# LITTORAL KARREN ALONG THE WESTERN SHORE OF NEWFOUNDLAND

By

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# ABSTRACT

The west coast of Newfoundland, from Port au Port Peninsula north to Pistolet Bay, displays many Lower Cambrian to Middle Ordovician carbonate rock formations. These host a wide variety of modern littoral karren in the form of solution pits, pans and grooves. Intrasite karren variation has been studied with respect to tidal range, biological species colonization and basic seawater properties of the tidal pools. An attempt is made to quantify intersite karren variation with respect to variations in lithology and the marine environment. This is the first study of littoral karren in a cold marine environment with seasonal sea ice fast to the coast.

Field methods used stratified random sampling because the karren distribution is essentially zonal in nature. Shore-normal, parallel transects were taken across the platforms, with metre square quadrats used to obtain representative samples from each karren zone. Temperature, salinity, conductivity and pH were recorded in inter-, supratidal and backshore rock pools, with more detailed chemical analyses at one selected site.

There is a general intrasite trend in karren development with karren diameter and microrelief increasing in size with increasing height above the mean low water mark (MLWM). This produces a corresponding inverse relationship between karren density and height above the MLWM. Bioerosion is not a factor in explaining karren variation within the littoral zone, and there were no established relationships between SpC or pH and karren development, although intersite variations in geology and the marine environment may be obscuring the importance of chemical dissolution here.

Bivariate and multivariate regressions are performed involving a number of geologic and marine environment variables, in an attempt to quantify intersite karren variations at western Newfoundland. Geologic factors, especially insoluble residue, are more important in determining if karren will develop beyond the scale of micropits at a given site, regardless of how exposed that shoreline is to the open marine environment. The marine environment, especially variations in the exposure index (*EI* ), appears to be more important than geology in explaining intersite karren variation between sites where measurable karren do occur

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# CHAPTER 1

# INTRODUCTION

## 1.1 Research Objectives

Coastal karst geomorphology involves the study of karstic features in coastal environments that possess soluble rocks. The most common karst landform occurring in coastal environments are karren (pits, pans and grooves). There have been many studies of karren and karst features on tropical coasts but, as yet, little documentation of coastal or littoral karren in temperate regions. The most detailed temperate littoral karren studies have been undertaken around the Bristol Channel, England (Ley, 1976 and 1979) and at Galway Bay, Ireland (Williams, 1971), Lundberg (1974 and 1977) and Trudgill (1987).

The west coast of Newfoundland in Atlantic Canada (Figure 1.1) was chosen as a study site for analyzing the occurrence of littoral karren, in an attempt to help fill this void which exists in the literature on karren development in the coastal zone. It is also the first study of littoral karren in a cold marine environment with seasonal sea ice fast to the coast. The research focuses on morphologic differences in the karren dimensions of diameter, microrelief and density. Intrasite karren variation is studied with reference to tidal range, and the occurrence of karren within the different onshore littoral zones. Intersite karren analysis involves an attempt to quantify karren variation with respect to variations in geology, which can affect the degree of karren development at a given site, as well as variations in the marine environment, which can affect the magnitude of all erosion processes acting upon the coastline where the karren are being formed. Since the karren models from Galway Bay are focused on bioerosion, biological species colonization is documented and discussed as a possible erosion agent for the karren at western Newfoundland. An attempt is also made to correlate the karren with basic seawater properties of the tidal pools (conductivity,

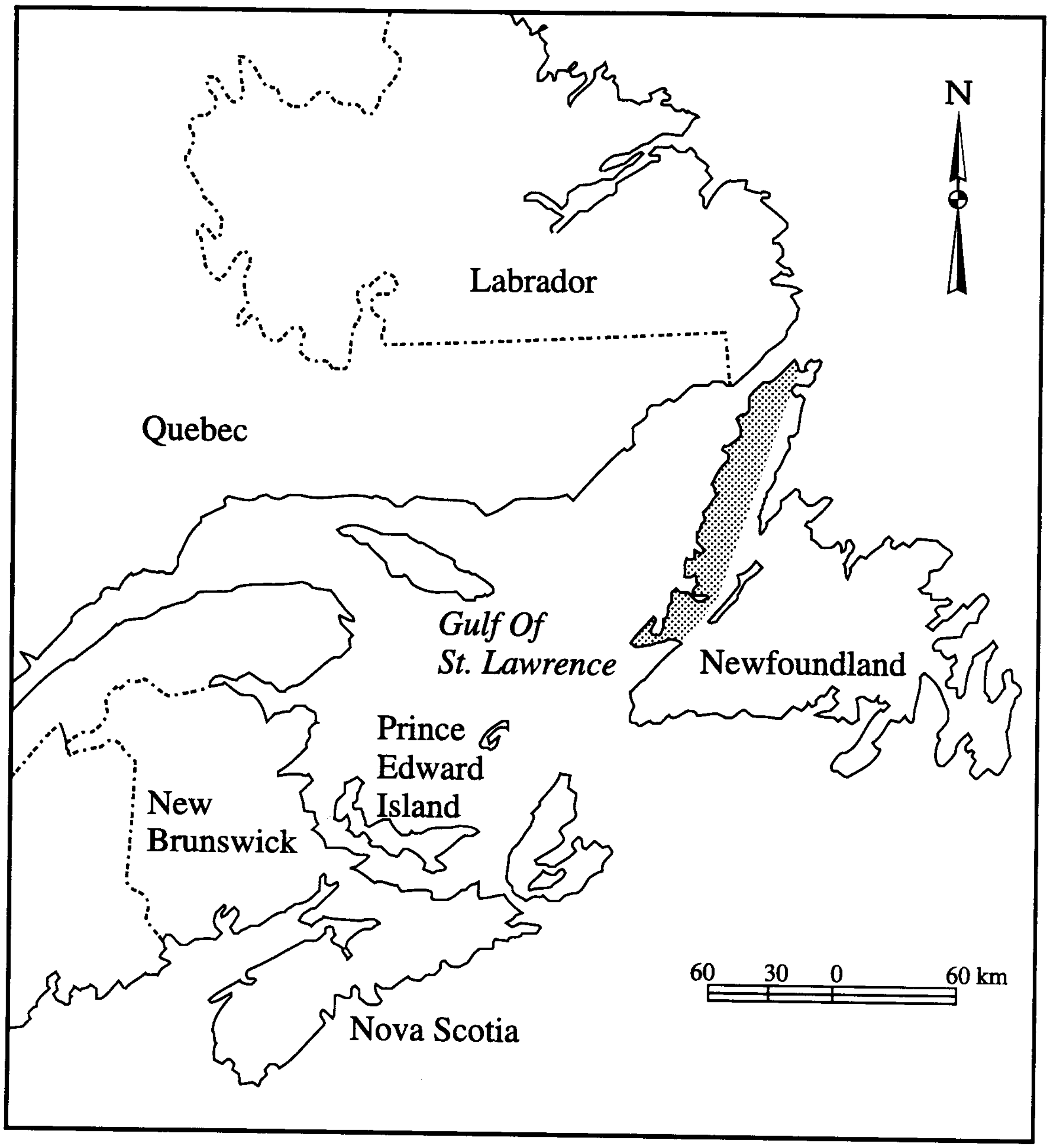



Figure 1.1 Location of western Newfoundland in Atlantic Canada.

salinity and pH), with a more detailed, process-oriented, chemical analyses performed where there existed an excellent range of saline conditions in the rock pools across the littoral zone.

## 1.2 Thesis Framework

This thesis is presented in seven chapters including this introduction. Chapter 2 provides the reader with the theoretical background pertinent to this study, as it discusses the development of littoral karren and the processes believed to be involved in their formation, including factors which affect rates of erosion in a given area. A summary is also provided on previous temperate region littoral karren studies in the literature. Chapter 3 describes the physiography of the study area, focusing on the geology, glacial history, climate and marine environment of western Newfoundland. Field methodology is presented in Chapter 4, with analysis and results of karren variation discussed in detail in Chapter 5. Chapter 6 extends the intersite karren variation results presented in Chapter 5 by investigating multivariate regression models comparing the effects of geology and the marine environment on karren development. Conclusions for both intra- and intersite karren variation are in Chapter 7, with some suggestions for future research.

# CHAPTER 2

# COASTAL KARST AND THE STUDY OF LITTORAL KARREN

## 2.1 Introduction

The littoral zone covers the coastal region between the seaward limit of terrestrial vegetation and at least 10 to 20 m offshore, where sediment is no longer affected by fair weather waves (Open University Course Team, 1989b). Karst landform studies within the littoral zone are focused on morphologic features occurring in relation to the marine tidal environment, from the subtidal zone through to the backshore, which is affected only by extremely high tides or storm wave action.

Littoral karren are common landforms along carbonate coastlines, although karren can also be found on other rock lithologies (Self and Mullan, 1996). Karren is a German term referring to small scale surficial karst solution features, which are classified according to their morphologic characteristics and location of occurrence (Ford and Williams, 1989; Table 9.1). Littoral karren assemblages refer to the wide variety of pits, pans and grooves which exist on carbonate coasts, forming from some combination of marine (mechanical erosion), chemical dissolution and biological erosion processes. The nature and magnitude of karren development varies from region to region, due to a number of variables which control rates of carbonate erosion.

## 2.2 The Development of Littoral Karren

### 2.2.1 Marine (Mechanical) Erosion

Marine erosion refers to the direct effects of wave energy, salt and frost weathering upon the coastal environment. Marine erosion processes can interact with chemical dissolution and bioerosion in carbonate environments to produce karst landforms in coastal regions, although it is stressed that they usually partially or completely destroy these same landforms.

Wave action is a major erosive agent for all types of lithologies. Its effectiveness is a function of several factors interacting together, collectively termed "wave climate". These include fetch, littoral and offshore gradients, the length of the littoral zone and the velocity of onshore winds (Pethick, 1984).

The wave climate of a particular coastal environment will determine the type of wave that breaks onto a coastline (Komar 1976; Blatt *et al.* 1980; Pethick 1984; Open University Course Team, 1989b). This is important because most wave energy is expended in the breaker zone, determining the amount of energy available to act as an erosive force upon the rocky coastal profile. High energy waves are associated with strong onshore winds, a longer fetch (or the distance of open water over which the wind blows), and intermediate coastal gradients, which allow the waves to plunge onto the shore generating great pressure upon the coast. Conversely, gentle or very steep coastal gradients will produce wave breaking patterns (spilling and surging waves respectively) conducive with lower energy releases, because wave height is minimized even in areas which are relatively exposed.

The primary erosive processes directly associated with wave action are quarrying and abrasion. A detailed discussion is provided by Trenhaile (1987). Quarrying is a process which actually removes rock. Wave energy acting upon the shore produces a shock pressure, where air is compressed within bedding planes, joints or holes in the rock and then is suddenly released as the water recedes. Quarrying has a negative impact on karren development, as it often breaks them apart (Ley, 1976).

Abrasion can also hinder the development of littoral karren, as it involves the scouring away of the rock surface, as a consequence of the dragging, rolling or throwing of clastic materials across the rocky shore. This results in smoothing the rock surface as the material passes over it, analogous to the action of sand paper. Abrasion effects can be enhanced in calcareous rocks by the solvent action of seawater, which can produce initial depressions associated with dissolution. This allows the scouring of clastics to be focused at these lodgment sites producing larger depressions. This, however, depends on the supply of clastic material acting upon a particular carbonate coastline, as an over-abundance of clastics will still produce an overall lowering of the rock surface (Ley, 1979).

The process of potholing is related to abrasion. Potholing occurs in the breaker zone of coasts, where larger clasts get trapped inside pre-existing hollows and rotate slowly around in a circular fashion (Zenkovich, 1967). The ability of the abrasive material to erode the rock within a pothole is a function of the size and amount of material, as well as the flow velocity (Sunamura, 1992). Thus, one would expect more exposed coastlines to experience a greater occurrence of potholes, associated with the increased wave energy, provided there is enough abrasive material available. The process of potholing on carbonate coasts may enhance karren microrelief, especially if the abrasive material is harder than the rock hosting the karren, as observed by Wentworth (1944), eventually increasing in size until individual potholes coalesce together and disappear (Zenkovich, 1967).

Salt weathering is a process occurring frequently in the upper intertidal and supratidal zones. Salt weathering is considered to be a chemical weathering erosion process, although it can produce some very destructive effects upon the rock surface, thereby making it appear to be a mechanical erosion process. Seawater contains a great abundance of ions in solution, which crystallize into various salts, especially sodium chloride (NaCl), when deposited onto the rock surface of the coastal zone. Water containing these salts seep into fissures and cracks within the rock, and facilitate erosion by increasing natural rates of hydration, temperature dependent crystal expansion, or by salt crystal growth out of solution (Cooke and Warren, 1973; Trenhaile, 1987). A state of supersaturation is essential for salt crystallization to occur (Winkler and Singer, 1972), a condition often prevalent in coastal environment spray zones. The supratidal spray zone of carbonate coasts is often characterized by high density pitting, due to the daily influence of salt water spray landing on the rock surface and evaporating in the sunlight, allowing salt crystal expansion to occur combined with the effects of solutional weathering.

Cold region limestone coasts are subjected to frost weathering and cannot be overlooked. This should especially pertain to any littoral karren existing on the shores of western Newfoundland. Plenty of moisture must be available in oder for frost weathering to be effective, as water seeps into fissures and joints within the rock, expands in volume upon freezing and eventually breaks up the rock (Matsuoka *et al.*, 1996). This may destroy any karren that rock is hosting. Frost weathering is most intense in the upper intertidal and supratidal spray zones, where there is the greatest number of frost cycles and available time for freezing to occur (Trenhaile and Mercan, 1984).

It should be noted that the effects of both salt and frost weathering are enhanced by the regular cyclicity of wetting and drying the rocks involved with these erosion processes. The rock expands upon taking up moisture and subsequently contracts during dessication. This in itself is an important weathering effect, but Hall and Hall (1995) believe that wetting and drying cycles alter internal rock properties (e.g. porosity), so that the rock is more conducive to frost and salt weathering. For example, the pressure of salt crystallization upon a rock is partially a function of porosity, with larger pores enabling more pressure to be exerted upon the rock (Iglesia *et al.*, 1994). If cycles of wetting and drying continually affect the rock substrate, then it is possible that the porosity may be enlarged, facilitating rates of salt weathering. The problem still exists in terms of separating these erosion processes and attempting to discern the relative importance of each in the weathering of rocks.

The role of pack ice must also be considered in relation to the magnitude and duration of not only mechanical processes of erosion, but also chemical and biological erosion processes acting upon the carbonate coast. For example, most of the shoreline along western Newfoundland is buffered by seasonal pack ice, which lasts up to five months along the Strait of Belle Isle coastline (Dept. of Fisheries and Oceans, 1986). There is some debate, however, as to whether pack ice acts more as a protective agent during the winter, or whether it aids in the destruction of the coastal profile from shore ice erosion (see Trenhaile, 1987). Sea ice can have a considerable effect on sedimentary coastal environments (e.g. Martini, 1981) and on the sea floor (e.g. Hequette *et al.*, 1995), but Trenhaile (1987) states that sea ice, especially floating sea ice, is an insignificant erosion agent on rocky coasts including carbonate coastlines. Neilson (1979) observed that the occurrence of an ice foot (narrow strip of sea ice) embedded in the intertidal zone, can disintegrate the rock or completely remove it if the ice foot breaks offshore, but Trenhaile argues that overall ice foot effects are minimal, as most of the ice foot usually melts *in situ*.

### 2.2.2 Chemical Dissolution

Water assumes an important role in all chemical weathering processes and, thus, the coastal zones in all lithologies are subjected to constant chemical erosion, including solution, hydrolysis, hydration and oxidation. However, carbonate coasts, primarily through the process of dissolution, are much more prone to the effects of chemical erosion than coastal environments of most other lithologies. This is because limestone is considered the most soluble of the common rocks (Selby, 1985).

Acid dissolution of carbonate rocks is facilitated by the addition of carbon dioxide ($CO_2$). Detailed discussion is beyond the scope of this study, but a brief summary of the carbonate mineral dissolution process is presented based on Stumm and Morgan (1980), Jennings (1985), White (1988) and Ford and Williams (1989).

Carbonation involves the dissolving of atmospheric $CO_2$ , a soluble atmospheric gas, into solution reacting with the water to form carbonic acid ($H_2CO_3^\circ$)

$$CO_2 \text{ (gas)} \rightarrow CO_2 \text{ (aqueous)} \tag{2.1}$$

$$CO_2 \text{ (aq)} + H_2O \rightarrow H_2CO_3{}^\circ \tag{2.2}$$

The carbonic acid dissociates into bicarbonate ($HCO_3^-$ ), which is the major solute anion of carbonate terrains and is also capable of dissociating itself

$$H_2CO_3{}^\circ \rightarrow H^+ + HCO_3^- \tag{2.3}$$

$$HCO_3^- \rightleftharpoons H^+ + CO_3^{2} \tag{2.4}$$

This creates an increase of $H^+$ ions in solution which, in turn, are capable of dissolving calcium carbonate ($CaCO_3$; Figure 2.1). The process is exactly the same for dolomite, although the presence of $Mg^{2+}$ in its chemical composition ($CaMg(CO_3)_2$) significantly reduces the solubility in many instances. Therefore, calcite (limestone) dissolution can be summarized,

$$CaCO_3 + CO_2 + H_2O \rightleftharpoons Ca^{2+} + 2HCO_3^- \qquad (2.5)$$

and for dolomite

$$CaMg(CO_3)_2 + 2CO_2 + 2H_2O \rightleftharpoons Ca^{2+} + Mg^{2+} + 4HCO_3^- \qquad (2.6)$$

Rates of carbonation rely primarily on temperature and pressure variations, but are also a function of a wide range of complications which occur in nature, either depressing or boosting dissolution rates. A review of these complications can be found in Ford and Williams (1989, p.62-79).

In order for a solution to dissolve calcite or dolomite, that solution must be undersaturated or aggressive with respect to those minerals. The saturation status of a solution can be determined mathematically and provides a measure of the potential aggressiveness of that solution with respect to $CaCO_3$. Saturation indices (*SI*) essentially measure the ion activity product ($K_{IAP}$) in comparison to the thermodynamic equilibrium constant ($K_{eq}$) for a given mineral

$$SI = \log \frac{K_{IAP}}{K_{eq}} \qquad (2.7)$$

In other words the proportion of potentially reactive $Ca^{2+}$ and $HCO_3^-$ ions in solution are compared to the equilibrium constant for that solution, which is a function of the existing conditions. A negative *SI* value indicates a solution which is undersaturated with respect to the mineral involved ($K_{eq} > K_{IAP}$). A positive *SI* value represents a solution saturated with the mineral ($K_{eq} < K_{IAP}$), and a value of 0.0 represents dynamic equilibrium with the mineral ($K_{eq} = K_{IAP}$), although equilibrium is difficult to

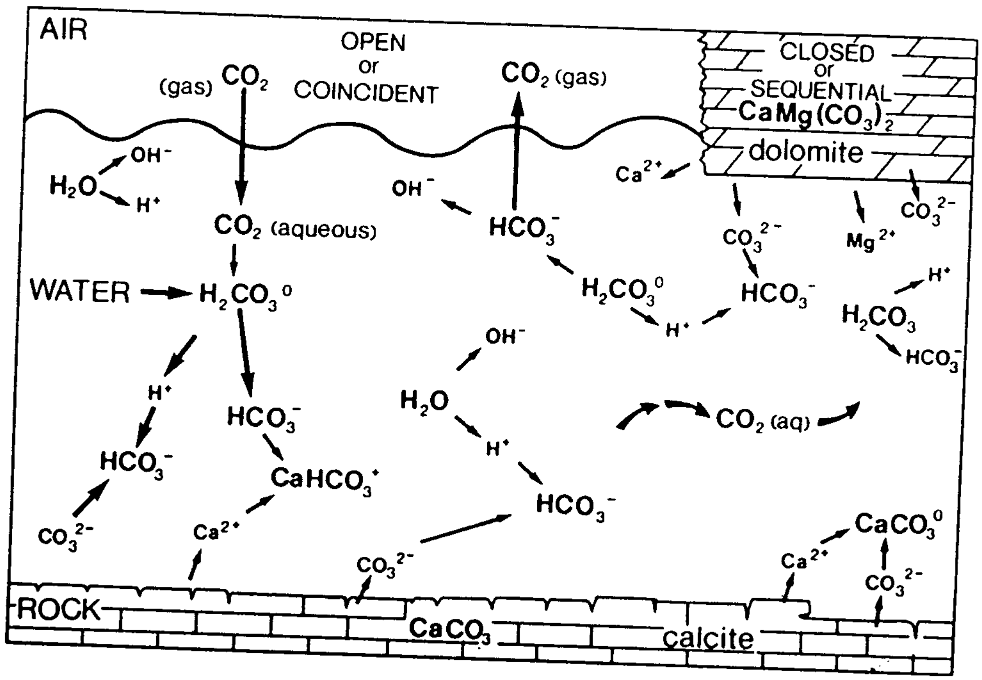



Figure 2.1 Cartoon illustrating the dissolved species involved with calcite and dolomite dissolution under coincident and sequential conditions (from Ford and Williams, 1989, p. 54).

attain. The activities of $Ca^{2+}$ and $HCO_3^-$ are determined directly from measured concentrations in solution, in relation to specific water conditions at the time of measurement, so that for freshwater solutions the saturation index of calcite can be summarized

$$SI_c = \log(Ca^{2+}) + \log(HCO_3^-) + pH - pK_2 + pK_c \tag{2.8}$$

where $pK_2$ and $pK_c$ are thermodynamic equilibrium constants, expressed as negative logs, for the carbonate solution system (see Ford and Williams, 1989 p. 56). Dolomite can be summarized

$$SI_d = \log(Ca^{2+}) + \log(Mg^{2+}) + 2\log(HCO_3^-) + 2pH - 2pK_2 + pK_d \tag{2.9}$$

Because the many ions involved with seawater produces a much more complex chemical environment (Table 2.1), determining its saturation status is more difficult, although it is recognized that standard surface seawater is supersaturated with respect to calcite (Morse *et al.*, 1980; Trudgill, 1985). Morse *et al.* (1980) are able to produce *apparent* solubility constants for aragonite and calcite, but the values are representative for a specified set of conditions for the open ocean. If this is the case then how is seawater capable of eroding carbonate coasts to produce karst landforms? There are also a number of factors hindering the quantification, and more precise determination, of carbonate dissolution in the littoral zone.

Seawater chemistry in the littoral zone is distinctly different from that of the open ocean, often creating undersaturated conditions in the tidal zones, as discussed by Revell and Emery (1957), Pytkowicz (1969), and Trudgill (1974, 1976a, 1976b and 1985). This is due to factors which affect the solubility constant of calcite and dolomite. These include temperature, salinity, pressure, presence of organic compounds and acids, mineral composition and flora and fauna colonization, all of which are constantly changing on a daily basis, especially in the intertidal zone. For example, calcite solubility may be boosted by increases in water temperature, pressure, and salinity, or from an abundance of decomposing organic matter. Organic matter releases $H^+$ ions into solution and increases $CO_2$ levels in the water by oxidation, both of which increase solubility rates. It is also noted that organic matter can lower solubility by coating the rock surface and acting as a buffer in hindering mineral dissolution. Calcite solubility is also enhanced by the presence of a low percentage of $Mg^{2+}$, one of several dissolution-inhibiting cations capable of lowering the overall dissolution rate of rocks (Lin and Shen, 1995), as solubility increases with increasing purity of the rock.

It has been shown as early as 1946 in a classic paper by Emery that the presence of littoral flora and fauna will boost the solubility potential of tidal pools on a diurnal basis. $CO_2$ levels are significantly boosted on a localized scale at night, when the $CO_2$ respiration from marine organisms is not utilized by plants for photosynthesis. This creates aggressive tidal pools which can then erode $CaCO_3$. This diurnal variation in the level of $CO_2$ within seawater is not nearly as pronounced in the open

Table 2.1 Average concentrations of the principal ions in seawater, in parts per thousand by weight (from the Open University Course Team, 1989a, p. 30).

| Ion | ‰ by weight | | |
|---|---|---|---|
| chloride, $Cl^-$ | 18.980 | | |
| sulphate, $SO_4^{2-}$ | 2.649 | | |
| bicarbonate, $HCO_3^-$ | 0.140 | | |
| bromide, $Br^-$ | 0.065 | negative ions (anions) total | = 21.861‰ |
| borate, $H_2BO_3^-$ | 0.026 | | |
| fluoride, $F^-$ | 0.001 | | |
| sodium, $Na^+$ | 10.556 | | |
| magnesium, $Mg^{2+}$ | 1.272 | | |
| calcium, $Ca^{2+}$ | 0.400 | positive ions (cations) total | = 12.621‰ |
| potassium, $K^+$ | 0.380 | | |
| strontium, $Sr^{2+}$ | 0.013 | | |
| | | overall total salinity | = 34.482‰ |

ocean as it is in the littoral waters.

