paper based on this work will be submitted after measurements are made in the field in the spring of 2010.
## APPENDIX A

**ANOVA Test Results at 0.05 Level of Significance**

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Treatment</th>
<th>Significant</th>
<th>P Value</th>
<th>Tukey HSD</th>
<th>P Value</th>
<th>Sig.</th>
</tr>
</thead>
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<td>1C 2C 3C</td>
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<td>1C and 2C</td>
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<td>o</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1C and 3C</td>
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<td>o</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>2C and 3C</td>
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<td>•</td>
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<td></td>
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<td>o</td>
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<td>1B and 3B</td>
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<td>---------------------------</td>
<td>---------------------------</td>
<td></td>
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</tr>
<tr>
<td>A - Basalt</td>
<td>1, 7 1 Week, 1.5 Hours Exposure</td>
<td>4, 10 1 Week, 1.5 Hours Immersion</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>B - Sandstone</td>
<td>2, 8 2 Week, 1.5 Hours Exposure</td>
<td>5, 11 2 Week, 1.5 Hours Immersion</td>
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<tr>
<td>C - Argillite</td>
<td>3, 9 3 Week, 1.5 Hours Exposure</td>
<td>6, 12 3 Week, 1.5 Hours Immersion</td>
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<td>1-6 Salt Water</td>
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<td>7-12 Fresh Water</td>
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</table>

ANOVA and Tukey's HSD of samples of similar lithology throughout the various tidal immersion and exposure frequencies in both the salt and fresh water treatments.
## APPENDIX B

### ANOVA Test Results at 0.05 Level of Significance

<table>
<thead>
<tr>
<th>Water</th>
<th>Treatment</th>
<th>Significant</th>
<th>P Value</th>
<th>Tukey HSD</th>
<th>P Value</th>
<th>Sig.</th>
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</thead>
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<td>1A and 1B</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1A and 1C</td>
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<td></td>
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<td>1B and 1C</td>
<td>0.001</td>
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<tr>
<td></td>
<td>2A 2B 2C</td>
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<td>0.001</td>
<td>2A and 2B</td>
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<tr>
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ANOVA and Tukey's HSD comparing the mean downwearing rates of the three rock types within each tidal elevation.
REFERENCES


Canadian Hydrographic Service, 2008. Canadian Tide and Current Tables. Fisheries and Oceans Canada, Ottawa, vol. 1 (Atlantic Coast and Bay of Fundy) and 2 (Gulf of St. Lawrence).


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