Higgins (1980) believes that an input of fresh groundwater at the coast is an additional and important factor in coastal dissolution, a factor first proposed by Wentworth (1939). Higgins, using coastal Greece as an example, suggests that the groundwater is capable of penetrating limestone rock, especially more porous platforms, and erode the rock from within by the standard dissolution process.

The mixing zone of fresh-seawater at carbonate coasts provides a powerful dissolution mechanism for relatively rapid rates of erosion. Mixing of seawater with fresh groundwater generates an undersaturated state with respect to calcite and aragonite, with the amount of undersaturation a function of $P_{CO2}$ (partial pressure of $CO_2$ ), temperature, ionic strength, degree of calcite saturation and pH (Plummer, 1975). Evidence suggests that this state of undersaturation is often significantly enhanced by the occurrence of bacterial processes, which may have an important role in further driving carbonate dissolution rates (Smart *et al.*, 1988; Sec. 2.2.3 B). Back *et al.* (1986) believe that mixing zone solutions have a significant role in the development of porosity and permeability of carbonate rocks in the geologic record.

Mixing zone dissolution is believed to be the primary mechanism for developing several phreatic coastal caves on Berry Head in South Devon, U.K. (Proctor, 1988). In the tropics mixing zone dissolution appears responsible for developing abandoned dissolution caves on Andros Island, Bahamas (Smart *et al.*, 1988; Whitaker and Smart, 1994), San Salvador Island, Bahamas (Mylroie and Carew, 1990; Mylroie *et al.*, 1994), Cayman Brac Island, British West Indies (Lips, 1993) and for extensive dissolution along the carbonate coast of the Yucatan Peninsula, Mexico (Back *et al.*, 1986).

### 2.2.3 Biological Erosion

The term phytokarst was introduced by Folk *et al.* (1973) to define any landform produced primarily by the eroding actions of flora and fauna, with types of phytokarst described in Bull and Laverty (1982). Viles (1984) prefers to use the term biokarst to summarize biologically linked landforms. One type of phytokarst is the destructive, or bioerosional, which pertains to the formation of karstic landforms from the eroding action of organisms. Bioerosion, especially in tropical environments, is considered the most prevalent and important coastal process of erosion on carbonate rocks. Many researchers have developed classifications, or models, of coastal landform development based on the organisms which formed them (e.g. Williams, 1971; Focke, 1978; Moe and Johannessen, 1980; Trudgill, 1987). Bioerosion here will be summarized under the two primary mechanisms of erosion; grazing and boring/burrowing.

A) Grazing Organisms

Grazing organisms are surface dwellers (epiliths) which erode the rock by scraping and/or consuming it while grazing upon microorganisms or flora (Figure 2.2). This is opposed to boring/burrowing organisms which are referred to as endoliths. Grazing is essentially a biological

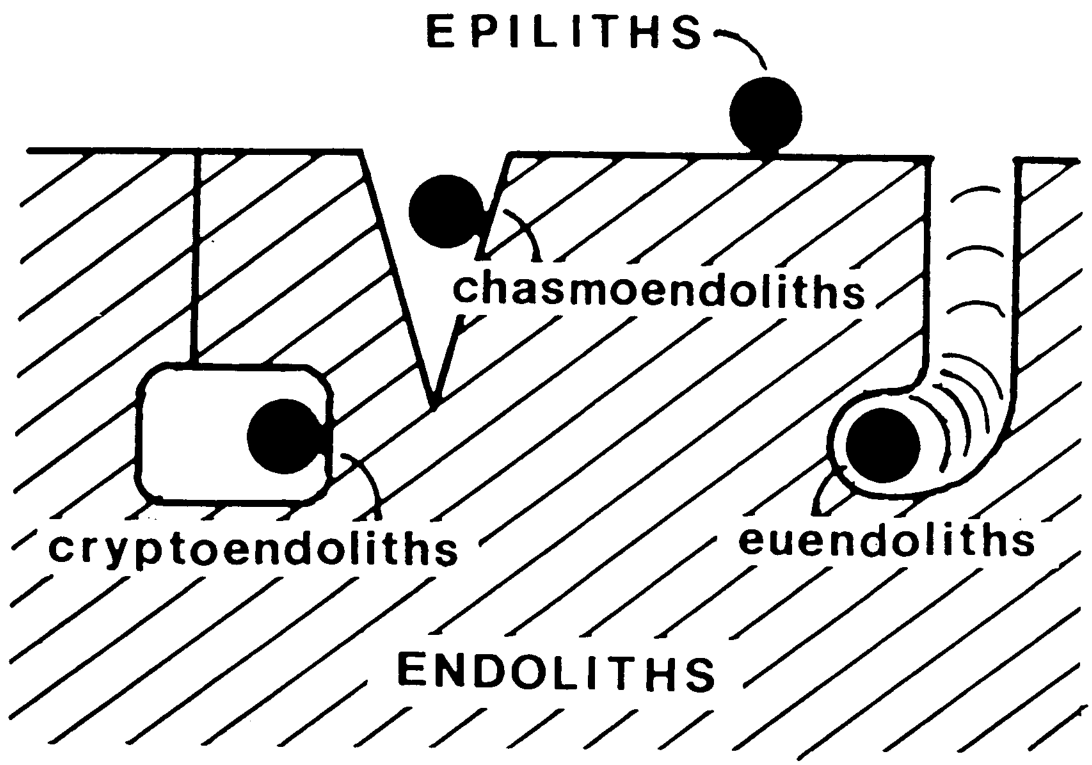



Figure 2.2 Illustration of the types of organisms in relation to where they inhabit carbonate substrate (from Golubic *et al.*, 1981, p. 476).

form of abrasion. There is often a general lowering or smoothing of the rock surface from these epilithic species, principally from gastropods (e.g snails) and echinoids (e.g sea urchins; Table 2.2), although some of the deeper grazers can also produce shallow pits on the surface.

Algae are the most important food source for these grazers. They are abundant throughout the littoral zone, either as chlorophyta (green algae), rhodophyta (red algae) or cyanophyta (blue-green algae), often forming a slimy covering on the rock surface. Cyanophytes are the most widespread algae species and possess the ability to fix nitrogen into their cell structure, so their existence is vital for any intertidal food chain (Trudgill, 1985).

There must be a delicate balance between grazing macroorgansims and boring microorganisms, in order to produce maximum grazing activity (Spencer, 1988). The amount of

Table 2.2 Summary of principle macroorganisms involved in bioerosion of limestone coasts (modified after Schneider, 1976, p. 50).

| Phylum - class | Type | Mechanisms | Resultant Morphology |
|---|---|---|---|
| Annelida - sipunculans polychaeta (worms) | endolithic | chemical dissolution and mechanical boring motions of shell | shallow, tubular borings and internally expanded borings |
| Arthropoda - cirripeds (barnacles) | endolithic | chemical dissolution (?) and mechanical boring from erosive chitinous studs | shallow, tubular borings |
| Echinodermata - echinoids (sea urchins) | both | rasping of surface and boring into rock by mechanical action of basal teeth and spines | deep, gnawing traces and hemispheric or cylindrical pits; occasionally grooves |
| Mollusca - amphineura (chitons) | epilith | surface rasping with radula | irregularly distributed grazing patches |
| Mollusca - bivalves (mussels/clams) | endolith | chemical and/or mechanical (?) | narrow "U" shaped burrows |
| Mollusca - gastropoda (snails) | epilith | surface rasping with radula and solution with the sole | meandering grazing trails |
| Porifera - clionid (sponges) | endolith | chemical solution of loosened rock chips | spherical chambers or honeycombed networks |

erosion of carbonate rocks attributable to the action of grazing is difficult to determine, though it is of particular significance on sheltered coasts where sand is absent (Trudgill, 1976a). Trudgill found surface erosion rates on Aldabra Atoll, Indian Ocean, attributable to grazing organsims, to be in the order of 0.61 mm $a^{-1}$ in non-sandy areas and accounts for up to one-half of the overall erosion taking place. This is opposed to 0.45 mm $a^{-1}$ surface removal by grazing organisms at sandy sites, which contributes to overall erosion rates in equal proportions to sand abrasion and other processes (e.g. solution, salt weathering etc.). Evidence suggests that grazing chitons have a role in long term coastal retreat in the Bahamas, for low energy, tide-dominated rocky shores (Rasmussen and Frankenberg, 1990) and sea urchin grazing limits coral reef growth in the Galapagos (Glynn *et al.*, 1979) and in Jamaica (Sammarco, 1982). Kiene and Hutchings (1994) found grazing to be the dominant erosion process for most of their sites at Lizard Island, Great Barrier Reef. They believe that the level of grazing controls the amount of boring at a given site, since extensive grazing of reef substrates reduces reef growth and controls the development of borers within the substrate.

## B) Boring/Burrowing Organisms

The other primary type of littoral organisms are the endoliths, or active rock borers (Figure 2.2). Within the endolithic group are the cryptoendoliths, which occur in discrete layers within porous substrates, the chasmoendoliths which inhabit existing rock cracks and joints, and the powerful euendoliths which actively bore into the rock (Spencer, 1988) and are the focus here. Organisms bore into the rock in search of food, protection from other macroorganisms or invertebrates, and from wave action and tidal currents characteristic of the littoral environment. Boring organisms are discussed in reference to their relative locations within the littoral zone based on published research by Schneider (1976), Risk and MacGeachy (1978), Torunski (1979) Schneider and Torunski (1983), Trudgill (1985), Hutchings (1986), Trudgill and Crabtree (1987) Trudgill *et al.* (1987), and Lazar and Loya, (1991).

It has been stressed for years that there exists a littoral flora and fauna zonation on rocky coasts (e.g. Stephenson and Stephenson, 1972). Species dwell at different littoral locations according to their ecological adaptations to the varied conditions of the sub-, inter- and supratidal zones. As far as boring organisms are concerned, in general, endolithic macroorganisms inhabit lower inter- and subtidal zones (Table 2.2), while the upper inter- and supratidal zones are dominated by endolithic microorganisms. It should be noted that rates of bioerosion provided for one reef or littoral environment cannot be extrapolated to other environments as rates of bioerosion vary significantly, depending on borer colonization and local environmental conditions (Hutchings *et al.*, 1992).

Boring sponges can be quite destructive on carbonate coasts, especially in tropical regions where they can account for large volumes of rock removal. Most species of boring sponges belong to the *Cliona* genus, which are capable of boring by chemical dissolution and by a process of amoeboid transfer, where extensions of the sponge tissue are able to penetrate the rock in a semi-circular pattern. Although boring sponges can penetrate rock depths up to 8 cm in the tropics (Spencer, 1988), excavations must be in continual contact with the water, since sponges are susceptible to desiccation. Sponges usually produce a network of small spherical, or honeycomb, chambers in the rock.

There are several echinoid species which are capable of grazing on top of the rock surface as well as eroding into carbonate substrate, especially the *Echinometra* genus in the tropics and the *Paracentrotus* genus in temperate regions. Evidence for echinoid erosion is much clearer than that for sponges, as they produce hemispherical grooves and burrows in the limestone, from the combined action of basal teeth and spines. In addition to species type, Bak (1994) found that echinoid erosion is also a function of size and population density, with bioerosion rates increasing rapidly with large sizes and higher densities, to the point where echinoid erosion can equal or exceed carbonate reef production. Trudgill *et al.* (1987) found erosion boring rates from *Paracentrotus lividus* to be in the order of 0 to 1.0 cm $a^{-1}$ at a sheltered site, increasing to 0.25 to 1.5 cm $a^{-1}$ on an exposed shore in Co. Clare, Eire. Reaka-Kudla *et al.* (1996) observed that about 25 kg $m^{-2}$ $a^{-1}$ of coral reef is lost in the Galapagos Islands, with *Eucidaris thouarsii* accounting for almost 75% of this erosion. Mokady *et al.* (1996) quantify the importance of echinoid erosion in the destruction of coral reefs in the Red Sea, and the conversion of the reef framework to carbonate sediments (7% - 22% total reef calcification, depending on location).

There are a number of bivalve species which can burrow quite deep into limestone, principally the bivalve mollusc *Lithophaga* (mussel) and *Hiatella arctica* (clam) in temperate and arctic regions. These species have the ability to bore into the rock by both chemical secretion and mechanical rotation, although exact methods are not fully understood. It is known that mechanical movement may involve rocking and rotational motions, while chemical secretion is often from within the glands of the organism. *Lithophaga* spp. are found in the lower intertidal zone, where wave energy at a given site is at a maximum and induces intense boring activity and deep tubular burrows. In tropical regions *Lithophaga* have been directly determined to be a principal species active in the development of low intertidal notches (Hodgkin, 1970; Trudgill, 1976a).

*Hiatella arctica* inhabits the subtidal zone of coastal areas and can produce very distinctive pitting within the rock. Trudgill *et al.* (1987) found Hiatella boring rates to be similar to that of the *Paracentrotus lividus* at Co. Clare, Eire, with an overall range from 0.125 to 1.0 cm $a^{-1}$, varying from a mean rate of 0.42 cm $a^{-1}$ on the exposed site and 0.33 cm $a^{-1}$ on the sheltered site.

Other boring macroorganisms include several barnacle species, especially of the *Lithotrya* genus, and worm species of the *Polydora* genus. *Lithotrya* are capable of mechanically eroding into the rock by erosive chitinous studs, producing oval-shaped borings up to 1 cm diameter and 10 cm depths (Warme, 1975). It is somewhat unclear in the literature what is the exact eroding process of the worms, and the degree of bioerosion they are capable of producing. It is believed that both chemical and mechanical processes are involved producing "U" shaped burrows up to 0.2 cm diameter and 10 cm depths (Risk and MacGeachy, 1978).

Principal boring microorganisms include various species of algae, fungi and lichen (Table 2.3), producing small networks of pitting or fretting on limestone surfaces on inter- and supratidal rock surfaces (except for fungi which inhabits the subtidal zone). Algae and fungi have received the most attention in the literature, in terms of documenting their boring mechanisms, patterns and

Table 2.3 Summary of the principle microorganisms involved in bioerosion of limestone coasts (modified after Schneider, 1976, p. 50).

| Organism | Phylum (Genus) | Mechanism | Resultant Morphology |
|---|---|---|---|
| Algae | Cyanophyta (e.g. *Calothrix*, *Hyella*)<br><br>Chlorophyta (e.g. *Ostreobium*)<br><br>Rhodophyta (e.g. *Porphyra*) | chemical solution (acid secretion) organic acids ? | network of fine filaments in the substrate |
| Fungi | Ascomycetes (e.g. *Halosphaeria*)<br><br>Deuteromycetes (e.g. *Periconia*) | chemical solution during colonization of the substrate from fruiting structures | same but to greater depths |
| Lichens | Teloschistaceae (e.g. *Caloplaca, Xanthoria)*<br><br>*Verrucaria*<br><br>*Arthropyrenia* | surface corrosion and boring by chemical solution from organic acids | tiny grooves and hemispheric pits on the rock surface |

rates of erosion within carbonate rock (Kohlmeyer, 1969; Golubic 1973; Golubic *et al.* 1975; Schneider, 1976; Kobluk and Risk, 1977; Risk and MacGeachy, 1978; Danin *et al.*, 1982; Tudhope and Risk, 1985; Trudgill, 1985; Risk *et al.*, 1987; Viles, 1987) and will be briefly summarized here.

Boring algae are the most widespread and destructive of all erosive organisms. The same major groups which are surface dwellers, cyanophyta, chlorophyta and rhodophyta, also possess significant boring capabilities, particularly the cyanophytes which inhabit the entire range of the tidal zones. Algae are able to bore into carbonate rock by the release of acid fluids from their cells, in their search for damper conditions of the inner rock. Thus, algae boring depths are greater in drier areas, where depths up to 30 cm have been recorded in arid regions (Danin *et al.*, 1982). Boring depths are, however, limited by the depth of sunlight penetration, as algae are phototrophic (light dependent) organisms. Algae are capable of producing variations in their boring pattern in different lithologies, although the general morphology of a fine network of small cavities remains the same.

Endolithic fungi are very similar to algae in terms of their role in relation to bioerosion of carbonate substrate. In fact, a large amount of carbonate borings attributable to algae may indeed be due to fungi, or a combination of both, as it is often difficult to discern between the two. Schneider (1976) was one of the first to differentiate between algae and fungi borings. From resin casts he found that algae will leave rough etchings on the walls of the borehole, but fungi boreholes are smooth, implying that different mechanisms are involved. Fungi can also bore into greater depths within the rock, especially in moist cavities, as they are heterotrophic, meaning that they are not light dependent. Instead, they rely on organic substances for nutrients, including algae, explaining why these organisms often co-exist together within the substrate. Hirsch *et al.* (1995) concluded that fungal diversity and degree of weathering of rock monuments was higher if algae was present.

Lichens occupy tidal pools in the inter- and supratidal zones, as well as often thickly colonizing surface rock in the supratidal and backshore zones. Endolithic lichens are capable of penetrating and eroding the rock surface so as to expel flakes of rock, often producing a characteristic puzzle-like pattern in the substrate (Danin *et al.*, 1982; McCarroll and Viles, 1995). Trudgill (1987) defines a lichen zone for a site at Co. Clare, Eire, in the supratidal zone, where there is evidence of shallow pitting (up to 30$\mu$m in dia.), grooves and inter-crystalline rock penetration. It can be argued that the existence of lichen cover also provides the rock surface with some protection from aggressive dissolution (Moses *et al.*, 1995; Fiol *et al.*, 1996).

Bacteria have long been identified as having an important role in the solution of carbonate rocks (James, 1994), but are still a poorly understood phenomena. Bacteria species will often colonize carbonate substrata together with other microorganisms, helping aid in chemical processes which will either promote limestone dissolution or precipitation. Evidence of bacterial corrosion exists within many caves (e.g. Cunningham *et al.*, 1994; James 1994; Martin and Brigmon, 1994), and in coastal limestone regions (e.g. Mylroie *et al.*, 1994, Stoessel, 1994; Whitaker and Smart, 1994). These studies stress the role of bacteria, such as *Thiothrix* spp. and *Thiobacillus* spp., in producing chemical acids, primarily through redox reactions of organic matter (carbon) or sulphur species, which can then dissolve limestone.

### 2.2.4 Rates of Erosion

Determining the rates of erosion on carbonate coasts is difficult, especially when attempting to separate the three primary types of erosion processes. Many researchers usually attempt to measure only one erosion process, often bioerosion, with the use of microerosion meters (MEMs), which is a direct measurement of surface lowering of the rock (e.g. see Trudgill 1976a and 1976b; Trudgill *et al.*, 1987; Spate *et al.*, 1995). MEM results, however, are not without sources of error primarily associated with the instrument, particularily if short term erosion rates are being monitered (see Trudgill, 1977, Viles and Trudgill, 1984 and Spate *et al.*, 1985 for details). Most MEM studies in the literature consist of short term measurement and any extrapolations of short term results over longer time periods should be made, and interpreted, with caution. Spate *et al.* do conclude that the accuracy of mean, *overall* erosion rates, especially at coastal sites, can be much more significant than the magnitude of error created by MEMs, especially if monitored over much longer time spans (e.g. Trudgill *et al.*, 1989; Smith *et al.*, 1995; Stephenson and Kirk, 1996).

Limestone tablets, often used to measure limestone solution rates, also produce results which may be suspect (see Trudgill, 1977 and Trudgill *et al.*, 1994 for details). Limestone tablets are suspended in solution and subsequent weight loss is recorded. However, the amount of weight loss is dependent upon several other external factors including climate, lithology, elevation and water surplus effects (Ford and Williams, 1989; Zhang *et al.*, 1995). This is especially true in coastal areas and it is questionable how much weight loss is actually attributable strictly to dissolution, although Crabtree and Trudgill (1985) and Trudgill *et al.* (1994) show that limestone tablets are useful for measuring spatial variations in solution rates at the soil-bedrock interface on a Magnesian Limestone slope east of Sheffield. More recently Dorn (1995) focused on *in situ*, microscopic measurements of rock and mineral porosity to quantify rates of chemical weathering in rocks over time.

The underlying problem here involves determining rates of erosion in coastal environments, where only one process is being measured (with measurement error) in an environment which involves the complex interaction of all three. In fact, many studies totally ignore the importance of mechanical erosion processes in relation to the development (or destruction) of karstic features. Because process analysis is so complex in the coastal environment, it has not been undertaken in this study. Instead, a morphology-focused perspective is utilized, where karren dimensions at different sites are studied in relation to variables which control overall rates of erosion. The two primary variables that govern the relative rates of erosion at a given site are the degree of exposure to the marine environment and the geology, with the tidal range further producing variations in the erosion rates within the littoral zone.

Increased exposure to the marine environment produces a corresponding increase in the magnitude of the erosive processes acting upon that coastline, potentially enhancing karren development. The negative or positive effects of the mechanical erosion processes on the shore will directly increase in magnitude with the increased wave activity (Sec. 2.2.1). Rates of chemical dissolution would increase from the more turbulent swash waters (Spencer, 1988). Bioerosion rates would either increase or decrease depending on the degree of exposure existing at a given site. Generally, increased exposure will produce an increase in bioerosion, as organisms are forced to bore to greater rock depths in search of better protection (e.g. Trudgill *et al.*, 1987 rates; Sec. 2.2.3B). There is also an increased availabilty of moisture seeping into the substrate, which creates more favourable conditions for species colonization within the rock (Trenhaile, 1987). At the same time, though, Golubic *et al.* (1975) stress that increased wave activity can also hinder colonization of exposed areas by some organisms, due to a stronger wave shock acting upon the substrate and an increased abundance of sedimentary particles. Trudgill (1985) notes that a threshold is reached where wave energy becomes so high that bioerosion is all but non-existent, as organisms simply cannot survive these harsh environments. Spencer (1988) observed that the number and variety of organisms decreases with increasing exposure but, at the same time, there is a change in the distribution and type of organism which is capable of surviving more exposed sites (e.g. echinoids - Trudgill *et al.*, 1987).

Rock lithology and structure are very important controls on rates and types of carbonate erosion, and the development of karst landforms as emphasized by Ley (1977), Trudgill (1985) and Ford and Williams (1989). Limestone is much more soluble than dolomite (Sec.2.2.2), but limestone solubility also varies depending on its composition. Solubility is reduced when there are a greater percentage of impurities (clay, sand, fossils, etc.) in the rock, especially when associated with low porosity and permeability, characteristic of rocks with a small, homogeneous grain size. There will be an increase in the development of karstic features when there are already inherent weaknesses within the rock, allowing water, salt and marine organisms easier access to greater rock depths. The angle and direction of dip of the rock strata is important, with low angle slopes often characteristic of smoother surfaces, while steeper sloping rock platforms, especially dip slopes, will produce a more pronounced surface roughness and localized relief (Trenhaile, 1987).

It is unclear in the literature which variable (exposure or geology) is the most important in terms of controlling the erosion processes. For example, would greater karst development be associated with either the most exposed sites regardless of the limestone properties existing there, or with coastal rocks which are most conducive to karst development regardless of location? It is a question which has not been fully addressed in the literature as yet.

The closest research study attempting to answer this question was by Smith *et al.* (1995). They studied the relative importance of variations in climate and lithology in relation to rates of erosion upon limestone rocks in eastern Australia. They found that different bedrock lithologies exposed under similar climatic conditions resulted in large variations in overall rates of erosion, while comparing bedrock sites with similar lithologies and climate revealed insignificant differences in erosion rates. These results strongly support the notion that lithologic variations are the most important factor involved in controlling limestone erosion.

Tidal range is important in producing intrasite karren variations across the shore platform affected by a diurnal or semi-diurnal tidal cycle. This is because the tidal range will determine the duration and magnitude of the erosion processes at different locations within the littoral zone (Trenhaile, 1987). Higher tidal ranges produce a more even distribution of the erosion processes, which should result in consistent karren development across the platform, assuming that other variables remain constant. A microtidal range (< 2 m) will concentrate the daily effects of maximum wave swash, spray and inundation onto a reduced area of the platform rock, thereby maximizing erosion rates at that area.

## 2.3 Previous Temperate Region Littoral Karren Studies

### 2.3.1 Introduction

There is a considerable amount of literature on tropical carbonate coasts and associated geologic properties and geomorphologic landforms, although it will not be reviewed in detail here. Tropical carbonate coasts have the advantage of possessing much younger lithologies, often composed of modern limestones, allowing for direct studies on shallow water limestone formation and diagenesis (Ford, Pers. Comm., 1994). Tropical climates and oceanic waters are particularly favourable to an increased colonization and species diversity of marine organisms, boosting both bioerosion and chemical dissolution upon these much younger, more porous carbonate rocks

(Trudgill, 1985). These factors aid in the much more extensive development of karst landforms in the tropics, and determination of mechanisms involved in their formation is easier, since many tropical islands and coastlines are tectonically stable (e.g. the Bahama Islands, Mylroie and Carew, 1990).

A pioneer study in temperate, littoral karren was undertaken by Guilcher (1958), who described limestone corrosion features, or *lapies* (French for karren), around the Bay of Biscay. He describes characteristic zonations within the limestone for three primary regions: the Asturias and Santander coast, the Saintoinge, Aunis and Poitou coasts and the West Brittany coast. This study brought together, in a qualitative sense, the interactive importance of geologic and exposure variables upon the magnitude of *lapies* development.

At the Asturias and Santander coast Guilcher describes storm wave and spray zone pinnacles (ranging from 0.15 m to 0.34 m ht.), an overhanging visor in the upper intertidal zone and a platform extending across the rest of the intertidal zone, into which there are cut ponds (up to 10 cm ht.). The Saintoinge, Aunis and Poitou coasts possesses limestones which are not as massive or hard as those along the Asturias and Santander coastlines, therefore, true corrosion forms do not exist except in isolated areas. The sheltered areas of the West Brittany coast hosts insignificant corrosion forms, yet the most exposed sites reveal the most spectacular corrosion features. A zonation of corrosion forms was observed at the exposed sites, from the spray zone lichen-dominated honeycombs, through to the development of pinnacles in the intertidal zone and a flat surface at the low tide mark and below.

Since then papers have been published for littoral karren-type features at the Netherlands (Focke, 1978) and Norway (Moe and Johannessen, 1980; Holbye, 1989). Focke (1978) produced profiles for sheltered, leeward, lateral and windward (exposed) sites, along with related organism colonization. Notches are the dominant landform along the sheltered, leeward and lateral profiles, with karren existing in the spray zone of the most exposed, windward profile (Figure 2.3). This spray zone, also affected by rough surf, has a very rugged topography of pits up to 500 $\mu$ high and influenced primarily by algae colonization, as well as dominated by grazing gastropods, both of

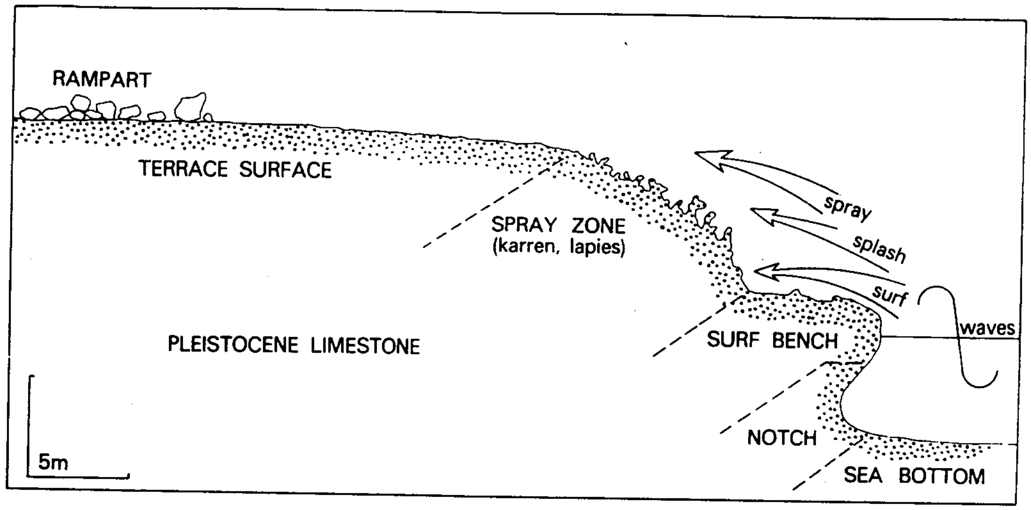



Figure 2.3 Morphological units along the windward cliff profile. Note the development of karren within the spray zone (from Focke, 1978, p. 139).

which are believed to be a factor in karren development.

Moe and Johannessen (1980) studied the occurrence of numerous small cavities in littoral carbonate rocks in northern Norway. They discovered species of algae and gastropods, primarily *Littorina* spp., colonizing these cavities and suggest that the cavities are a direct result of *Littorina* scraping the rock while grazing upon the algae. The cavities are located predominantly in the intertidal zone, increasing in diameter from 1 to 2 mm in the lower intertidal zone, to about 10 mm above the high tide line. They also proposed that the existence of cavities above the littoral zone must have formed during a higher sea level stand than today.

Holbye (1989) studies the occurrence of bowl-karren on the marble coasts of northern Norway, which he believes are formed, not from bioerosion, but from dissolution of the coastal marbles from high energy wave swash. It is possible that bioeroders colonize the karren once formed, at which point they may enhance pit depth over time. He classifies the bowl-karren based on size and density of the features, and it was found that the bowl-karren are best developed along exposed coastlines, especially with platform rocks which slope at angles greater than 25° towards the sea. A karren zonation also exists within the littoral zone, as the largest karren occurs above high tide where the rock is only affected by high water and storm swash. This is apparently the only active zone of karren formation, with only scattered karren occurring in the intertidal zone.

Tafoni (alveoli, honeycomb features) are weathered cavities found in all rock lithologies and environments throughout the world. Tafoni genesis is discussed in detail by Martini (1978), Mustoe (1982), Trenhaile (1987) and Mottershead and Pye (1994). Tafoni are believed to be formed from physical disintegration of the rock grains, due to the effects of salt weathering and/or continual wetting and drying of the rock surface. Mottershead and Pye (1994) believe that the tafoni forming on the coastal slopes at South Devon, U.K. are a function of chemical dissolution along the grain boundaries of the greenschist rock located there, although this may be specific to the mineralogical composition of the greenschist. Tafoni are best developed in homogeneous rocks located at coastal (Martini, 1978; Gill, 1981; Matsukura and Matsuoka, 1991; Mottershead and Pye, 1994; Spate *et al.*, 1995; Hunt, 1996), arid and alpine regions (Smith, 1978; Fahey, 1986; Matsuoka, 1995; Kirchner, 1996), where there is an ample supply of salts.

There has not been much detailed study of the rates of coastal tafoni formation. Martini (1978), Gill (1981) and Spate *et al.* (1995) only describe the appearance of the tafoni. Matsukura and Matsuoka (1991), from their study of tafoni on the southwest tip of the Boso Peninsula, Japan, reveal that the highest rates of erosion and tafoni deepening occurred during the initial stages of development, reaching a maximum of 1.67 mm $a^{-1}$. This is based on current maximum tafoni depths of 11 cm at this site. Erosion rates then appear to decrease over time, possibly due to reduced exposure to the sun and wind. Using twenty-four sites in three areas of Japan, Matsukura and Matsuoka (1996), investigated coastal tafoni growth as a function of porosity and mechanical strength of the rock (using the Schmidt hammer test; see Ford and Williams, 1989 for explanation) They found that tafoni growth is faster in association with rocks which have larger pore spaces and/or a lower mechanical strength. Mottershead and Pye (1994) do not provide rates of tafoni erosion for their current study of tafoni located along the backshore of the coast, but do mention rates of recorded intertidal tafoni erosion to be in the order of > 0.6 mm $a^{-1}$. Tafoni on the Maltese Islands (Hunt, 1996) range in size from 0.4 m dia. to over 5 m dia., but no rates of erosion are given.

Although most coastal karst studies are based on oceanic coastal zones, there are important documentations of freshwater coastal karst in temperate regions. There is a qualitative description of karstic pits on the drained floor of Lago di Loppio lake in Trentino, Italy (Perna, 1991), and several studies for the Bruce Peninsula region of Lake Huron, Ontario by McMaster students (Cowell, 1976, Hyatt, 1985, and Bell, 1986), where pitting is a dominant feature along the dolomitic coastline of the Bruce. This is especially true at Tobermory, where a variety of pit morphologies have been identified, in both subaerial and subaqueous rock formations, by Vajoczki (1993) and related to glacial eustatic lake levels and the coastal erosion processes associated with the spray zone of waves. Cowell proposed the possible role of rainwater as the primary agent in pit initiation, which he believed formed only above the lake's surface, but were enhanced in the littoral zone by the erosion processes. Enyedy-Goldner (1994) observed similar pitted littoral zones to that of the Bruce on Manitoulin Island (about 40 km north of the Bruce). She found several coastal locations of dolomite rock hosting high density, small, circular pits averaging 15 to 25 cm in width and 10 to 15 cm in depth.

The most extensive littoral karren, temperate studies have been undertaken in recent decades in Galway Bay, Ireland, the Bristol Channel, England and on Vancouver Island, B.C. and provide the basis for the littoral karren study performed along the shore of western Newfoundland. Thus, a more detailed review of these studies are necessary.

### 2.3.2 Galway Bay, Ireland

Models of littoral karren formation along the Burren coast, Galway Bay have been based on bioerosion of carbonate coastal rocks. Phytokarst have been observed in several ancient marine caves, which now lie within the current position of the intertidal zone, and are believed to have been formed by bioerosive algae (Simms, 1990). However, more detailed analysis have been performed for surface littoral karren by Williams (1971), Lundberg (1974 and 1977) and Trudgill (1987).

Williams (1971) produced transects at different sites along the coast, illustrating variations in karren morphology with different degrees of exposure and biological organism zonation. For example, for the most exposed site (Figure 2.4), he derives five littoral karren zones based on karren morphology which, in turn, are a function of the type and intensity of bioerosion within that zone, achieved by the dominant organism(s) inhabiting it. The delineation of these zones is somewhat arbitrary, since in reality there is a gradation of species distribution across the littoral zone and zonal boundaries are somewhat subjective. To illustrate this point, Lundberg (1974 and 1977) coalesced William's zones 4 and 5 for her Galway Bay model, believing that there is a limited transition from mussel- to echinoid-dominated pits.

Both Williams and Lundberg found maximum karren microrelief to occur in the mid-intertidal zone, in conjunction with barnacle and mussel species (*Chthamalus* and *Mytilus* respectively), although maximum rates of erosion were associated with echinoid erosion in the lower intertidal and subtidal zones. Lundberg also provided a detailed species description and complete morphologic karren summary for her four zones, with representative cross-sections and models of karren growth for individual pits.

Trudgill (1987) also produces transects across both exposed and sheltered coastal sites along Galway Bay, and defines three primary morphologic zones within the littoral zone (Figure 2.5). The lower intertidal zone is dominated by shallow, wide platform pools formed by the boring sponge *Cliona*, with scanning electron microscope (SEM) observations revealing evidence of chemical solution within pools not colonized by organisms. Maximum microrelief occurs in the mid-intertidal zone, up to 0.5 m depth, correlating with high concentrations of boring algae spp. and the existence of permanent pools of water, allowing further colonization of *Paracentrotus*, *Cliona*, and *Hiatella*. This then leads to further bioerosion and greater pinnacle development. The other defined morphologic zone occurs above the high water mark and is dominated by the lichen spp. *Xanthoria*, *Caloplaca*, and *Verrucaria*, producing high density pitting and a fretted or cockled surface.

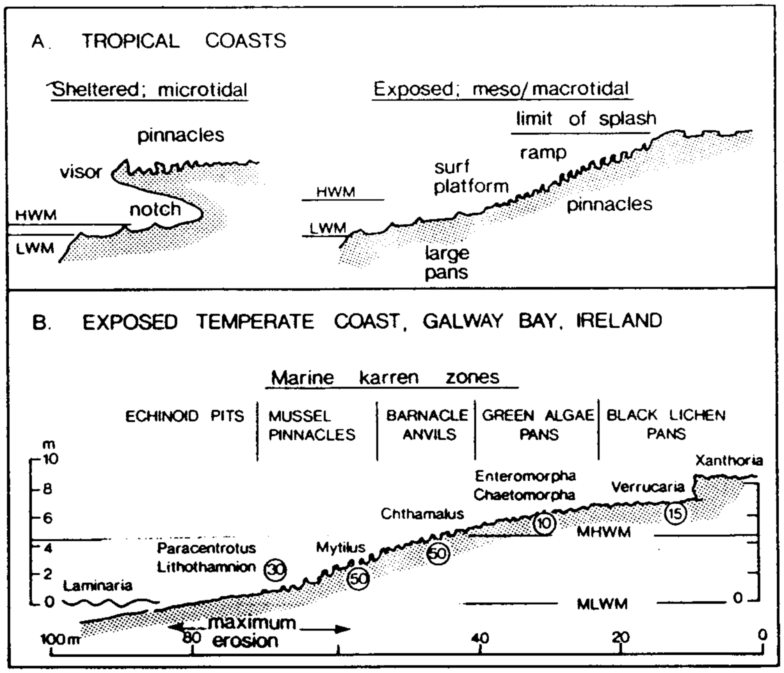



Figure 2.4 Transect of an exposed limestone coast in Galway Bay, Ireland. Latin names equal principal colonizing species, and circled numbers are local relief in centimetres (after Williams, 1971 and modified in Ford and Williams, 1989, p. 394).

### 2.3.3 Bristol Channel, England

Ley (1976 and 1979) undertook a detailed quantitative analysis of karren for twelve different foreshores in the Channel. He attempted to explain both intra- and intersite variations in karren development, not in terms of biological agencies, but by variations in geologic and marine factors including lithology, platform structure, degree of exposure, tidal range and sand supply. A similar research design is implemented for the western Newfoundland study, where there also exists a range of conditions. This is opposed to Galway Bay where the studies were undertaken for a limited number of sites, which possessed similar lithologies (i.e. Carboniferous limestone) and gentle, dip-sloping platforms.

Ley develops a calculus-derived landform shape index to quantify the shape of the surface,

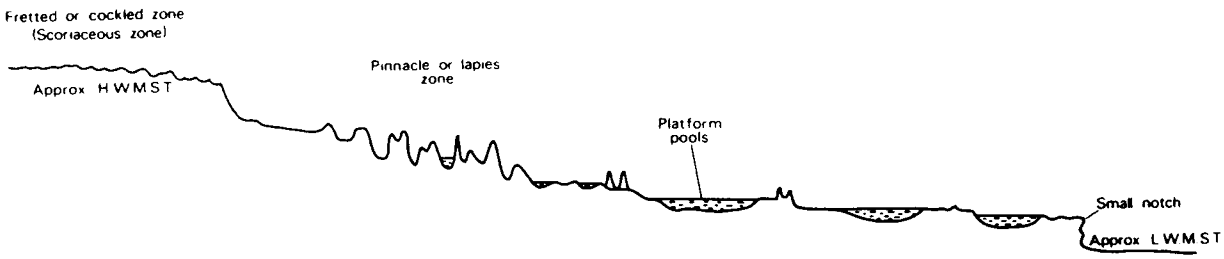



Figure 2.5 Schematic shore profile showing the principle morphologic zones for Co. Clare, Eire (from Trudgill, 1987, p. 112).

with increasing microrelief producing a higher index value. Results revealed that maximum karren development again occurred in the mid-intertidal zone, decreasing outwards in both directions. Ley attributed this intrasite karren variation to the tidal regime, which affects the distribution of the erosion processes along the littoral zone, with the mid-intertidal zone receiving maximum swash energy on a daily basis. Intrasite karren variation decreases with increasing tidal range, as larger tidal ranges will limit the duration of time of maximum swash activity at a given point (Sec. 2.2.4).

Ley then produces a multivariate model of karren development in an attempt to determine reasons for intersite variations, implementing representative shape indices for each platform as the dependent variable, and the above-mentioned geologic and marine factors as the independent variables, which are outlined in more detail in Table 2.4. It was found that the most important variables controlling karren development across the foreshores were insoluble residue and dip of the strata (Sec. 2.2.4), which determine rates of erosion of the carbonate strata. However, the magnitude of the erosion processes acting upon a given site, regardless of the geologic conditions, is governed by exposure factors, tidal range (which varies from 6.3 m to 12.3 m) and sand supply.

### 2.3.4 Vancouver Island, B.C.

Stephan (1987) studied the occurrence of littoral karren at Neroutsos Inlet, a sheltered site located in north Vancouver Island. The mean tidal range for the inlet is about 2.7 m (mesotidal),

Table 2.4 A list of the primary variables incorporated in Ley's (1976) multivariate model of karren variation along the Bristol Channel.

| Variables | Description |
| --- | --- |
| **Geologic Factors** | |
| Lithologic Properties | Insoluble Residue |
| | Porosity/Permeability |
| | Micro-lithological Variables (thin section properties) |
| Structural Controls | Strata Dip Angle and Direction |
| | Thickness of Strata |
| | Length of the Platform |
| | Backshore Slope |
| | Frequency and Direction of Jointing |
| | Height Control (i.e. relative height of the foreshores in relation to the tidal range) |
| **Marine Factors** | |
| Degree of Exposure | Regional Fetch |
| | Local Exposure Factor |
| | Biological Exposure Scale |
| | Pitting Exposure Scale |
| Offshore Slope (bathymetry) | |
| Proximity to Sand | |
| Tidal Range | |

which is significantly lower than that of Galway Bay (about 4.0 m average) and the Bristol Channel. Eight carbonate beds were examined along the eastern shore of the inlet.

It appears that a zonal pattern in terms of microrelief exists, with small pits at the lower intertidal zone, increasing in size towards the mid to upper intertidal zone, with the greatest range in karren dimensions occurring at the mid-intertidal level. However, pit morphology is consistent throughout the littoral zone, with constant width/depth ratios maintained throughout the transects.

# CHAPTER 3

# PHYSICAL BACKGROUND OF WESTERN NEWFOUNDLAND

## 3.1 Location of Regional Study Sites

The study area spans over three hundred kilometres of coastline along western Newfoundland, from the Port au Port Peninsula north to the Cook's Harbour region (Figure 3.1); specific sites are indicated where coastal outcroppings of carbonate rock host littoral karren. There are several carbonate rock formations of Lower Cambrian to Middle Ordovician age along the coast, with the occurrence of littoral karren being most associated with the St. George Group, the Cow Head Group and the Table Head Group limestones. The remainder of the coast is composed of non-carbonate rocks or shingle beaches. The major sites represented in Figure 3.1 can be grouped into four regions, i) the Port au Port Peninsula, ii) the Cow Head Peninsula region, encompassing the Cow Head Peninsula, Lower Head, Broom Point and Daniel's Harbour, iii) the Port au Choix Peninsula region, encompassing the Port au Choix Peninsula, Pointe Riche Peninsula, Ingornachoix Bay shoreline and the New Ferrolle Peninsula and, iv) the Cook's Harbour region in the north of the Northern Peninsula.

## 3.2 Geologic Formations Hosting Littoral Karren

### 3.2.1 Carbonate Platform Development for Western Newfoundland

Carbonate platforms are very large, complex depositional environments formed by the accumulation of sediment in an area of subsidence and/or sea level rise. Sediment production is directly correlated with the biodiversity of carbonate-secreting organisms which, in turn, are a function of the climate and oceanography of the region (Read, 1986; Tucker and Wright, 1990; James and Kendall, 1992). The growth potential of carbonate deposition and platform development

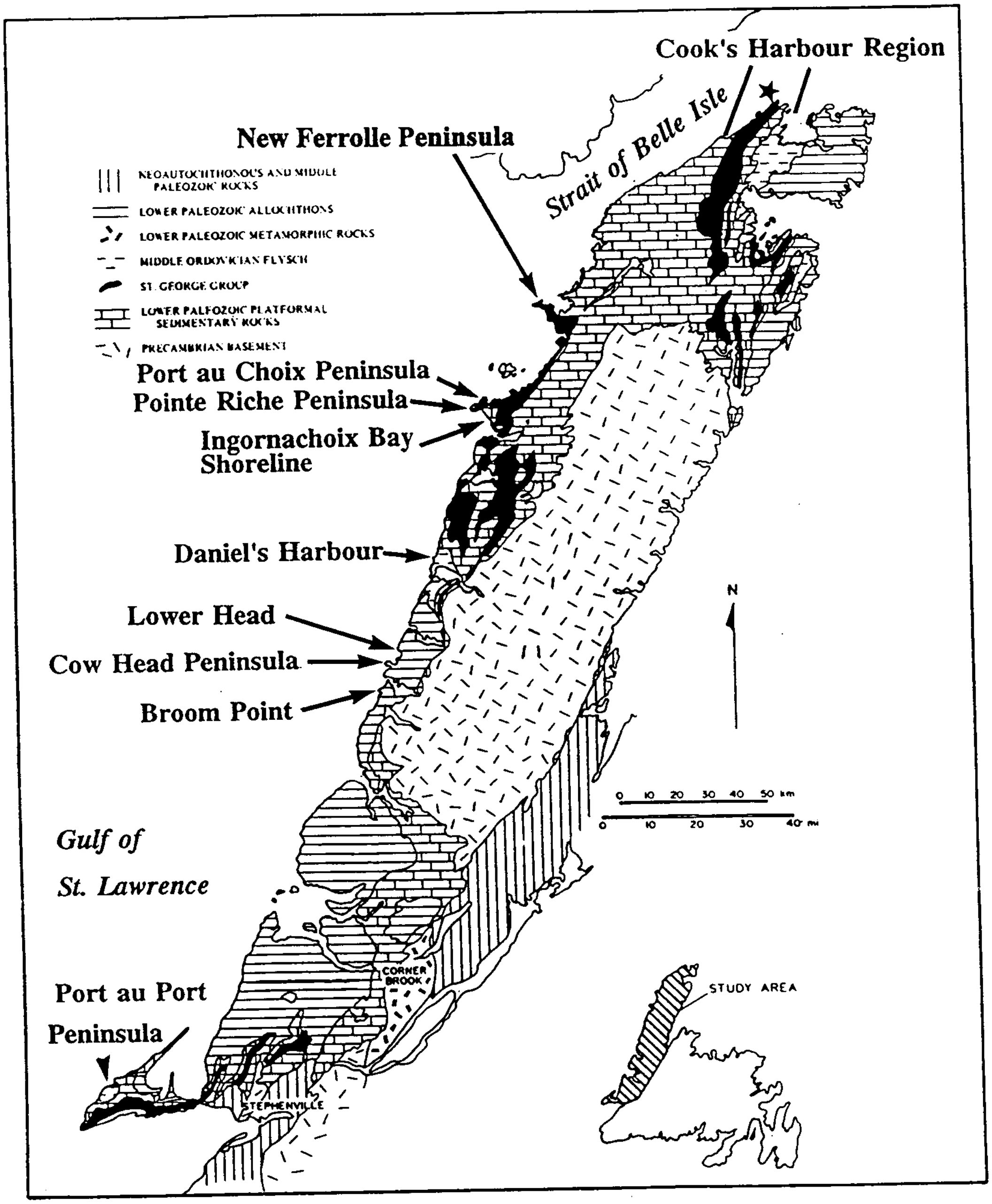



Figure 3.1 Geology of the study area along the coast of Western Newfoundland (modified after Knight and James, 1987, p. 1928), with specific sites indicated where there are littoral karren.

can change dynamically with time, interacting with changes in eustasy and tectonics, clastic sediment influx and antecedent topography (James and Kendall, 1992; Jones and Desrochers, 1992), as well as shelfal accommodation (Jacquin and Vail, 1995).

The St. Lawrence Platform, located along the northwest margin of the northern Appalachian Orogen, is responsible for the origin of the carbonate formations of the west coast of Newfoundland. It provides an excellent example of platform evolution in relation to eustasy fluctuations. James *et al.* (1989) define four phases and nine events of platform growth generally attributed to eustasy, from Early Cambrian to Late Ordovician time, where different environmental settings produce different sedimentation sequences in the geologic record (Figure 3.2).

Phase 1 involved initiation of a pre-platform shelf (Labrador Group) about 550 to 570 ma (Early through Middle Cambrian time). This phase coincided with the initiation of the new continental margin from the onset of seafloor spreading, producing basal sandstones (Bradore Formation - event 1) overlain by open-shelf sediments composed of limestone, shale, siltstone and minor sandstone (Forteau Formation - event 2). A eustatic fall in sea level then produced deposition of a thick offlap sequence of terrigenous clastics and minor carbonates (Hawke Bay Formation - event 3).

Phase 2 (Late Middle to the end of the Cambrian) saw the development of a high-energy, narrow carbonate platform about 200 km wide (Port au Port Group). At the same time deep water deposition of the allochthonous Cow Head Group of limestone conglomerates occurred. Sedimentation during this phase took place in two stages, separated by a eustatic lowering of sea level. The first stage (event 4) involved deposition of carbonate conglomerates with platform margin progradation. During the second stage (event 5) there was vertical accretion of quartzose carbonate turbidites.

Phase 3 was the evolution of a low-energy, wide-rimmed platform, producing the St. George Group of carbonates along with continued deposition offshore of massive limestone conglomerates of the Cow Head Group (Lower to Middle Ordovician). During event 6 the rate of carbonate sedimentation was roughly equal to that of relative sea level rise, producing peritidal formations (low energy tidal zone deposits; Watts Bight and Boat Harbour). The upper sequence (event 7) was

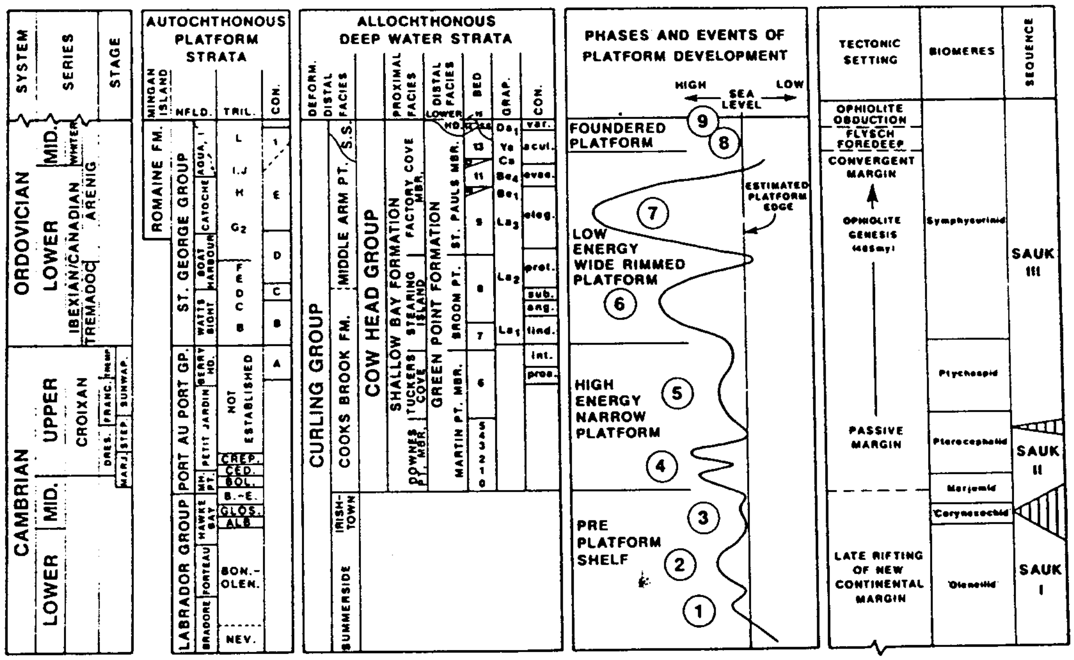



Figure 3.2 A diagram illustrating the chronostratigraphy and biostratigraphy of the different autochthonous and allochthonous sequences in western Newfoundland, along with the four phases and nine events of platform development with associated sea level history (modified after James *et al.*, 1989, p. 138).

mainly subtidal, represented by the upper part of the Boat Harbour Formation and the Catoche and Aguathuna Formations. This was a time of highest stand of sea level and onlap deposition was extensive, indicating a greater rate of carbonate sediment production than relative sea level rise.

Phase 4 saw the demise of the carbonate platform under tectonic forces, too complex to discuss in detail here. A period of subsidence during this time produced sedimentation of the Table Head Formation (Middle Ordovician - event 8), stratigraphically higher than the St. George Group, and recorded breakup and foundering of the outer platform. The inner platform was uplifted and underwent extensive karstification.

The carbonate formations that host the greatest littoral karren development are the autochthonous St. George Group, Table Head Group and, to a lesser extent, the Codroy Group, as well as the allochthonous Cow Head Group of deep water carbonates. For this reason these formations will be discussed in more detail.

### 3.2.2 St. George Group

The St. George Group refers to cyclic deposits of limestones, dolomitic limestone and dolostones, upon the Early Ordovician continental shelf (Figure 3.2), with an aggregate thickness of about 600m. They outcrop at many locations along the west coast of Newfoundland (Figure 3.1). The literature suggests an environmental setting of tide-dominated epeiric seas (shallow, inland seas) during this time, producing shallowing-upward sequences of tidal deposits (Pratt and James, 1986; Knight and James, 1987). Lithologic evidence for such an environment includes alternating sequences of thin-bedded muddy and grainy carbonates, vertically aggrading into one another, possessing flaser (mud laminae), lenticular and wavy bedding (0.2 to 3 m thick), as well as the presence of stromatolites (about 0.6 m relief and an avg. dia. of 1 m.), local bioturbation, patch reefs and oolites, and rare evaporites within these formations (Tucker and Wright, 1990). There is also the occasional presence of thick, massive-bedded units (up to 3 m thick) of a high energy marine origin, interbedded with low energy tidal flat carbonate deposition, indicating deposition on a shelf edge along the margins of a sea (Cumming, 1983).

Pratt and James (1986) propose a tidal flat island model of carbonate deposition, with specific reference to the St. George Group (Figure 3.3). In the epeiric sea, which existed during this time, there were low-relief islands (less than 10 km in size) and banks built up by the local tidal regime representing small-scale peritidal cycles; they produce several laterally discontinuous sub-, inter- and supratidal deposits arranged in shallowing-upward units (only a few metres thick). These islands accreted vertically and migrated laterally in response to the supply of local sediment and changing regional hydrographic conditions, instead of fluctuations in the rates of relative sea level change.

### 3.2.3 Table Head Group

The Table Head Group lies stratigraphically higher than the St. George Group, forming during Middle Ordovician times (Figure 3.2), with an aggregate thickness of about 530 m. There are outcrops along the Strait of Belle Isle coastline, the Pointe Riche Peninsula, Ingornachoix Bay shoreline and most of the Port au Port Peninsula (Figure 3.1). The Table Head Formation is a relatively uniform lithological unit, composed of crystalline, fossiliferous limestone and, in general, represents characteristics of subtidal open marine environments (Cumming, 1983).

Klappa *et al.* (1980) and Stenzel *et al.* (1990) describe the formation of the Table Head Group in three stages related to development of a foreland basin. The first stage involved fragmentation and uplift of an existing carbonate platform, with subsequent deposition of shallow-water carbonates on an unstable shelf. The second stage involved breakup of the new platform and, either, deposition of deep water sediments directly upon the shallow-water limestones or the creation of submarine topography, with resultant sediment gravity flows burying the foundered blocks with conglomerates from older shelf carbonates. This foreland basin succession was then uplifted in the third stage, generating carbonate debris flows and turbidity currents offshore.

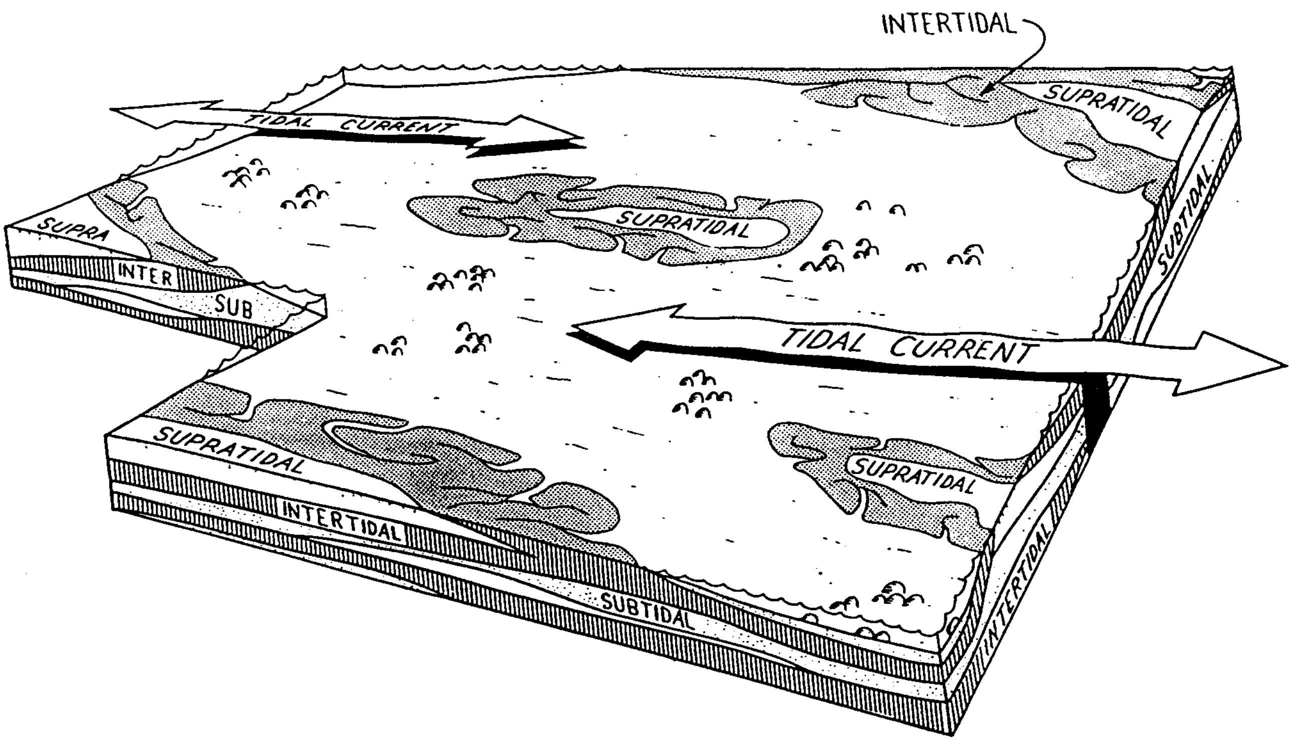



Figure 3.3 Hypothetical, three-dimensional reconstruction of a portion of an epeiric sea, showing five low-relief islands, oriented parallel to the tidal currents, with the possible stratigraphic record of laterally discontinuous sub-, inter- and supratidal deposits (from Pratt and James, 1986, p. 340).

### 3.2.4 Codroy Group

The Upper Mississippian Lower Codroy Group outcrops along portions of the south-southwest coastline of the Port au Port Peninsula, stratigraphically overlies the Table Head Group of carbonates and has an aggregate thickness of 85 to 102 m. As discussed in Dix and James (1989), the lithologies of the major formations are quite wide-ranging, reflecting varying environments of deposition. There was alluvial fan deposition (terrestrial) producing red beds of the Lower Cove Formation (about 15 m thickness). A warm, shallow water to marginal marine setting then yielded biohermal and conglomerate carbonates of the Big Cove Formation (about 50 to 53 m thick). A subtidal, hypersaline to brackish, setting initially produced laminated and conglomerate limestones of the Ship Cove Formation (about 8 m thick), which were subsequently overlain by thick gypsum (evaporite) deposits of the Codroy Road Formation (12 to 26 m thick), once hypersaline (high salinity) conditions were established.

### 3.2.5 Cow Head Group

The allochthonous Cambro-Ordovician Cow Head Group outcrops in the Cow Head Peninsula region and at Broom Point (Figure 3.1). It consists of a 300 to 500 m thick sequence of deep-water limestone conglomerates and shale (Coniglio and James, 1990). The conglomerates are classified into five facies (Hiscott and James, 1985, p.736-738; James and Stevens, 1986, p.43-49; Figure 3.4), based upon grading, sedimentary structures, matrix content, sorting, fabric and clast type. There are also clasts, within the limestone conglomerates, of dolomite, chert and calcium phosphate granules and pebbles (James and Stevens, 1986).

Facies A are grainy, pebble to cobble conglomerates that have cross-stratified and ripple-laminated tops, grading from calcarenites with 10 to 20% platy clasts, to true conglomerates with 10 to 20% calcarenite matrix. Facies B is composed of poorly sorted limestone plates in a matrix of argillaceous and/or carbonate mudstone. The matrix comprises 10 to 20% volume with a chaotic fabric. Clast size ranges from cobble- to boulder-sized "rafts" of ribbon or parted muddy limestones. Facies C consists of limestone chip conglomerates, where the matrix comprises less than 10%

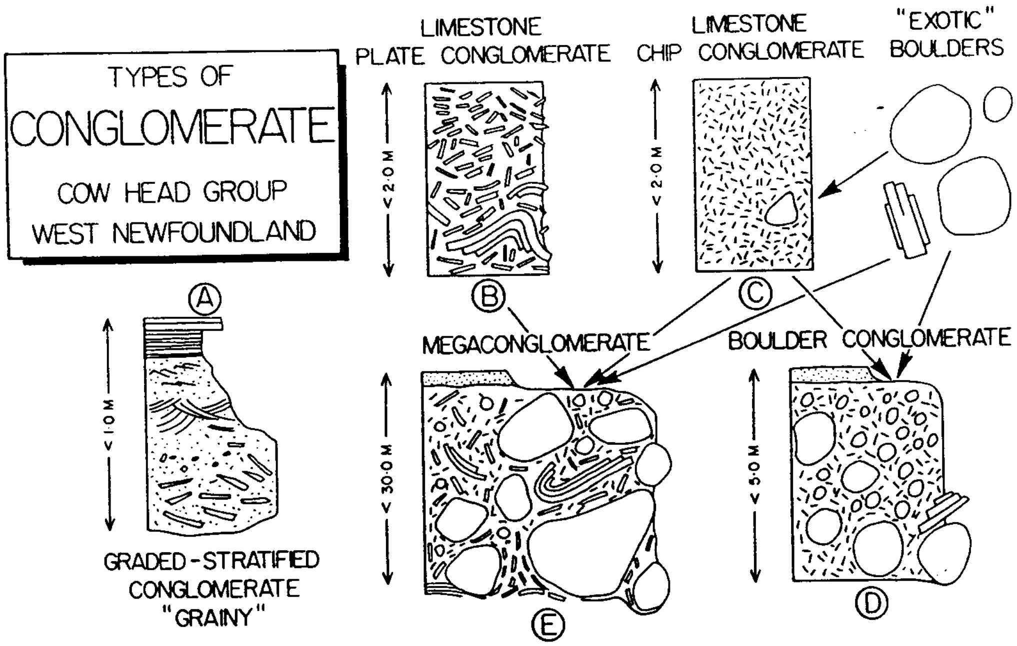



Figure 3.4 Classification of limestone conglomerate facies of the Cow Head Group. Note that the limestone plate and chip facies (B+C), along with exotic boulders, are end members, which combine to produce the mega and boulder conglomerate facies (E+D; from Hiscott and James, 1985, p. 736).

volume and is composed of finely crystalline calcite, dolomite or argillaceous lime mudstone. The clasts are generally pebble- to cobble-size, with no obvious fabric or grading. Facies D are the boulder conglomerates with the same matrix, fabric and grading as facies C, but the clasts are cobble- to boulder-size and have originated from outside the depositional environment. Facies E are the megaconglomerates and are the thickest, muddiest and most chaotic of the different facies. The matrix consists of green terrigenous mud and/or large blocks of a shaly substrate.

It is clear in the literature that the Cow Head Group of carbonates was formed in deep water, as a base-of-slope sediment apron of carbonate and shale, from Middle Cambrian through Middle Ordovician time. The base-of-slope apron model refers to the deposition of shallow-water debris into the basin, originating from the whole platform margin (Tucker and Wright, 1990). Although the depositional history of the Cow Head Group is not entirely clear, it appears that debris flows and closely associated turbidity currents, were the primary transport mechanism of the carbonates offshore from the platform margin (Hiscott and James, 1985; James and Stevens, 1986; Coniglio and James, 1990).

Debris flows occur when a critical shear stress has exceeded the yield strength of the debris (Blatt *et al.*, 1980), while turbidity currents refer to a gravity flow of water containing suspended sediment, in which the sediment is supported by a component of turbulence (Walker, 1992). Debris flows are responsible for transporting the poorly sorted conglomerates described above, and turbidity currents deposited the finer-grained sediments which can be carried in suspension. Coniglio and James (1990) argue that the fine-grained mudstones, shales and siliclastics of the Cow Head Group can be explained by turbidite deposition, but are also formed by early diagenesis of adjacent argillaceous sediments.

## 3.3 Glacial History of Western Newfoundland

### 3.3.1 Quaternary Glaciation of Newfoundland

The Quaternary Period is believed to have started about 2.5 ma BP. It was a time of intense glaciation over much of North America and Europe. In North America the most recent glacial period is the Wisconsinan, marking the end of the Pleistocene and the beginning of the warmer Holocene Epoch. Most of the available evidence used to reconstruct glacial patterns and history is provided by the Wisconsinan records of glacial advance and retreat.

The Wisconsinan glaciation began about 70 ka BP and was at its maximum 21 ka BP, when northern North America was almost completely blanketed by the huge Laurentide Ice Sheet or the western Cordilleran Ice Sheet (Pielou, 1991). All of Newfoundland was covered by ice at some time during the Quaternary, but it is generally agreed that it was not affected much by the main Laurentide Ice Sheet (Brookes, 1970, 1972 and 1982; Rogerson, 1982; Grant, 1977, 1987 and 1989; Tucker and McCann, 1980; Quinlan and Beaumont, 1982). Instead, Newfoundland was covered by a number of smaller, local ice caps, separated from the Laurentide ice sheet by an ice-free Gulf of St. Lawrence. The Laurentide Ice Sheet occupied only the northern region of the Northern Peninsula near Labrador.

From summaries in Rogerson (1982) and Grant (1989), the main centres of ice over the island were located on the Avalon Peninsula (southeast region), Northern Peninsula and the central part of the Newfoundland Uplands (centre of the island). These centres are believed to have expanded, radiating outwards, at least four times during the Wisconsinan, covering most of the island at one point or another except for some high coastal and inland summits (nunataks). There is no consensus in the literature on the extent of glacial advance in Newfoundland, but glaciers did not extend far from present coastlines. Deglaciation commenced around 13 ka BP on the island and was completed by 8 ka BP.

### 3.3.2 Response to Deglaciation: Sea Level Change for Western Newfoundland

Reconstructing relative sea level change (RSL) for Newfoundland during the Holocene is not straightforward, due to the effects of glacio-isostatic rebound, although local tectonics are not a factor because Atlantic Canada rests upon a passive margin (Scott *et al.*, 1987). The term isostasy relates to the state of equilibrium that the earth's crust maintains with the underlying mantle (Summerfield, 1991). Glacio-isostasy is one form of isostatic adjustment; the large continental ice sheets, which covered much of the land during the Wisconsinan, greatly increased the weight of the crust causing it to subside lower into the mantle. As the ice sheets started to melt and recede, this added load on the local crust was removed and the crust rebounded.

Attempts to determine post-glacial changes in relative sea level must take into account crustal rebound, which will vary from region to region depending on location with respect to an ice centre. Quinlan and Beaumont (1981) produced a quantitative model of RSL zones for Atlantic Canada, based on maximum ice advance and related crustal rebound, during the Late Wisconsinan. This was subsequently modified by Scott *et al.* (1987) based on field data (Figure 3.5), provided

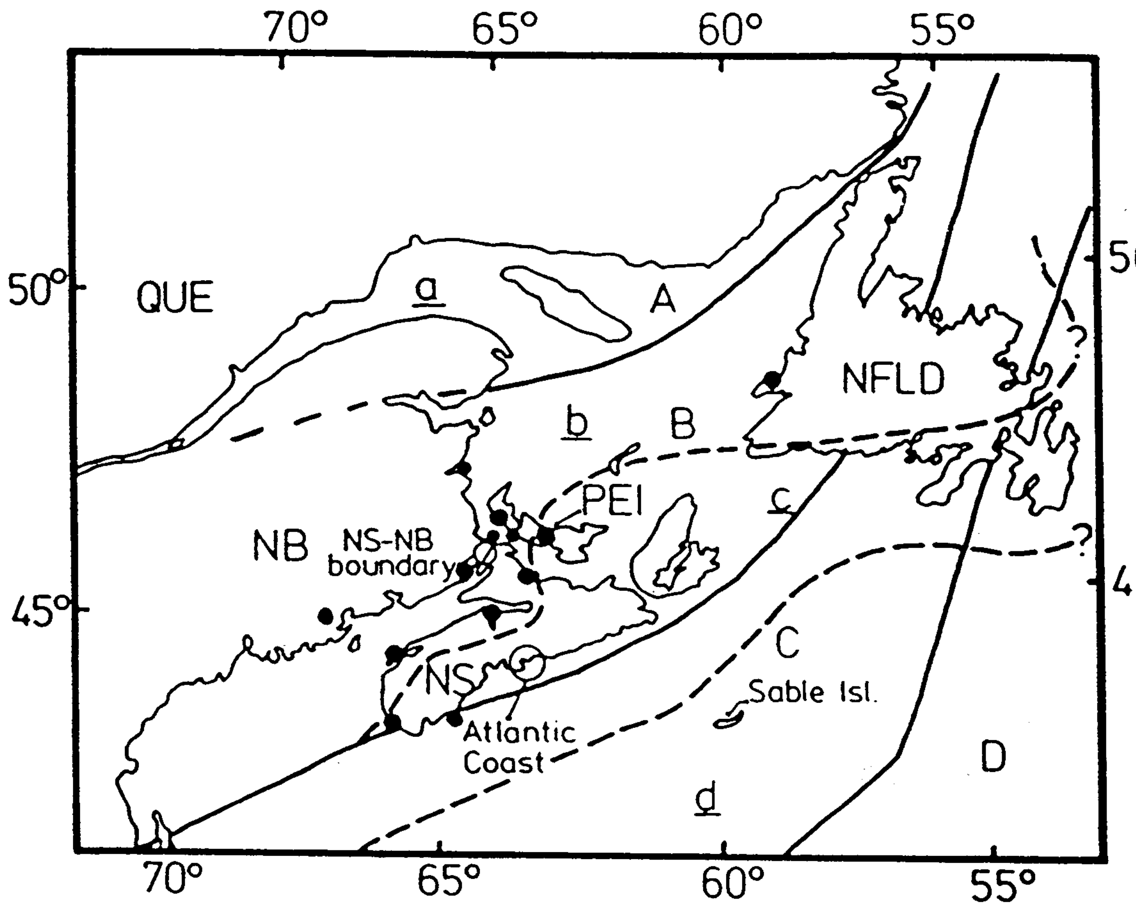



Figure 3.5 Theoretical sea level zones for Atlantic Canada based on Quinlan and Beaumont's 1981, maximum ice load model during the Late Wisconsinan glaciation (solid lines, capital letters), modified on the basis of field observations (dashed lines, small letters). Dots represent sites of available RSL curves (from Scott *et al.*, 1987, p. 88).

by foraminiferal zonations recorded in thick salt marsh sequences throughout the region, which give a measure of RSL change during the Holocene.

The west coast of Newfoundland, including all major regions in this study, is within zone B of the Scott *et al.* (1987) model. This zone was inside the former ice margin and underwent substantial crustal rebound during deglaciation. It was also affected by the migration of a peripheral bulge as the rebound was occurring. This peripheral bulge is believed to have formed when the ice load forced mantle material out from beneath the ice sheet to its periphery (Quinlan and Beaumont, 1981). The peripheral bulge then migrated with the ice sheet as it retreated. The resultant effect on RSL change was one of substantial RSL fall during most of the Holocene, producing a number of raised marine features, followed by a late RSL rise that continues to the present day.

There are only a few published documentations of regional RSL changes for western Newfoundland, confirming its status within zone B. Most published work focuses on the Port au Port Peninsula region, especially Port au Port Bay and St. Georges's Bay south of the peninsula (Figure 3.13; Brookes, 1977; Brookes *et al.*, 1985; Shaw and Forbes, 1990; Forbes *et al.*, 1993; Shaw and Forbes, 1995). The published interpolated RSL curve by Brookes *et al.* (1985) corresponds to the zone B pattern of sea level change deduced by Scott *et al.* (1987; Figure 3.6). From Figure 3.6 it is apparent that RSL dropped from about 13 ka BP to a lowstand position at -11 to -14 m, after which RSL rose, at a decreasing rate, towards the present level. The migration of the peripheral bulge (Liverman, 1994) and the rise associated with the increased water volume from glacier meltwater acted to overcome the rates of isostatic rebound (Shaw and Forbes, 1995). From 5.8 ka BP to 2.8 ka BP RSL rose a rate of about 32 cm/century; after 2.8 ka BP the rate declined to about 7 cm/century. Since the publication of this RSL curve, increased data collection has revealed a post-glacial sea level lowstand occurring at 9.5 ± 1 ka BP, not 5.8 ka BP, when sea level was 25 m below present water depth (Shaw and Forbes, 1995).

The only other published RSL curves for western Newfoundland are along the Strait of Belle of the Northern Peninsula by Grant (1980; 1989; 1992). The post-glacial RSL history for this coastline is one of continuous emergence (i.e. constant RSL fall), due to a more direct influence of

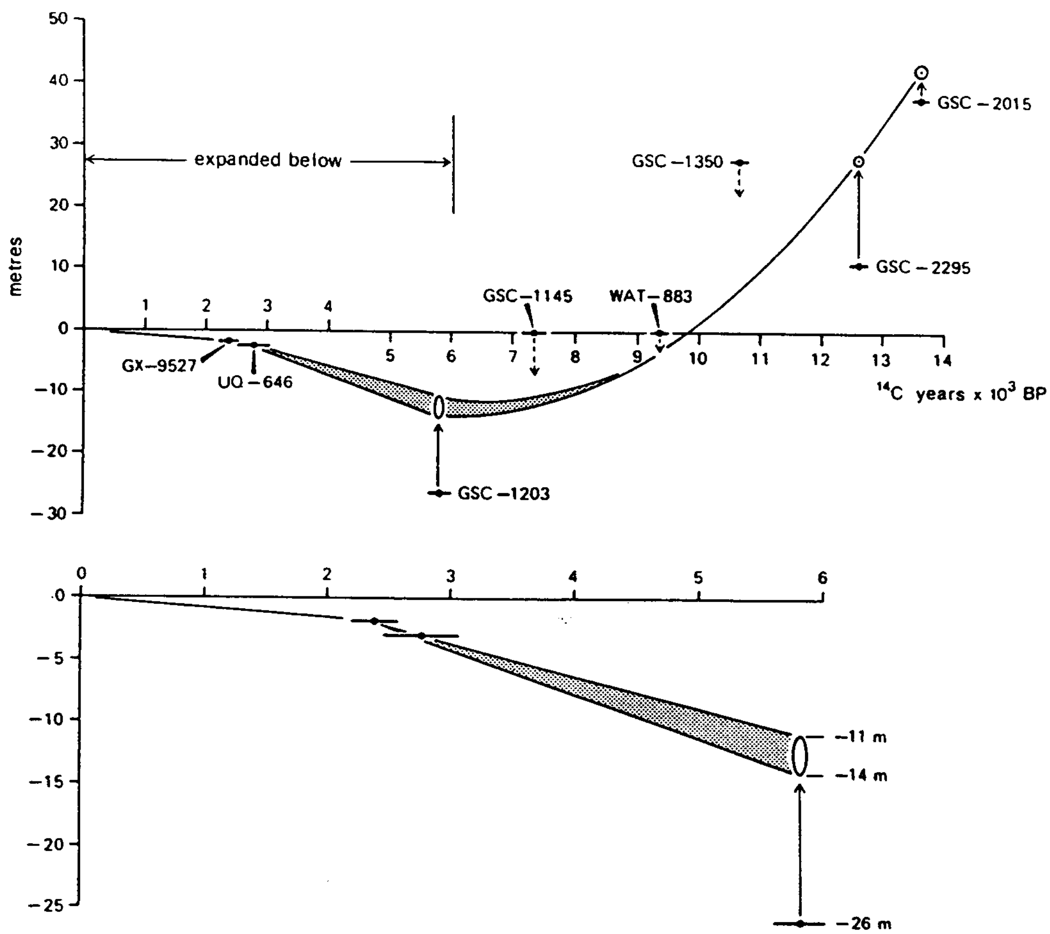



Figure 3.6 Postglacial RSL history for Port au Port and north St. George's Bay, adjacent to the Port au Port Peninsula, western Newfoundland (from Brookes *et al.*, 1985, p. 1044)

the Laurentide ice sheet on the area. This is contradictory to the zone B pattern of RSL change for western Newfoundland by Scott *et al.* (1987; i.e. zone A). Grant proposed two trends in the rate of RSL fall for the region; the first phase began at 12.8 ka BP with RSL falling at a rate of 4.3m/century up to 5 ka BP, at which point the rate of RSL fall slowed to 0.14m/century. This suggested pattern of RSL change for the Northern Peninsula extends just south of the Port au Choix Peninsula (Figure 3.1; Liverman, 1994) and, therefore, encompasses the Port au Choix Peninsula region of this study.

By dating several *Hiatella* shells within boreholes, Brookes and Stevens (1985) determined the position of RSL for the Cow Head Peninsula region to be 8 m asl about 8.25 ka BP. Unfortunately, post-glacial patterns of RSL change remain unknown for this area, due to a lack of data collection.

The effect of eustatic variation on coastal karst landform development and cave genesis is well established (Ford and Williams, 1989; Mylroie and Carew, 1990; Lips, 1993). RSL changes may be an important long term process in relation to the occurrence of karren at a coastal site. There are several instances of raised karren to be found at many of the study sites in Newfoundland: they are 20 m or more asl and are too distant from the contemporary shoreline to be affected by the erosion processes even during storm activity. They probably were formed when RSL, and the littoral zone, was at that location early in the Holocene before RSL significantly dropped. No attempts, however, were made to quantify this proposed correlation. Most of the karren analysed in this study are affected to some degree by the modern erosion processes and the current position of the littoral zone.

## 3.4 Climate of Western Newfoundland Study Regions

### 3.4.1 Introduction

The climate of Newfoundland is affected by a number of factors associated with a maritime environment. The cold Labrador Current from the north and the warm Gulf Stream originating in the Gulf of Mexico, have significant roles in air mass movement over the region and the duration of sea ice cover during the winter (Brookes, 1972). Winter temperatures are lowered by the presence of sea ice, enhan cing the effects of arctic air masses from the northwest, while summer temperatures are somewhat moderated by cooler offshore water temperatures, during times when the island is affected primarily by maritime tropical air masses from the south.

### 3.4.2 Temperature and Precipitation

Because the study area spans over 300 kilometres of coast, there is some variation in climate. Monthly climographs of temperature and precipitation for Stephenville (Port au Port Peninsula), Rocky Harbour (Cow Head Peninsula region), the Port au Choix Peninsula region and St. Anthony (Cook's Harbour region) are presented in Figure 3.7. The moderating effect of the ocean is evident for all sites, as there is not a great range in mean monthly temperature or precipitation. The temperature rarely falls below -10°C in the winter and seldom exceeds 18°C in summer. Note that there is a 3.1°C difference in the mean annual temperature between Stephenville (the most southerly station) and St. Anthony which is 3° latitude further north and more affected by the Labrador Current. Sea ice is usually present in the St. Anthony and Strait of Belle Isle region for at least four months, during which time strong northeast winds blow over the region; the Port au Port Peninsula region is generally free of ice year round (Dept. of Fisheries and Oceans, 1986).

All of Newfoundland receives significant precipitation throughout the year, either in the form of rain or snow. The weather is often very damp and/or foggy. The four study regions are similar in the amounts of precipitation they receive on a monthly basis. The Port au Choix Peninsula region (Figure 3.7) is the 'driest', receiving 1042.30 mm mean annual precipitation, while the Cow Head Peninsula region (the wettest) annually receives almost 1200 mm total precipitation. All regions can expect at least 60 mm of precipitation every month, as it is not uncommon for precipitation to fall for at least half of the month. Precipitation is greatest in the winter, especially November through January, which is related to intense winter storms which track through the region. The west coast is subjected to some of its most violent storms during November and December (Payne, Pers. Comm., 1991). Spring and summer are the driest times of the year, especially the

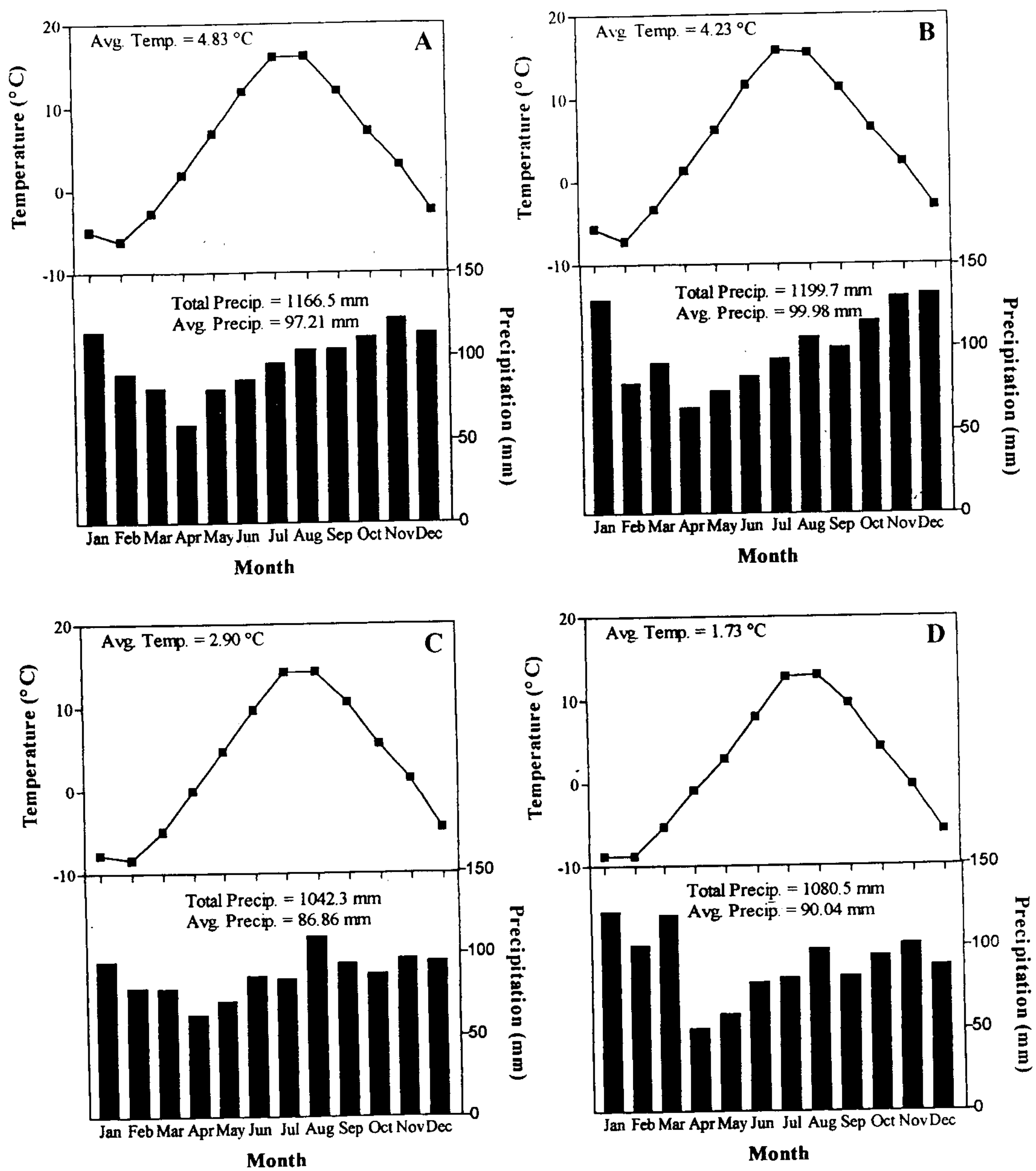



Figure 3.7 Monthly climographs of temperature and precipitation for the four primary study regions along the west coast, for the period 1951-1980 (data from Environment Canada, 1982a). A) Stephenville, B) Rocky Harbour, C) Port au Choix Peninsula region, using available data from stations at Daniel's Harbour and Plum Point, both of which are approximately equidistant from Port au Choix, and D) St. Anthony.

months of April and May.

### 3.4.3 Wind

Wind data are available for the larger centres along the west coast. Representative wind rose diagrams are presented in Figure 3.8 for Stephenville, Daniel's Harbour and the St. Anthony region. At all stations WSW winds are dominant in terms of the frequency of occurrence. There is a secondary strong frequency of NNE winds and very infrequent winds from the SSE. This is no doubt related to the coastal effects on local circulation patterns, with prevalent onshore winds blowing from the southwest onto the west-facing coast.

Wind frequency does not always correlate with velocity, however, as the strongest winds may not come from the dominant wind direction. Table 3.1 displays average annual wind speeds for the three stations; it is clear that the highest wind speeds are associated with the direction of maximum fetch (Sec. 2.2.1). For Daniel's Harbour (the station with the highest average wind speed and lowest percentage of calm days) and Stephenville the highest wind speeds correlate with the dominant SW wind. In the St. Anthony region, however, the strongest winds come from the NNE, as this station was located in the area of Pistolet Bay (Figure 3.1, Environment Canada, 1982b), where the greatest fetch is towards Greenland several hundred kilometres away. Winds coming from the WSW are still quite strong, but somewhat dampened by the land barrier separating the station from the west coast. Winds from the ESE have the lowest average velocity, due to obstruction by the Long Range Mountains, which extend through most of the Northern Peninsula.

Wind frequency and velocity are important indirect factors with respect to karren development at a given site. Winds help to determine the wave climate of a coastal region and the strength of marine erosion processes acting upon carbonate coasts (Sec. 2.2.1), in turn affecting the colonization of marine organisms and rates of bioerosion (Sec. 2.2.4). With this in mind it would appear from the wind data presented here, that the winds at Daniel's Harbour and the St. Anthony region are the most favourable for karren erosion. Stephenville has the lowest average wind speed for all directions and the greatest percentage of calm days, thus, wave energy at the Port au

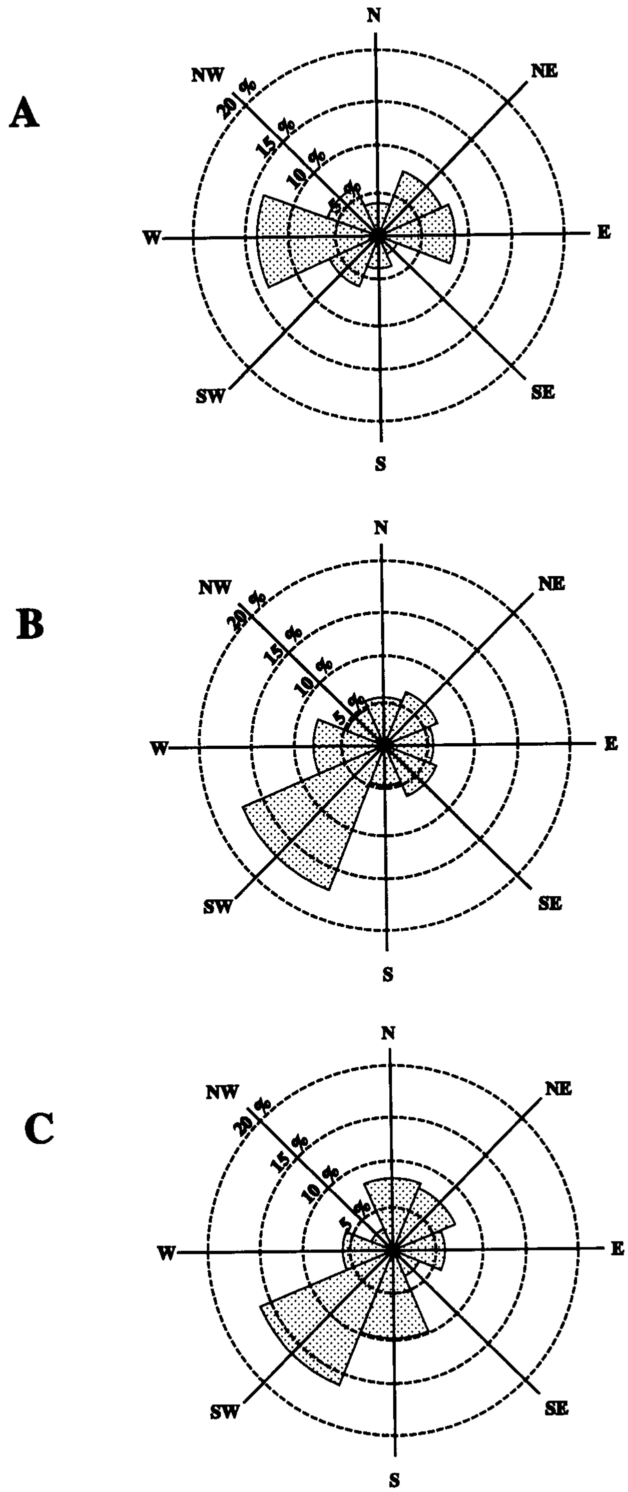



Figure 3.8 Windrose diagrams of annual wind frequency, 1955-1980, for A) Stephenville, B) Daniel's Harbour and C) the St. Anthony region (data from Environment Canada, 1982b).

Table 3.1 Comparison of mean annual wind speed for Stephenville, Daniel's Harbour and the St. Anthony region (data from Environment Canada, 1982b).

| Wind Direction | Stephenville (km/hr) | Daniel's Harbour (km/hr) | St. Anthony (km/hr) |
|---|---|---|---|
| N | 14.3 | 17.3 | 23.0 |
| NE | 11.6 | 18.3 | 20.6 |
| E | 18.0 | 15.2 | 16.4 |
| SE | 16.0 | 18.4 | 19.8 |
| S | 16.5 | 17.0 | 16.9 |
| SW | 18.5 | 32.2 | 20.6 |
| W | 19.5 | 24.1 | 19.6 |
| NW | 17.3 | 18.9 | 16.4 |
| Average | 16.5 | 20.2 | 19.2 |
| Percent Calm | 10.8 | 1.3 | 2.6 |

Port Peninsula is probably not as strong as for the other regions. It should be noted that the Port au Port Peninsula does have a very exposed Gulf (south and west) shore, where wave energy would be higher than the very protected shores of Port au Port Bay.

## 3.5 The Marine Environment

### 3.5.1 Degree of Exposure

Degree of exposure refers to the extent that a coastal area is exposed to the open marine environment and maximum force from wave energy and erosion processes. Exposure to the direction of maximum fetch and the coastline configuration are the most important factors in determining the available wave energy at a coastal site, especially since the strongest onshore winds are often associated with the direction of maximum fetch in coastal areas.

Figure 3.9 displays the direction and length of maximum fetch for the four major study regions. The direction of maximum fetch for the Port au Port Peninsula (approx. 450 km), the Cow Head Peninsula region (approx. 610 km) and the Port au Choix Peninsula region (approx. 680 km) is southwest towards New Brunswick. This is correlated with the dominant wind direction and/or velocity (Sec. 3.4.3) at these sites. It is also easy to see that wave energy will be reduced with a northwest wind, because fetch is limited at all sites except the Port au Port Peninsula. Maximum fetch for the Cook's Harbour region, along the coast of the Strait of Belle Isle, is NNE towards Greenland (approx. 500 km) and northeast towards Iceland (approx. 1000 km). The coast at the northern tip of the region may be affected by east winds, which are not obstructed by any land barriers across the Atlantic Ocean.

A rough indication of the available wave energy at a given site can be obtained from the presence and size of beach shingle, with larger shingle diameters expected with longer fetches and higher wave velocities. Shingle was found throughout most of the sites, either as part of a storm berm in the backshore, or scattered about upon the scarp-face platforms on the carbonate rock. Representative samples of shingle were measured for long and short axial dimensions at, or near, areas where profiles were constructed. Critical threshold velocities ($\tau_{crit}$), necessary to move sediment and shingle in coastal environments have been established for waves and wave-generated currents (e.g. Komar, 1976). However, their calculation requires complicated measurements of the maximum orbital velocity produced by the waves and/or current velocity 1 m above the bed in a shallow marine setting, something that was not undertaken in this study. Direct relationships between $\tau_{crit}$ and mean grain diameter, in shallow marine environments, have been defined (see Gardiner and Dackombe, 1983, p.197), but are not applicable to the complex movement of swash water and storm waves involved with sediment transport towards the backshore (Middleton, Pers. Comm., 1994).

As a consequence, another method was sought to provide at least an approximate quantification of the available wave energy present within the various regions. There have been many beach profile studies involving the relationship between grain size and beach gradient

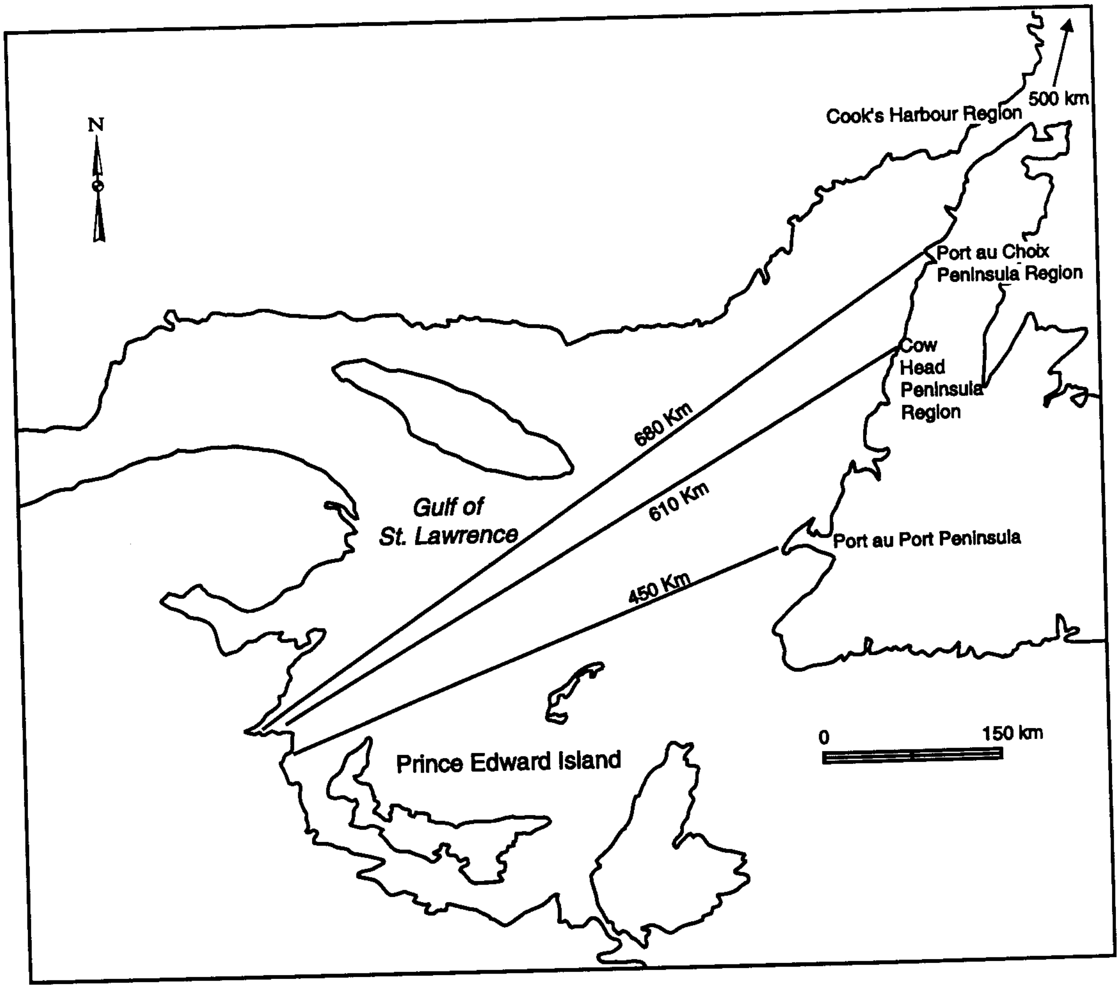



Figure 3.9 Distance and direction of maximum fetch for the four major study regions of western Newfoundland.

(Pethick, 1984). These studies relate sediment transport to the work performed by onshore and offshore water movement. The amount of sediment moved in either direction can be represented by its weight, and it has been shown that estimates of onshore and offshore work, across the beach profile, can both be calculated using the following equations (Pethick, 1984)

$$\text{onshore work} = (\text{sediment weight}) \times (\tan\theta + \tan\beta) \times s \tag{3.1}$$

and

$$\text{offshore work} = (\text{sediment weight}) \times (\tan\theta - \tan\beta) \times s \tag{3.2}$$

where
$\tan\theta =$ angle of internal friction (intergranular)
$\tan\beta =$ beach gradient
$s =$ distance sediment is moved

This model is applied to the coastlines of western Newfoundland, to provide an estimation of onshore work necessary to move the shingle across the platforms. Table 3.2 presents the data required to calculate this estimation of onshore work for the shingle found at different coastal settings. Note that tan $\theta$ was dropped from the equation, because it only applies to sediment transport across sand and gravel beaches, and not to the movement of shingle across carbonate rock platforms being studied here. Sediment weight was not measured in the field, but was estimated using an average specific gravity value for sedimentary rocks of 2.65, multiplied by the average volume of the shingle for that coastline (the majority of shingle was sedimentary). Volume is determined using average diameter of the shingle (long and short axis), which is considered to be roughly the same diameter as that of a sphere (Blatt *et al.*, 1980), so that

$$V = \frac{4}{3}\pi r^3 \tag{3.3}$$

where
$V =$ volume $cm^3$
$\pi =$ pi
$r =$ radius

Table 3.2 Average weight of beach shingle, onshore gradient, distance from the mean low water mark (MLWM) and estimated onshore work involved in moving the shingle across the littoral zone for the major study regions.

| Region (direction and distance of maximum fetch for that shoreline in km) | Average Shingle Weight (g) | Gradient ($\beta$) | Tan $\beta$ | Distance from the MLWM (m) | $\Delta E$ (N m$^{-1}$) |
|---|---|---|---|---|---|
| Cook's Harbour Region (NNE - 500) | 788.13 | 2.43 | 0.043 | 80.00 | 2711 |
| Ingornachoix Bay (SW - 700)* | 1178.40 | 3.05 | 0.053 | 60.00 | 3747 |
| Ingornachoix Bay (cove WSW - 150) | 108.03 | 5.45 | 0.10 | 22.00 | 238 |
| Pointe Riche Peninsula (WNW - 75) | 144.06 | 0.69 | 0.01 | 100.00 | 144 |
| Pointe Riche Peninsula (SW - 700)* | 2326.45 | 2.29 | 0.04 | 85.00 | 7910 |
| Port au Choix Peninsula (ENE - 3.5) | 295.23 | 6.65 | 0.12 | 18.00 | 96 |
| Port au Choix Pen. (N - 80) | 295.23 | 4.57 | 0.08 | 30.00 | 709 |
| Port au Choix Pen. (W - 110) | 48.07 | 2.58 | 0.05 | 40.00 | 638 |
| Cow Head Peninsula (WSW - 340) | 384.58 | 3.43 | 0.06 | 75.00 | 1731 |
| Cow Head Pen. (N - 170) | 35.98 | 3.45 | 0.08 | 25.00 | 100 |
| Cow Head Pen. (S - 2) | 81.05 | 2.00 | 0.03 | 11.50 | 28 |
| Port au Port Peninsula (NNE - 350) | 1116.07 | 5.48 | 0.10 | 25.00 | 2790 |
| Port au Port Peninsula (NNE - 325) | 374.06 | 5.48 | 0.10 | 25.00 | 935 |

* coastline is exposed to maximum fetch and wind velocities for that region (shore-normal orientation)

For example, average shingle diameter for the Cook's Harbour region is 8.28 cm. By using equation 3.3 the corresponding volume of this shingle averages 297.23 $cm^3$ and, when multiplied by the specific gravity (2.65), produces an average weight of 788.13 g.

Gradient ($\beta$) measures the angle of slope from the mean low water mark (MLWM) to the shingle location, using the shore-normal profiles constructed for that site, which provide both a distance and height measure necessary for calculating gradient.

$$\beta = \frac{\text{elevation}}{\text{distance}} \sin^{-1} \tag{3.4}$$

Due to the complex nature of the platform morphology, often evident at the different sites, these gradients have been simplified to represent an idealized uniform slope.

The amount of energy lost due to bed friction and water percolation into the beach is proportional to the amount of work performed (Inman and Bagnold, 1963) so that

$$\Delta e_{\text{onshore}} = (\text{sediment weight}) \times (\tan \theta + \tan \beta) \times s \tag{3.5}$$

producing a value for energy losses by bed friction per unit area (N $m^{-1}$ ). The energy losses presented in Table 3.2, therefore, represent a minimum estimate of the onshore energy consumed during the movement of shingle across the platforms. Energy losses for the carbonate coasts here would probably be associated with loss of water into cavities, joints and fractures within the rock, as well as the existence of very rough, uneven surfaces over which the shingle must often travel. There are probably much higher energy levels associated with these coasts than those presented here, especially during storm conditions in the late autumn, since complex gradients associated with scarp slope platforms are not taken into account.

In determining the importance of the variables in equation 3.4, scattergraphs are presented between shingle weight and onshore energy loss in Figure 3.10A, and the combination of gradient

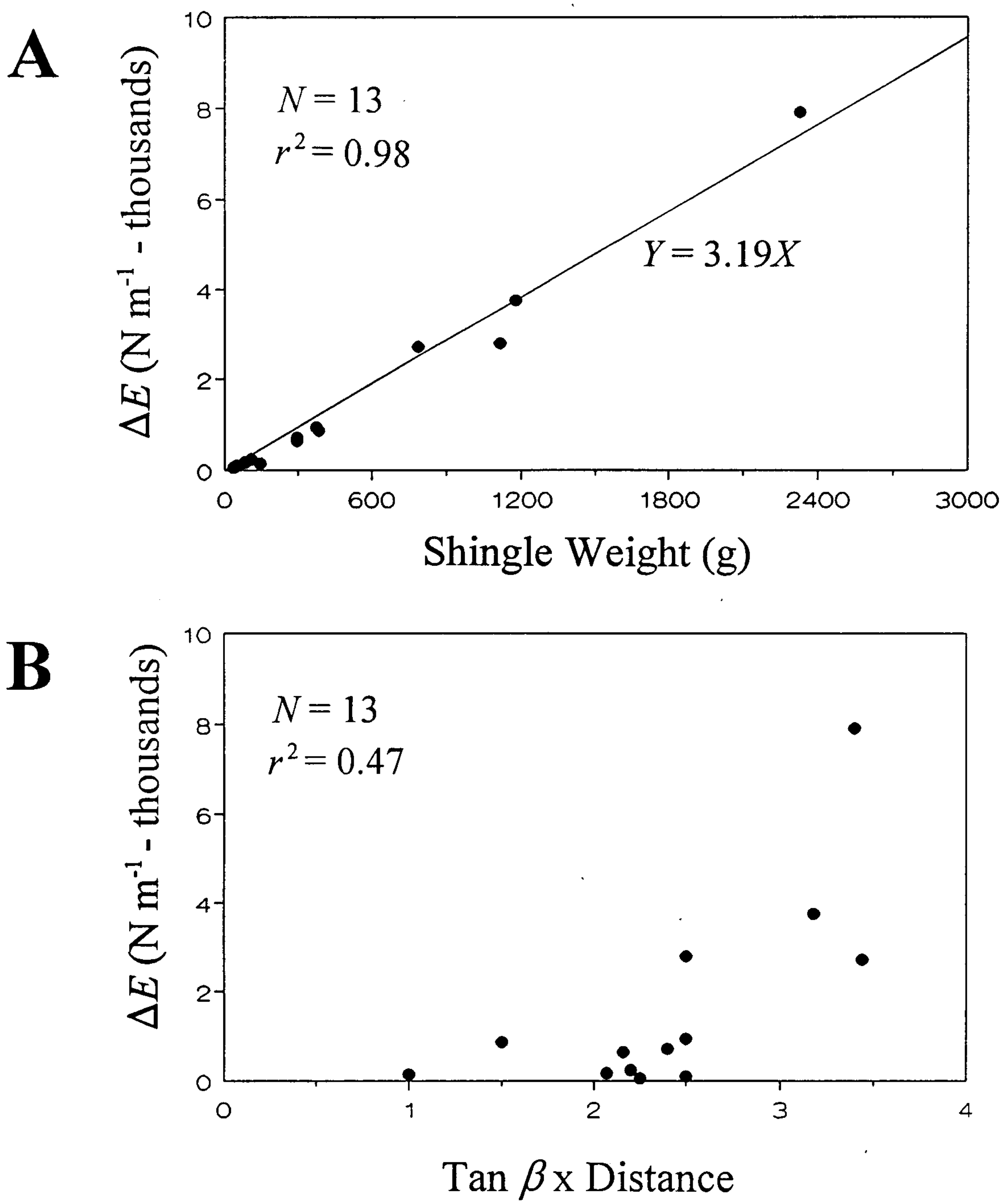



Figure 3.10 Scattergraphs of A) shingle weight and onshore work (linear equation was forced through the origin) and B) gradient times distance and onshore work. Shingle weight is much more significant than gradient and/or distance in determining the value of $\Delta E$.

and distance with onshore energy loss in Figure 3.10B. Shingle weight ($r^2$ = 0.98) is clearly the important variable in determining the energy required to move the material, while the combined influence of onshore gradient and distance ($r^2$ = 0.47) are of secondary importance. This would explain why the $\Delta E$ values in Table 3.2 are highest in association with heavier shingle. For example, the Port au Port Peninsula data presented here have significantly different $\Delta E$ values (2790 to 935 N $m^{-1}$ ) despite possessing the same gradient and distance values. It also explains why the Pointe Riche Peninsula (WNW maximum fetch) $\Delta E$ is only 144 N $m^{-1}$, despite possessing the longest shingle distance from the current water line.

As mentioned, available energy used for onshore sediment transport generally increases with an increased fetch (Sec. 2.2.1). Figure 3.11 is a scattergraph of maximum fetch distances and $\Delta E$ for the coastlines presented in Table 3.2, producing a fairly distinct exponential relationship ($r^2$ = 0.73). Those coastlines which are exposed to maximum fetch distances for that region (Figure 3.9), as well as maximum average wind velocities (Table 3.1), or at least possess significant fetch lengths, have a higher $\Delta E$ than those for relatively sheltered coastlines. This verifies the expectation that larger and heavier shingle will be transported across the littoral zone with increased exposure. It should be noted that the direction of maximum fetch and shingle movement by waves, may not always be in a shore-normal direction complicating the calculation of $\Delta E$. Also, ice rafting during the winter from the seasonal sea ice cover, may transport shingle farther than expected for the for the available energy at that site. The somewhat low $r^2$ emphasizes that maximum wave energy, available for onshore work at a given coastline, is not strictly controlled by length of fetch, but is related to other factors which determine the wave climate of a region (Sec. 2.2.1). As a group these fetch lengths all represent the semi-enclosed Gulf of St. Lawrence (except the Cook's Harbour region), and it would be expected that $\Delta E$ values for the Atlantic coast of Newfoundland are higher.

### 3.5.2 Tidal Range

A tide is any periodic fluctuation in water level in response to the gravitational attraction of the moon and sun (Figure 3.12; Dalrymple, 1992). The highest tides occur when the sun and

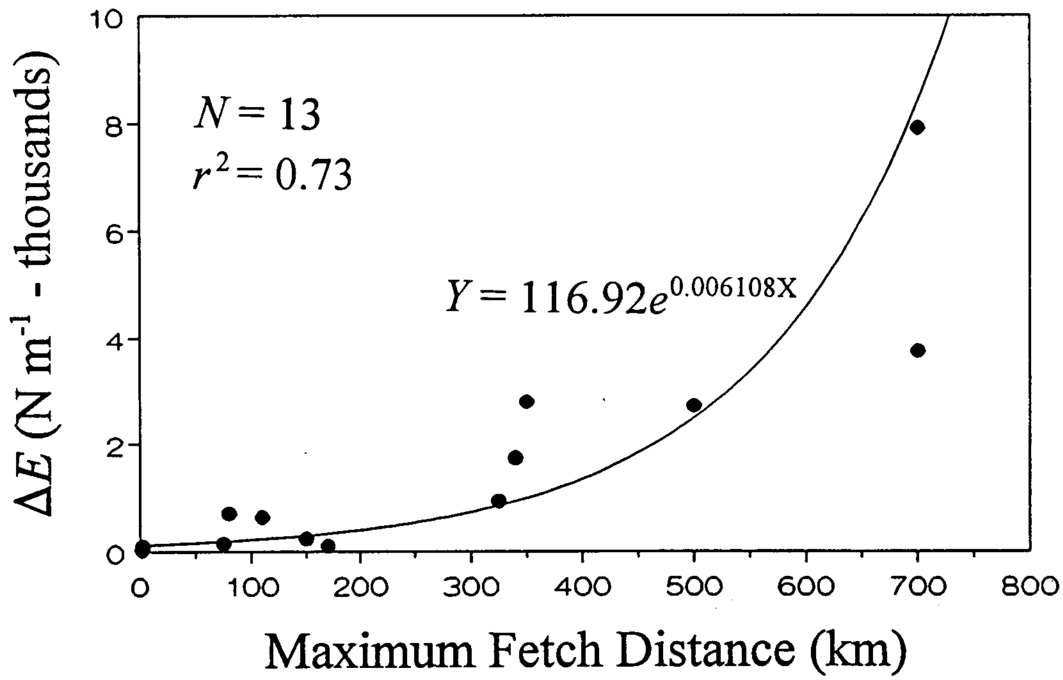



Figure 3.11 Scattergraph of fetch and onshore work illustrating the exponential increase of $\Delta E$ with increasing exposure.

moon are in a straight line with the earth during new or full moon phases (spring tides). When the sun and moon are at right angles to one another, then the lowest tides are produced (neap tides). Local effects modify this general pattern with enclosed bays usually experiencing larger tidal ranges than open ocean coastlines, because the original tidal wave can be amplified within bays from the effect of resonance. Resonance involves the return of the ocean tidal wave from the head of the bay, back to the mouth, where it can then meet up with the next incoming tidal wave increasing its magnitude (Open University Course Team, 1989b).

The Gulf of St. Lawrence and the Strait of Belle Isle are defined as microtidal; less than 2 m average tidal range or the difference in water level between successive high and low tides. This is due to the fact that these bodies of water (especially the Gulf of St. Lawrence which is almost an enclosed sea) are not large enough to enhance the initial effect of the tidal forces. The coastline

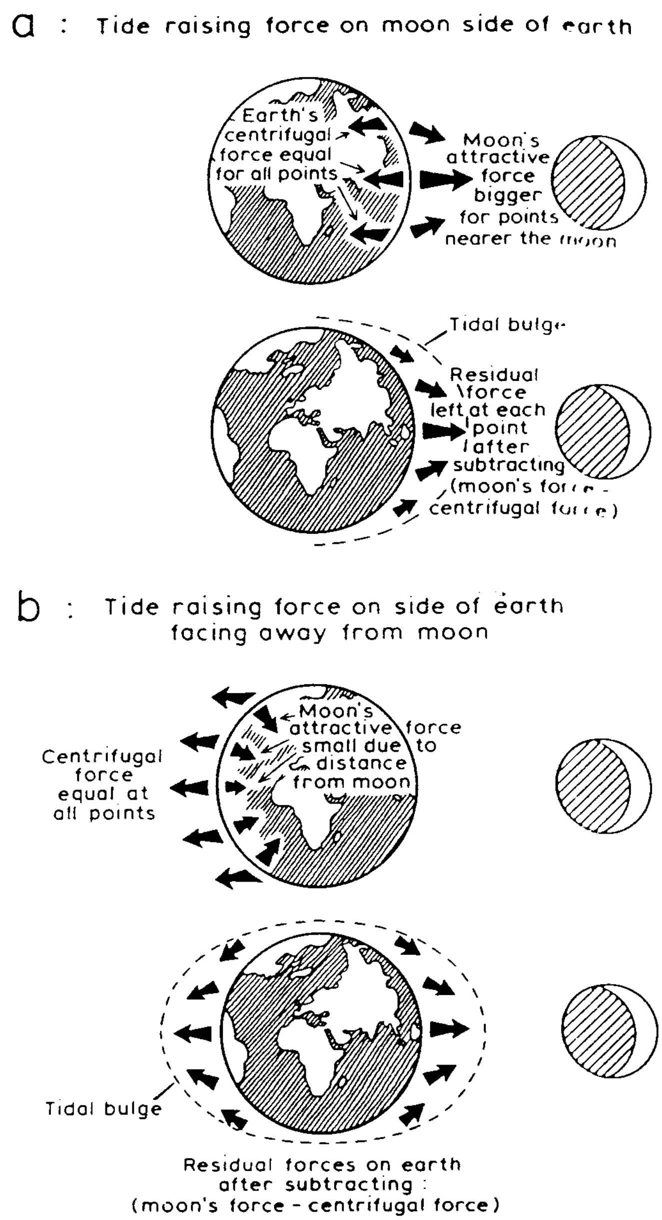



Figure 3.12 Symmetry of the tide producing forces (from Pethick, 1984, p. 49).

configuration essentially does not allow for resonant amplification to take place, except in local bays where the tidal range may reach an average, but not more than, 2 to 2.5 m. The tidal cycle is semi-diurnal so that there is a high tide approximately every 12.5 hrs., although each high tide is not the same height on a given day.

### 3.5.3 Offshore Bathymetry

Nearshore and offshore sea floor gradients are also important in determining the types of waves and the available wave energy at a coastal site (Sec. 2.2.1). Figures 3.13 to 3.16 present bathymetric maps for the four major study regions.

Offshore gradients are quite steep for most of the Port au Port Peninsula (Figure 3.13), Cow Head Peninsula (Figure 3.14), Pointe Riche Peninsula and the west-northwest coast of the Port au Choix Peninsula (Figure 3.15), and the Strait of Belle Isle adjacent to the Cook's Harbour region (Figure 3.16). In fact, the drop-off from the coastline is up to 20 m at times. As a consequence, the waves characteristically do not break before reaching the coast, and surge onshore with a strong velocity upon the carbonate littoral platforms. Areas such as Long Point and parts of Port au Port Bay, Port au Port Peninsula, Ingornachoix Bay and the east side of the Port au Choix Peninsula possess more gentle offshore gradients. Therefore, waves break offshore several times (in the fashion of spilling breakers) before they reach the littoral platform; this reduces the available wave energy at these sites, even with a southwest wind (maximum fetch).

It should be noted that there are many local variations in the gradients presented here; the scale of the maps does not permit detailed display of nearshore gradients within coves and bay areas along the peninsulas. For example, submerged reefs adjacent to the south coast of the Cow Head Peninsula reduce the otherwise quite steep gradient, producing plunging breakers and the steepest type of wave break adjacent to the platform shore (Sec. 2.2.1). Wave energy along this particular coastline is among the most extreme for all study sites, especially with a southwest wind. Most of Cow Cove, on the southeast side of the Cow Head Peninsula, is relatively shallow; one would expect the spilling breakers characteristic of gentle gradients but, with a strong SSW wind, the waves surge onshore with significant wave energy.

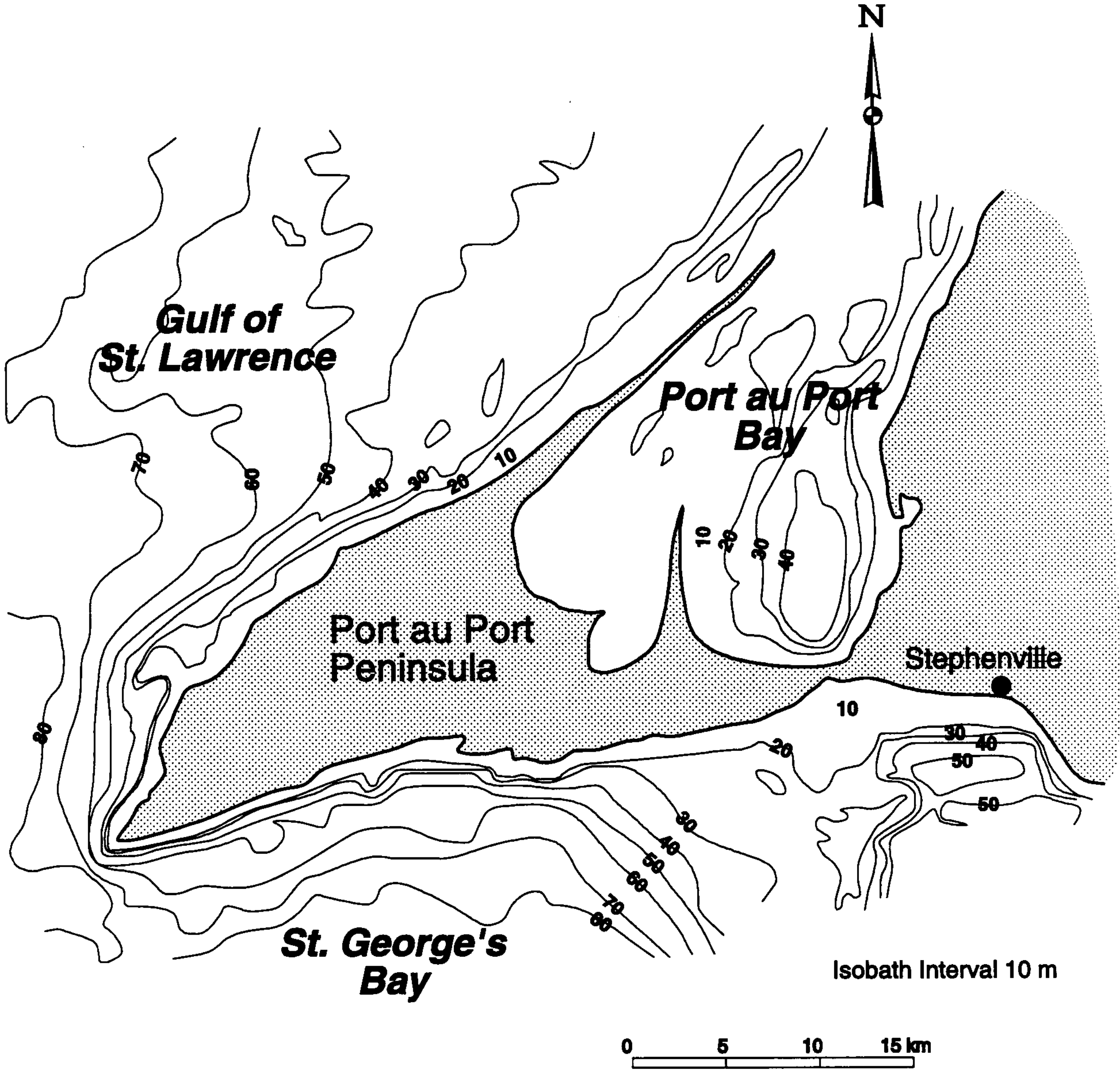



Figure 3.13 Offshore bathymetric map for the Port au Port Peninsula region (from natural resources chart 15088, Canadian Hydrographic Service, 1972a).

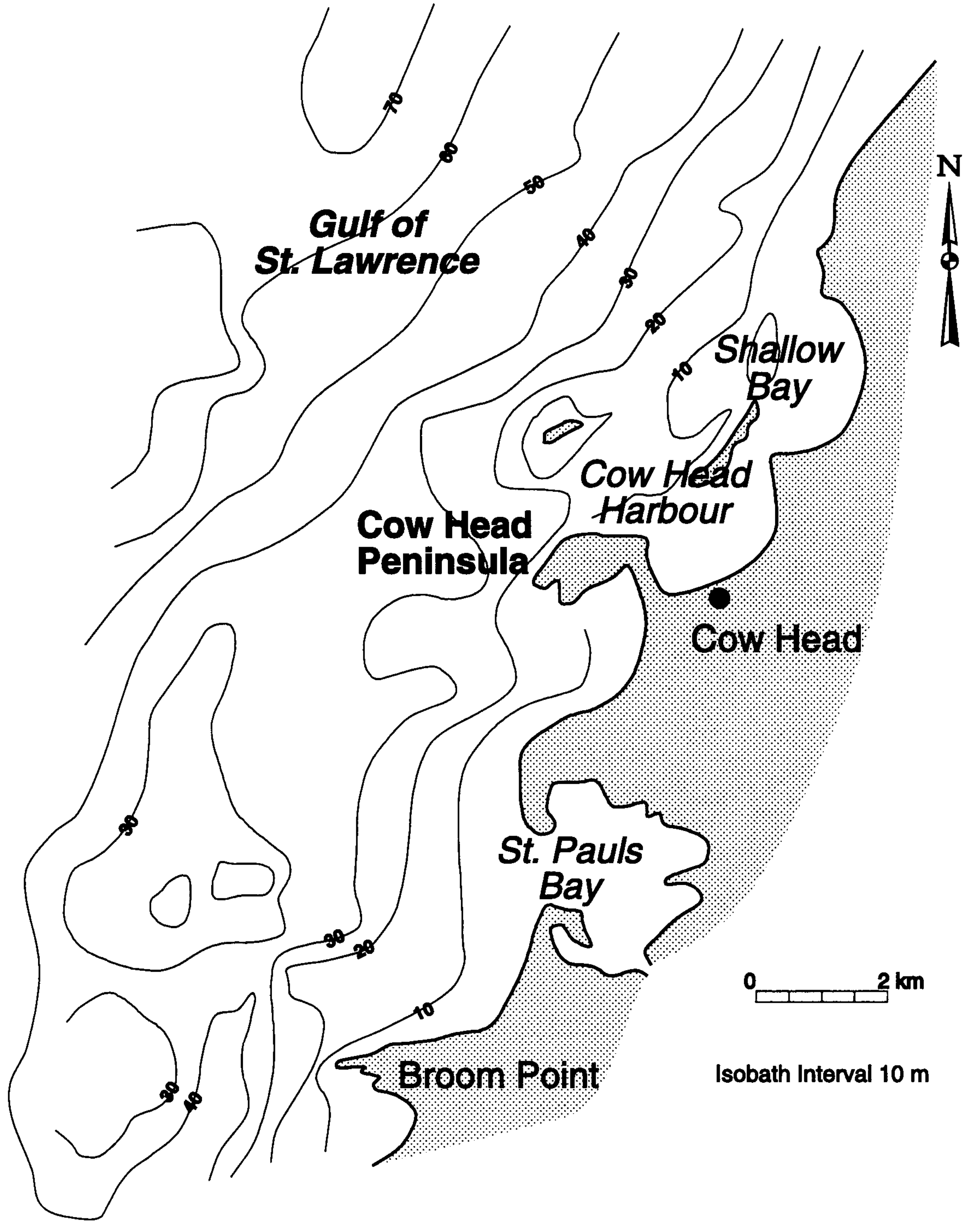



Figure 3.14 Offshore bathymetric map for the Cow Head Peninsula region (from natural resources chart 15096, Canadian Hydrographic Service, 1972b).

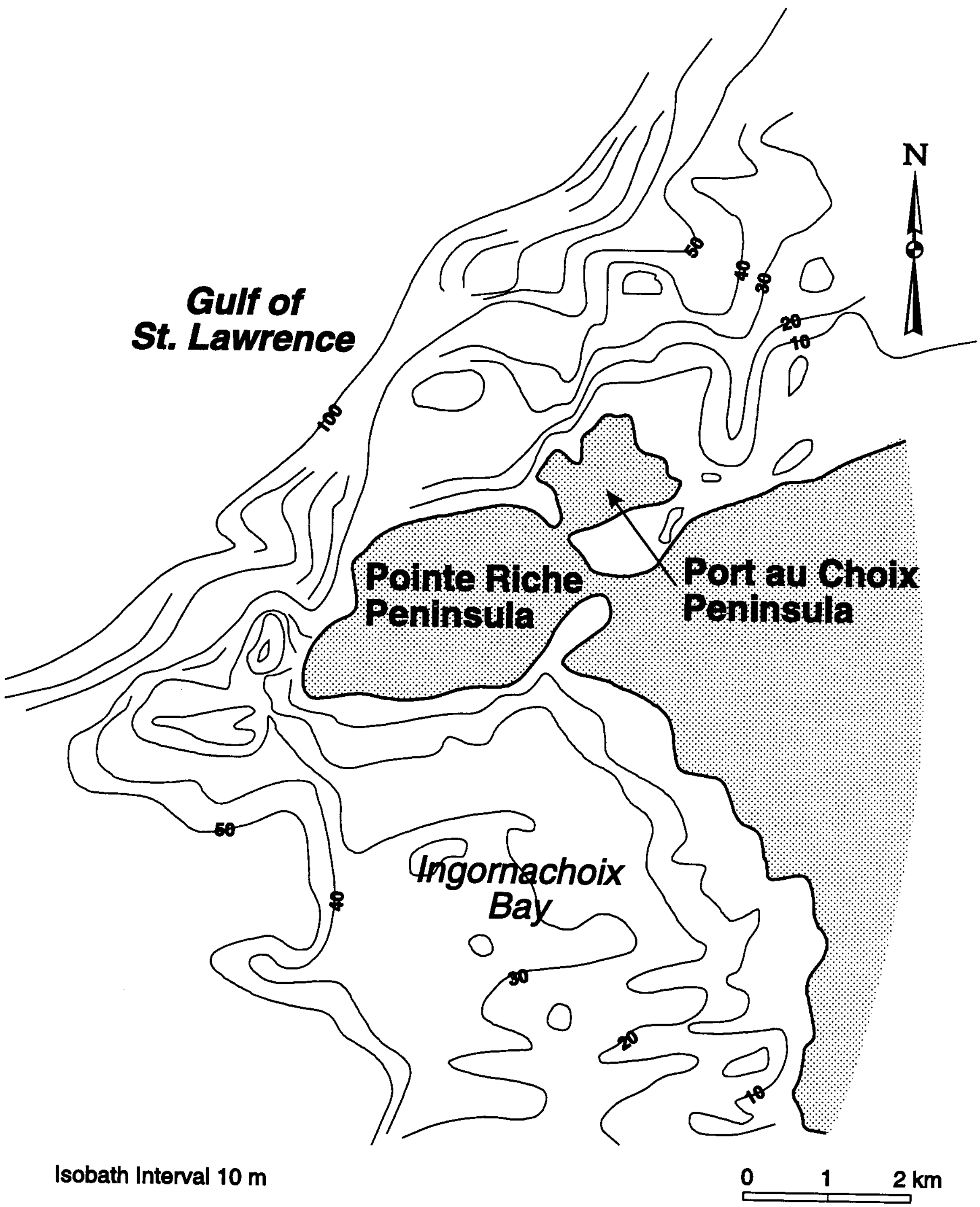



Figure 3.15 Offshore bathymetric map for the Port au Choix Peninsula region (from natural resources chart 18606, Canadian Hydrographic Service, 1972c).

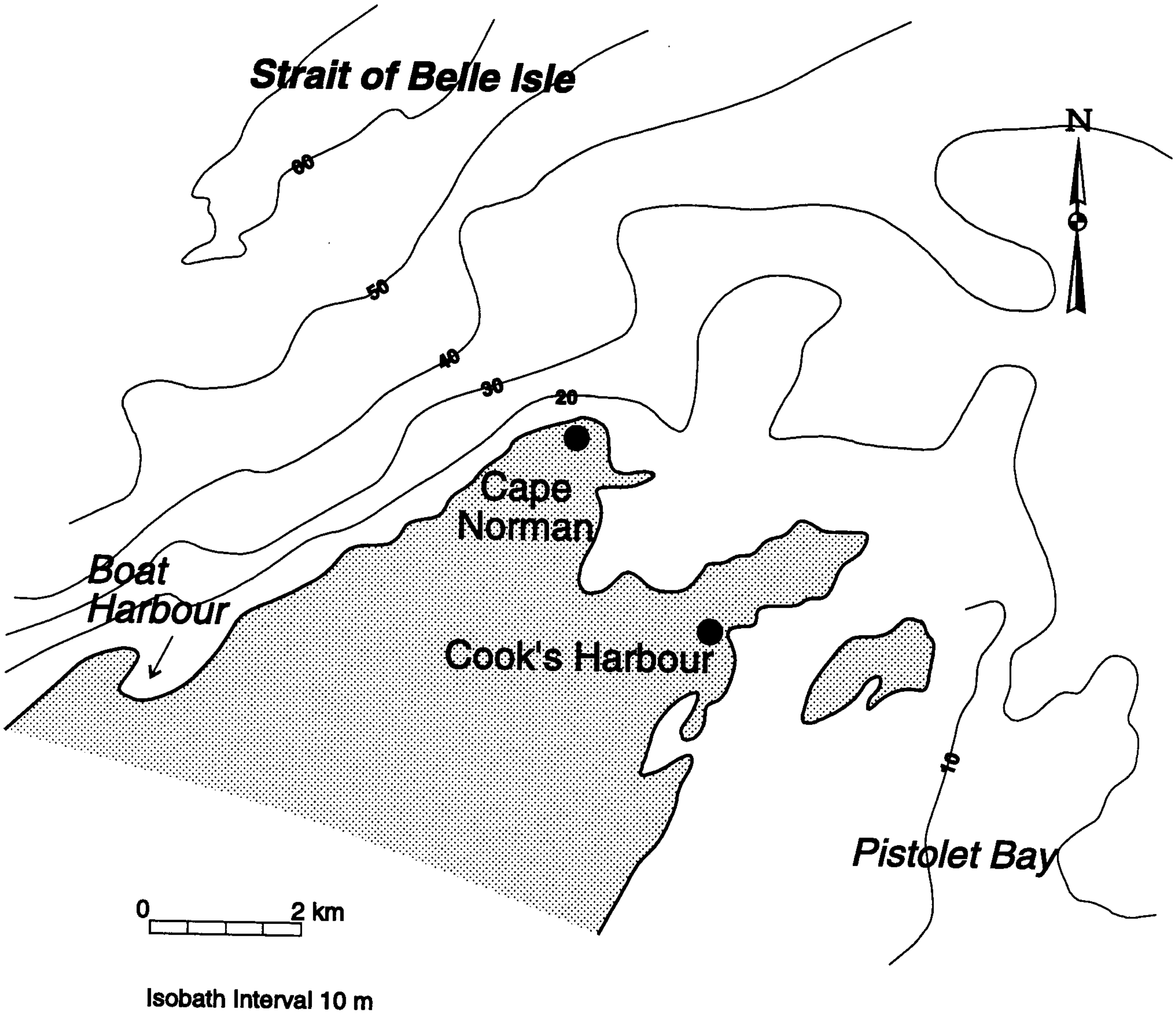



Figure 3.16 Offshore bathymetric map for the Cook's Harbour region (from natural resources chart 18614, Canadian Hydrographic Service, 1972d).

# CHAPTER 4

# FIELD METHODOLOGY

## 4.1 Location of Karren Sites Within the Four Regions

Detailed transect (profile) and quadrat studies were undertaken at coastal areas where there was extensive karren development (Table 4.1). For the Port au Port Peninsula sites were established at Long Point, the east side of The Bar, portions of the south and eastern shoreline of Port au Port East Bay, as well as Lower Cove and Ship Cove on the south side of the Peninsula (Figure 4.1). Such variety of sites provided a range of rock lithologies, platform structures and varying marine environments within this region. Rock samples were also taken and observations made where there is limited karren development at Three Rock Point and Jerrys Nose. The remainder of the coastline is comprised of shingle or sediment beaches, or inaccessible steep cliffs, such as the southwest corner of the peninsula.

Major study sites within the Cow Head Peninsula region (Figure 4.2) include various locations on the peninsula, which was studied in detail with representative profiles constructed for each shore. Small-scale maps and/or quadrat sampling of karren was also done at Lower Head, Belldowns Island, Stearing Island, Broom Point (about 10 km south of the Cow Head Peninsula; Figure 3.1) and Daniel's Harbour (about 40 km north of the Cow Head Peninsula; Figure 3.1).

For the Port au Choix Peninsula region, profiles were taken along the coastline of the Port au Choix and Pointe Riche Peninsula, Gargamelle Cove and Ingornachoix Bay (Figure 4.3). The Port au Choix Peninsula has varying degrees of exposure, with most shorelines hosting karren despite minimal platform development in some areas. Most of the karren at the Pointe Riche Peninsula are restricted to the area near the navigation light at the western side of the peninsula, and portions of the south side towards Gargamelle Cove. Ferrolle Point, located on the New Ferrolle

Table 4.1 Listing of study sites within the four primary regions.

| Region | Site | Transects/Quadrats (Maps) |
|---|---|---|
| **Port au Port Peninsula** | The Bar | Four/Thirteen |
| | Long Point | Three/Fourteen |
| | Lower Cove | Two/Eleven |
| | Ship Cove | Zero/One |
| | Port au Port East Bay | Two/Five |
| **Cow Head Peninsula Region** | Cow Head Peninsula | Four/Nine |
| | Broom Point | One/Five |
| | Stearing Island | Zero/One |
| | Belldowns Island | Zero/One |
| | Lower Head | One/One |
| | Daniel's Harbour | Zero/Two |
| **Port au Choix Peninsula Region** | Port au Choix Peninsula | Six/Twenty |
| | Pointe Riche Peninsula | Five/Twenty-one |
| | Ingornachoix Bay | Nine/Twenty-seven |
| | Gargamelle Cove | Two/Six |
| | New Ferrolle Peninsula | One/One |
| **Cook's Harbour Region** | Cape Norman Point | One/Five |
| | Cape Norman East | One/Four |
| | Cape Norman West | Four/Fifteen |

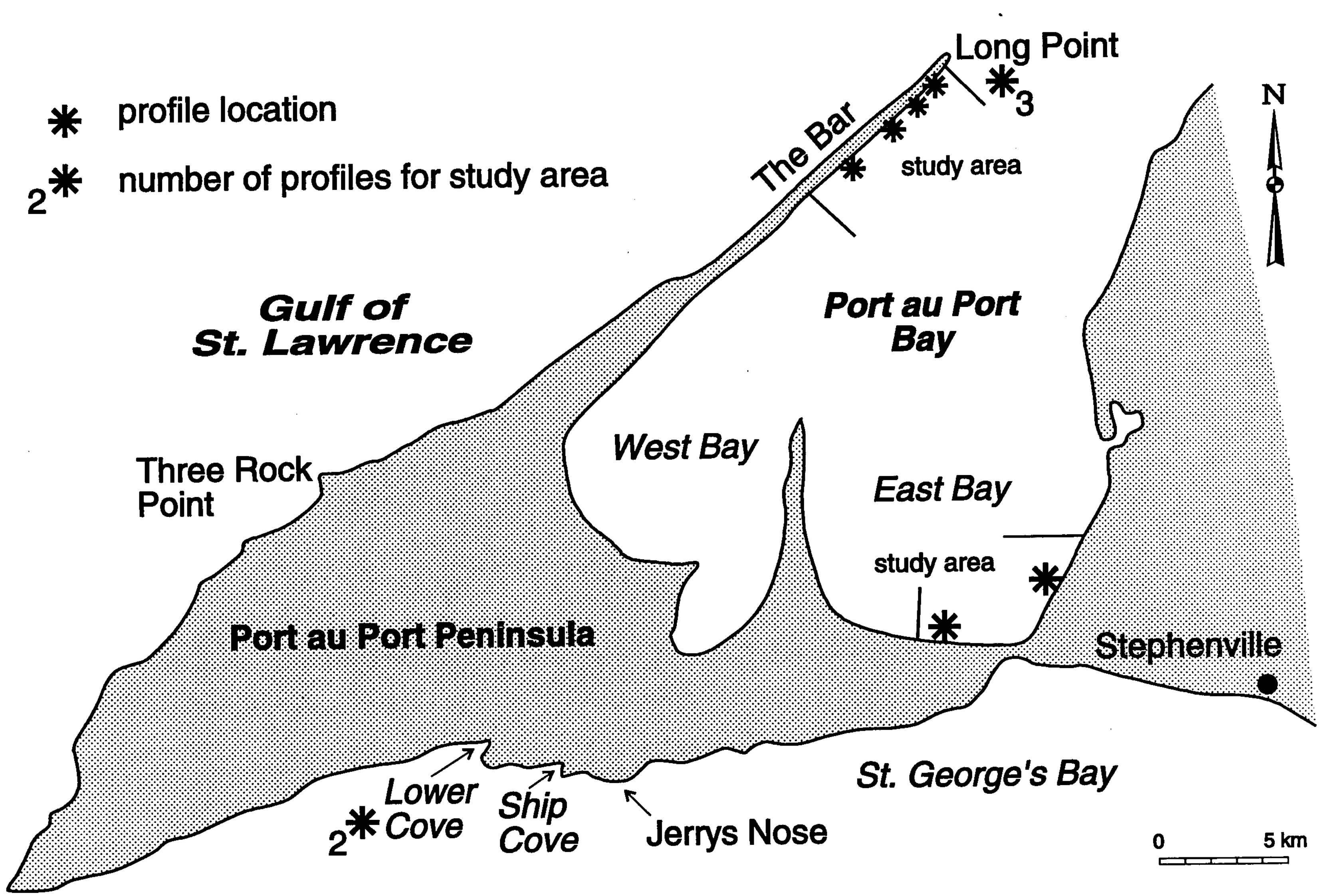



Figure 4.1 Map of the Port au Port Peninsula illustrating the approximate location of karren study sites and profiles.

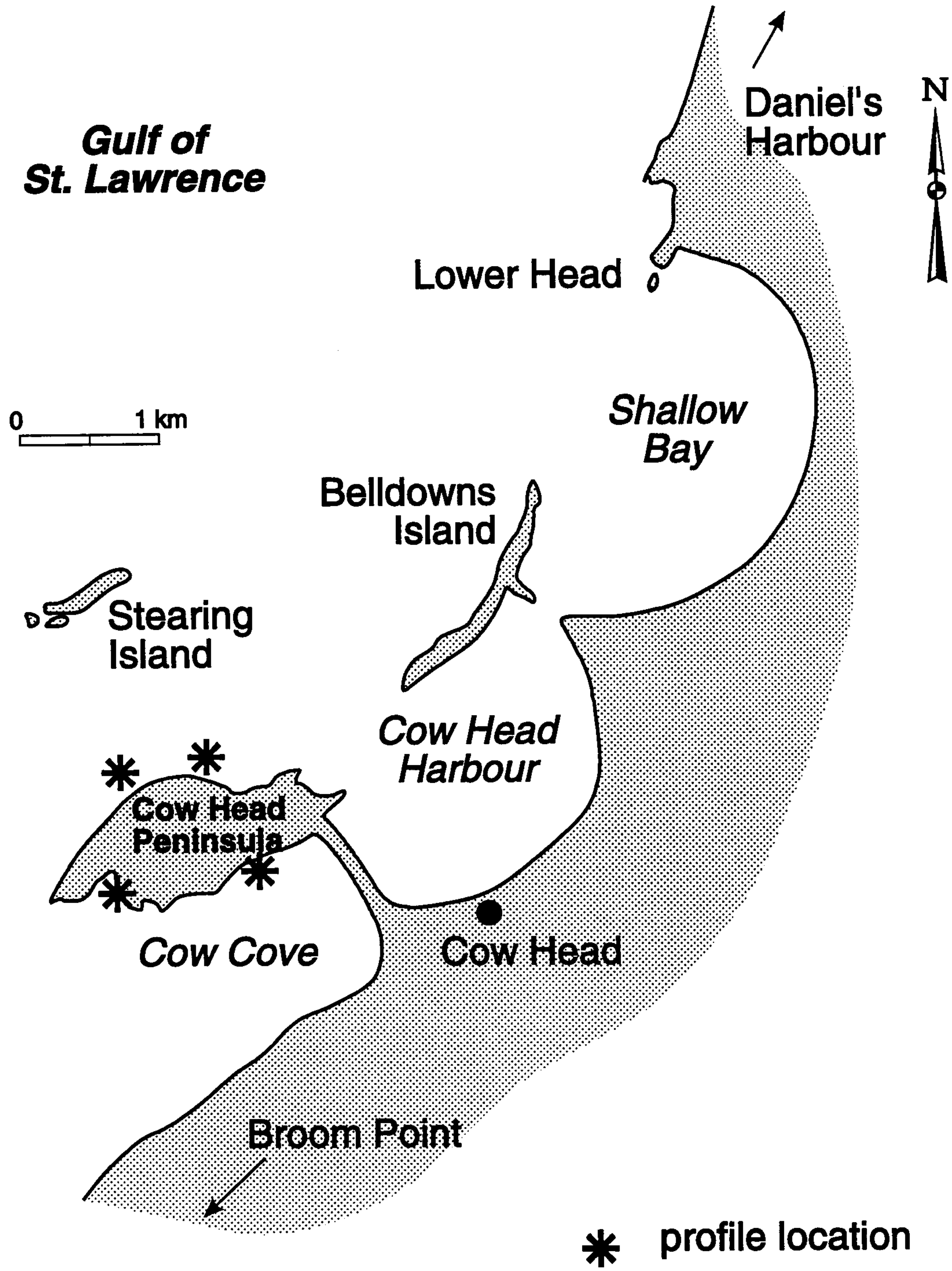



Figure 4.2 Map of the Cow Head Peninsula region illustrating the approximate location of karren study sites and profiles.

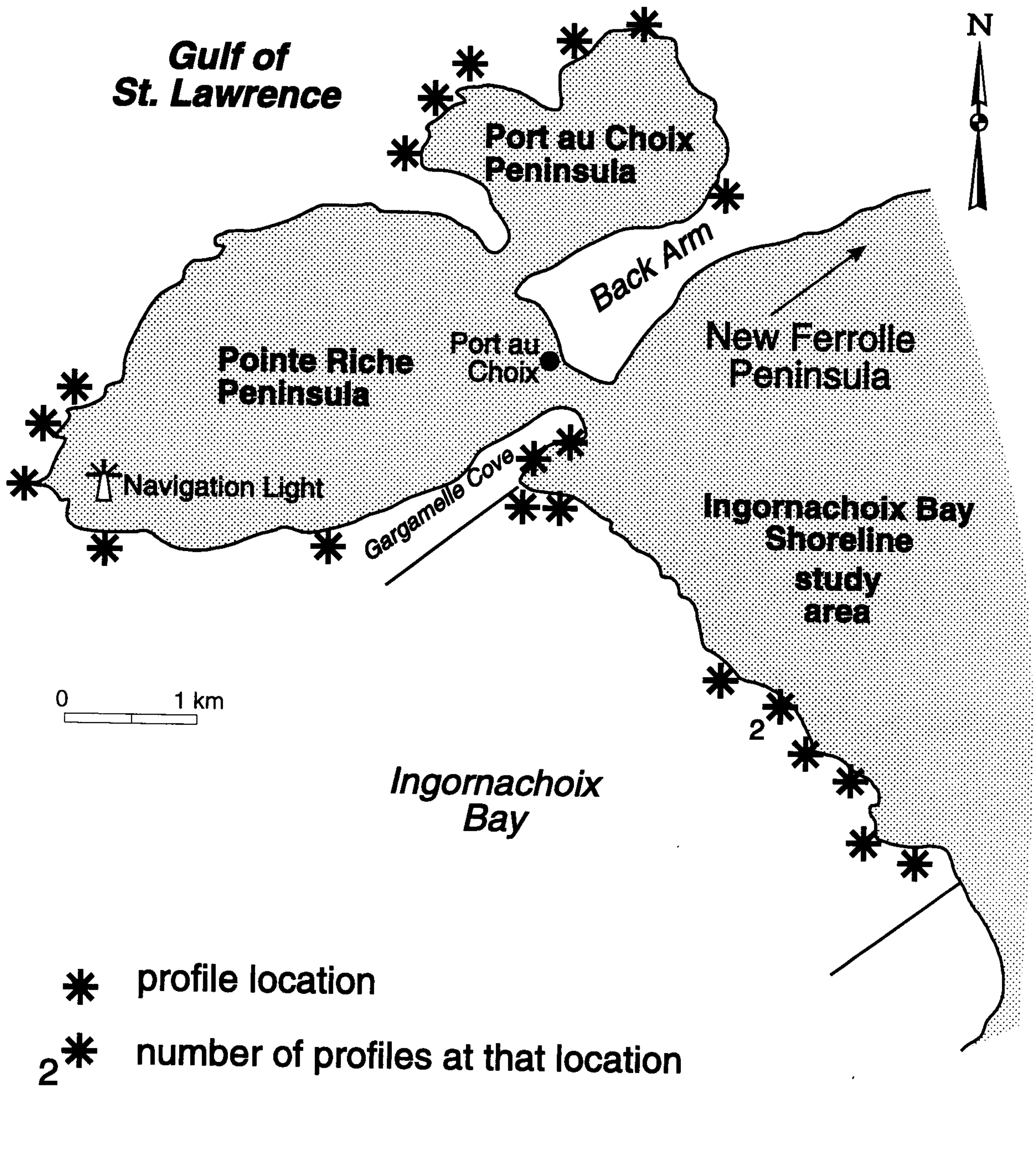



Figure 4.3 Map of the Port au Choix Peninsula region illustrating the approximate location of karren study sites and profiles.

Peninsula (about 40 km north of the Port au Choix Peninsula; Figure 3.1), is included in this region as an example of a negative site, as there was almost zero karren development on this dolomitic limestone rock of the St. George Group.

The coastline between Boat Harbour and Cape Norman, along the Strait of Belle Isle coastline (Cook's Harbour region; Figure 4.4), is a site of dramatic karren development, as well as sea caves, sea stacks and other karst features. The spatial extent of littoral karren, however, is often limited because of a lack of platform development. Outside of the study area there is a minimal occurrence of karren south of Cape Norman, along the Cape Norman Bay shoreline, and in the area near the community of Cook's Harbour and the Cooks Harbour shoreline out to Cooks Point. West of Boat Harbour there is only micropitting, due to the dolomitic rock that prevails along the coastline there. This region is dominated by a huge expanse of limestone pavement further inland, that is naturally devoid of trees.

## 4.2 Construction of the Littoral Profiles

Most of the karren sites displayed a variety of littoral karren, in great abundance at times, so that a method of sampling had to be employed in order to produce proper representative samples. Field methods were designed to produce a stratified random sampling of the karren, with shore-normal, parallel profiles constructed across the platforms, because the karren distribution was essentially zonal in nature (across the various littoral zones). The precise location of profiles was determined by the presence of karren with the best zonal distribution at a given site, as well as reflecting variations in the morphology of the coastal platforms at the various sites. Profiles were also constructed for both sheltered and exposed coastlines, to provide a basis of examining any variation in the degree of karren development with varying exposure. A total of 44 profiles were produced over all of the sites.

Representative littoral profiles, and accompanying photographs, are provided here for the Port au Port Peninsula at Long Point (Figure 4.5), the east side of The Bar (Figure 4.6) and for Lower Cove (Figure 4.7 and 4.8). Profiles were constructed across the entire defined littoral zone

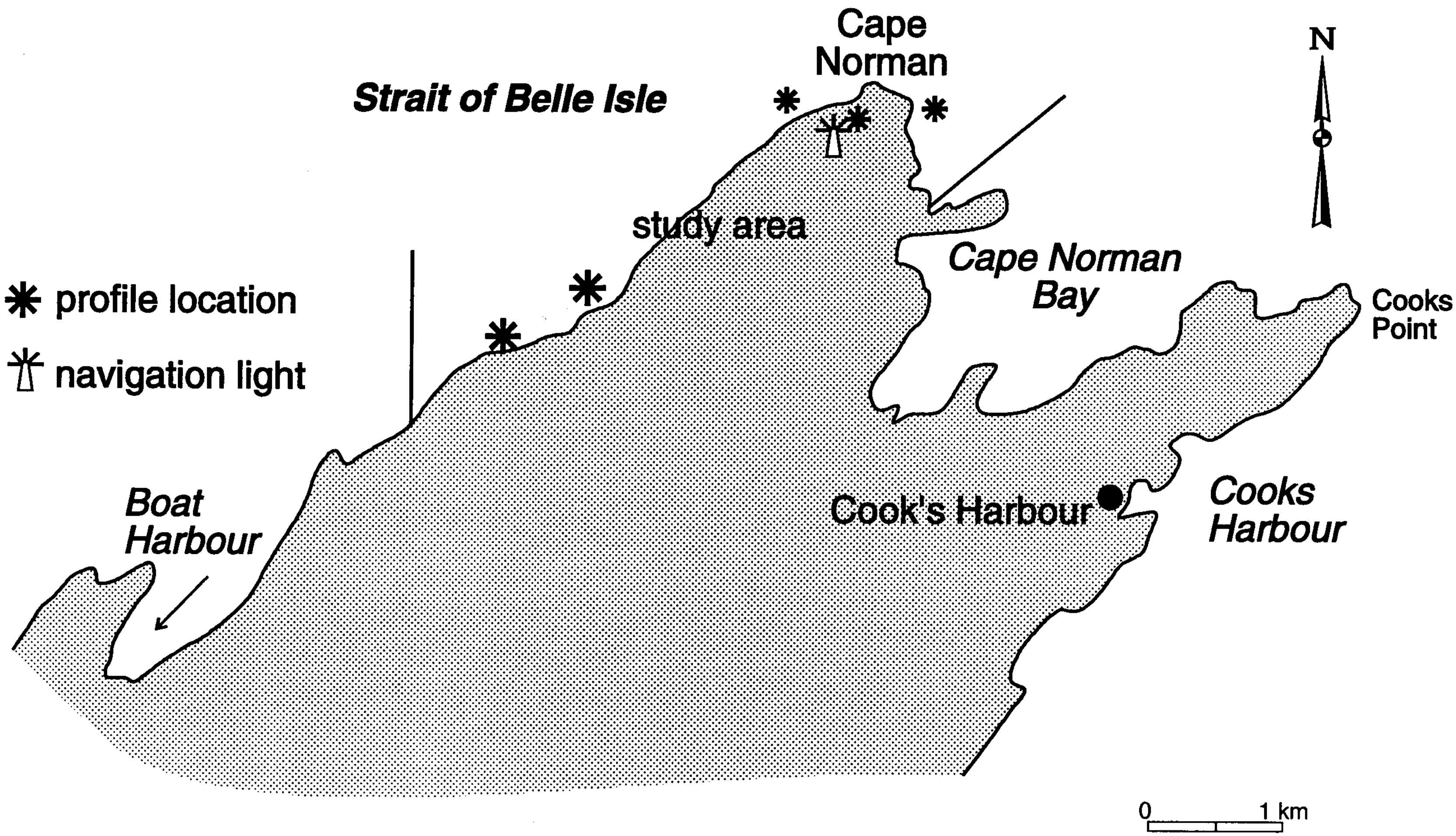



Figure 4.4 Map of the Cook's Harbour region illustrating the approximate location of karren study sites and profiles between Boat Harbour and Cape Norman Bay.

A

B

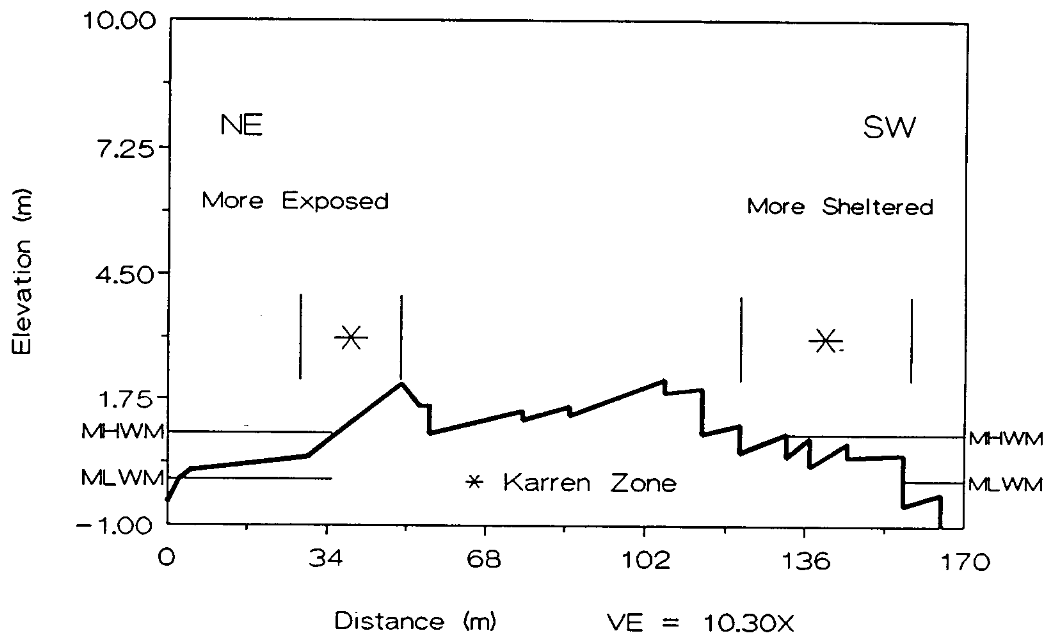
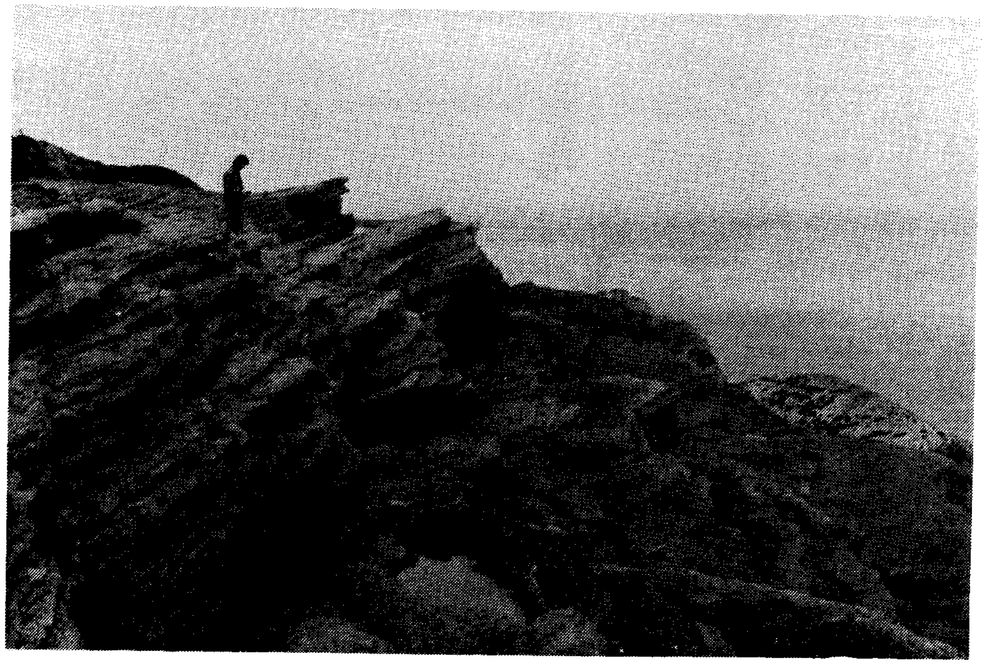



Figure 4.5 Illustrations of the Long Point study site on the Port au Port Peninsula. A) Photograph of Long Point at low tide. Person is standing near the location where the profile was constructed. B) Profile across the same area revealing the occurrence of karren within the littoral zone. Horizontal scale has been exaggerated about 2.4 times.

A



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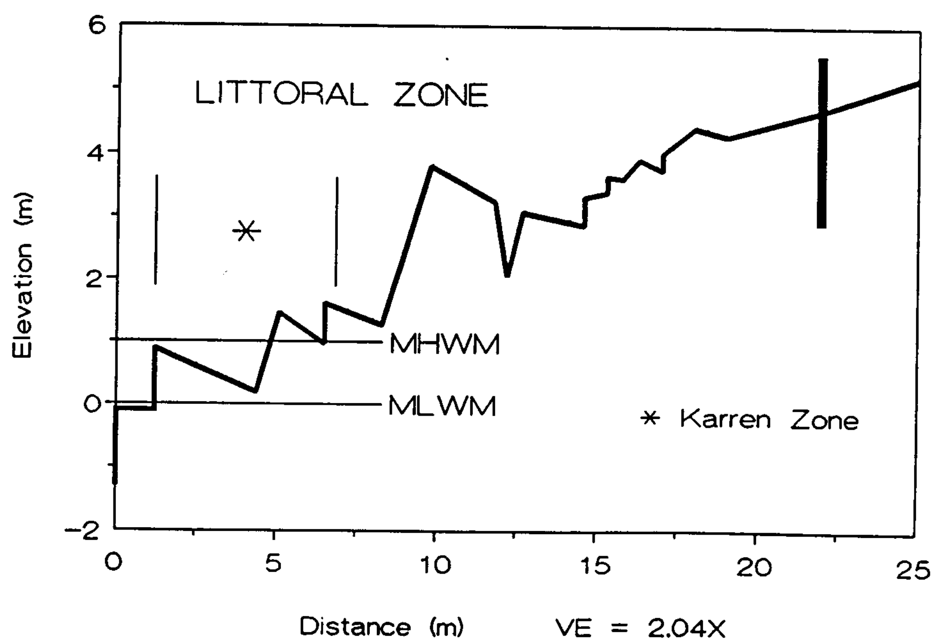



Figure 4.6 Illustrations of the scarp slope morphology on the east side of The Bar, Port au Port Peninsula. A) Photograph of The Bar. Person is standing near the location where the profile was constructed. B) Profile of The Bar revealing the occurrence of karren within the littoral zone.

Figure 4.7 Photograph of the eastern shore of Lower Cove, on the south side of the Port au Port Peninsula, illustrating the location of the study area and the shore-parallel profile presented in Figure 4.8.

(Sec. 2.2.1), from as far offshore as possible (subtidal) through to the backshore, with the landward limit of the littoral zone indicated. Note that the profile selected for Lower Cove is a shore-parallel profile, as the karren variation here is more dramatic alongshore, as opposed to the normal zonal pattern of karren. The platform is divided into sections which are separated by water. Karren zones are delineated along all profiles, where karren existed and warranted further analysis. All profiles are referenced to the mean low water mark (MLWM), which is established as zero elevation. The elevation of the MLWM is calculated by using tide tables, published for the Gulf of St. Lawrence region by the Department of Fisheries and Oceans (1990) for several reference ports, within the region, where tide gauges are present. Data were also obtained for several secondary ports along the west coast of Newfoundland, and there was at least one port within, or nearby, the study regions. Data for the secondary ports provided daily tidal predictions, for each month of the year, along with the times and heights of high and low tide measured by the tide gauges.

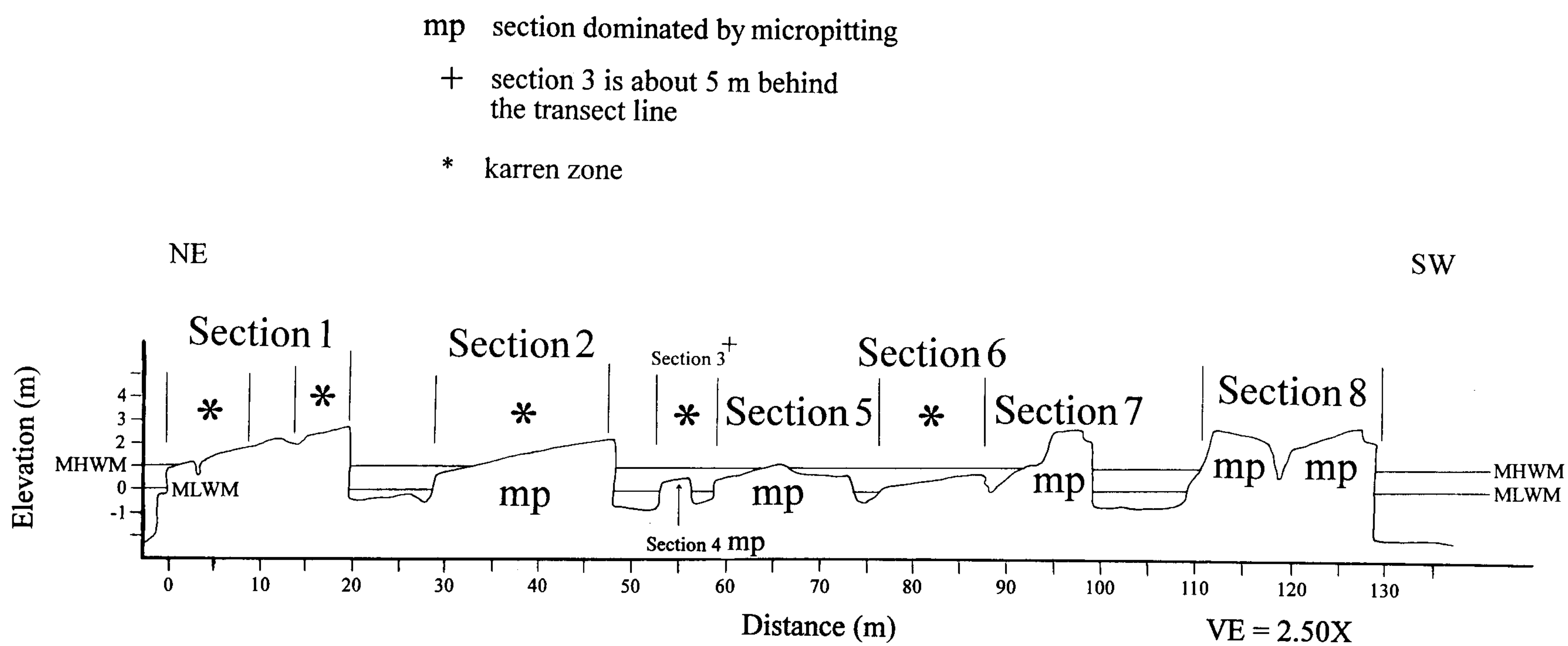



Figure 4.8 Shore-parallel profile across the eastern shore of Lower Cove, trending in a northeast to southwest direction, illustrating the alongshore variation in the occurrence of karren.

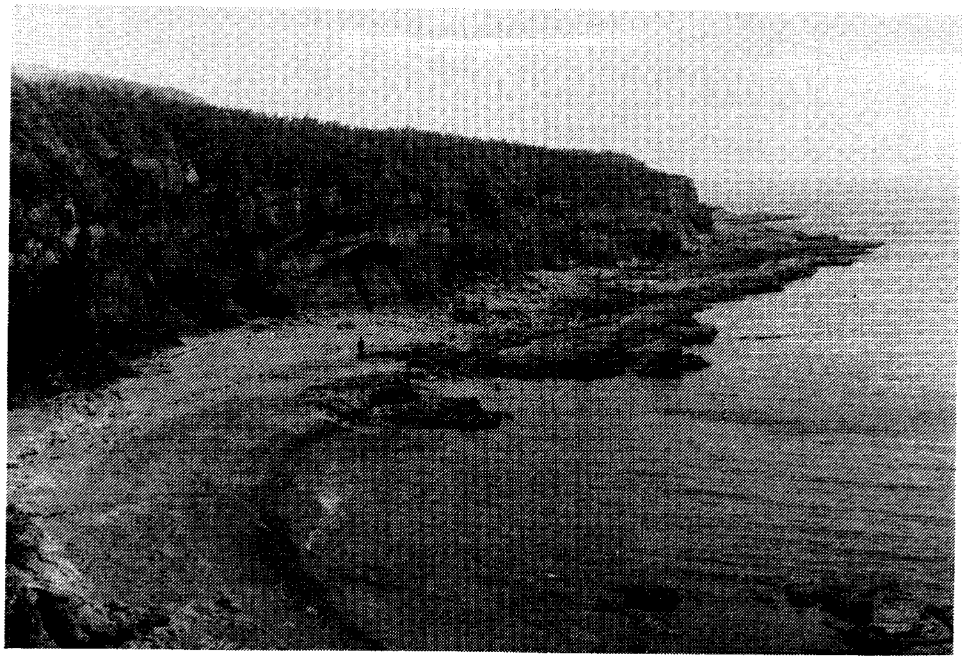
Thus, in order to determine the elevation of the MLWM for the profiles, the time of day, and position of the tide, was recorded when the profile was surveyed. By using the mean tidal range for that site, and for the month that the profile was surveyed, the height difference from the time the tide was measured to the position of the MLWM can be calculated. All elevations of the profile are then corrected relative to the position of the MLWM, which is the average position of low tide for that region. The mean high water mark (MHWM) is the average high tide level for the region. There are times during spring and neap tidal periods (Sec. 3.3.2) where the height of high and low tide will be more dramatic than indicated on the profiles.

The Cow Head Peninsula is quite variable in its coastal morphology, as revealed in Figures 4.9 and 4.10. There is a combination of shingle-dominated and broken platform on the northern shoreline (Figure 4.9A), scarp slopes (rock dipping landward) and more extensive coastal platform outcrops on the WNW shoreline (Figure 4.9B and Figure 4.11A), and contrasting dip slopes (rock dipping seaward) on the southwest coastline (Figure 4.10A and Figure 4.11B), plus a SSW coastline where the littoral zone is very limited (Figure 4.10B).

The Port au Choix Peninsula is very shingle dominated and there is limited platform development (e.g. Figure 4.12A), although there are areas along the north and west coasts (Figure 4.12B) where scarp sloping profiles were produced. The Pointe Riche Peninsula has scarp slopes along the northeast coast of the peninsula (Figure 4.13A), but also has dip slopes along the south side of the peninsula (Figure 4.13B). Note the more extensive karren development along the backshore of the scarp sloping platform, with karren often occurring at the base of "steps" in the depression areas where water can accumulate. Very gentle dip sloping strata occur along the shoreline of Ingornachoix Bay, (Figure 4.14), where the nearshore and offshore gradient is very gentle, and the horizontal extent of the intertidal zone is at its greatest.

Most of the coastline in the Cook's Harbour region consists of vertical cliffs, although there are areas where horizontal strata exist and profiles could be constructed (Figure 4.15). The tidal range is smaller in this region than in the other regions (< 1 m) and, as evidenced from the profile in Figure 4.15B, there is often no intertidal zone, due to the sharp offshore dropoff from the

A



B

Figure 4.9 Photographs of the Cow Head Peninsula. A) Photograph illustrating the morphology of the northern shore of the peninsula. B) Photograph illustrating the more extensive, scarp sloping platform of the WNW shoreline.

A

B

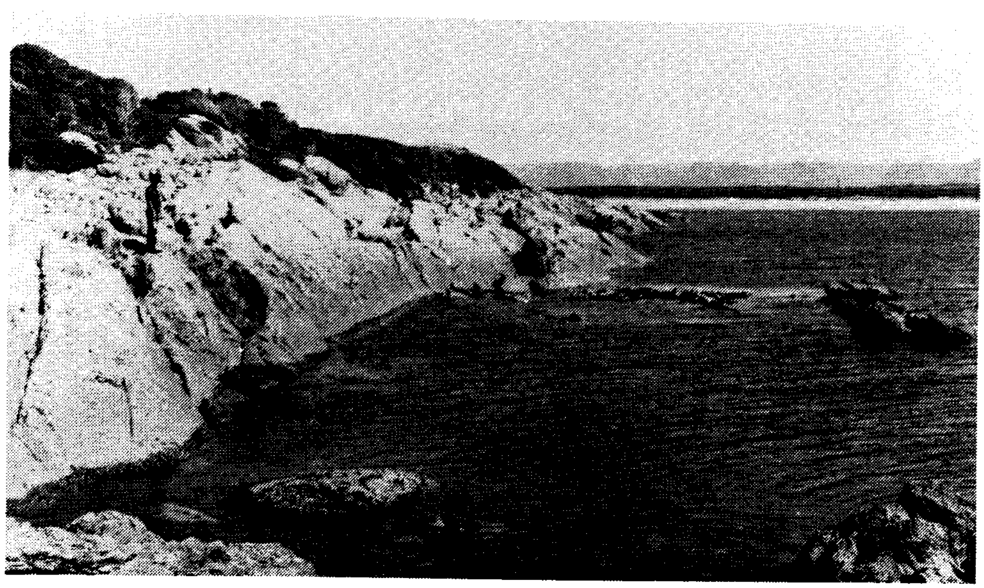
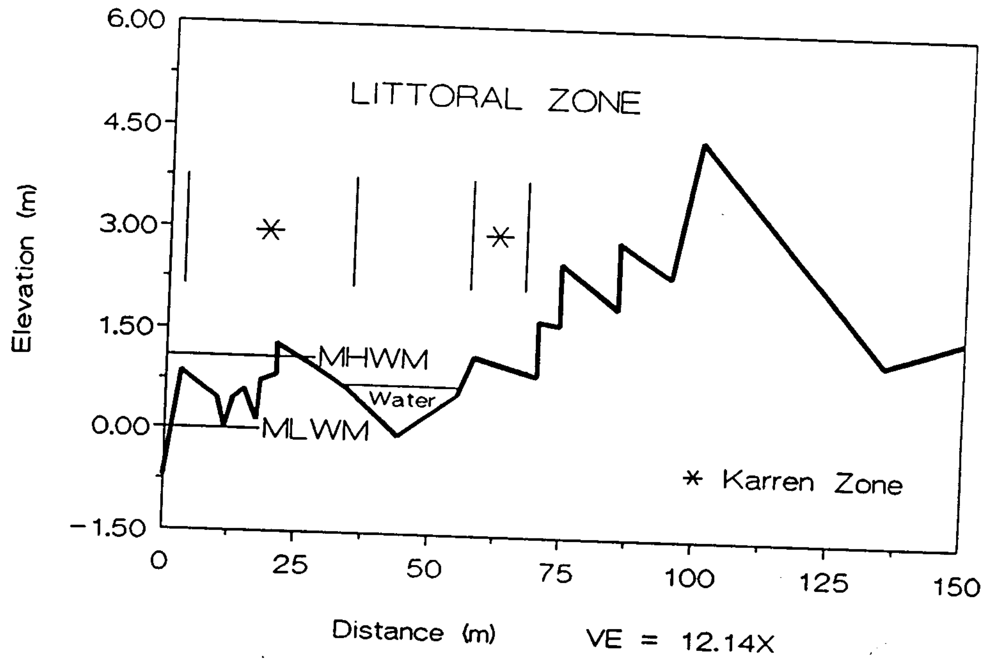


Figure 4.10 Photographs of the Cow Head Peninsula. A) Photograph illustrating the relatively steep dip slope of the south side of the peninsula. B) Photograph illustrating the very steep dip slopes of the sheltered, SSE coastline, revealing very limited platform development.

A

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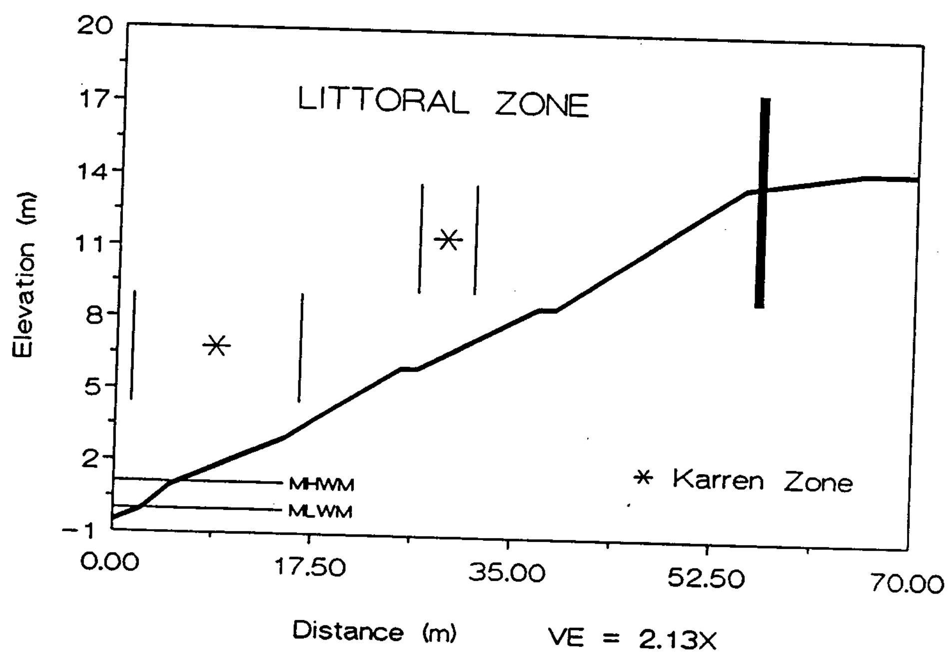
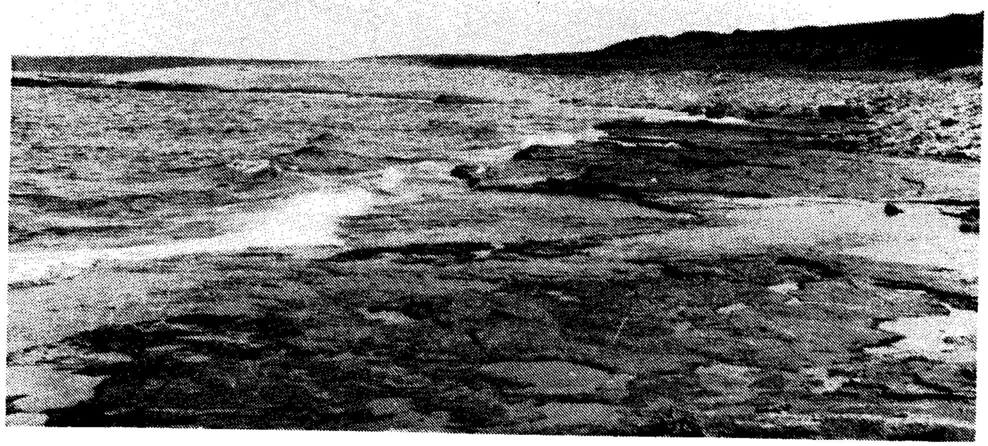



Figure 4.11 Representative profiles of the Cow Head Peninsula. A) Expanded profile of the WNW platform, illustrating the location of karren zones within the littoral zone. Horizontal scale has been exaggerated about 2 times. B) Dip slope of the south side of the peninsula, illustrating the location of karren zones within the littoral zone. Note the steep gradient of the platform.

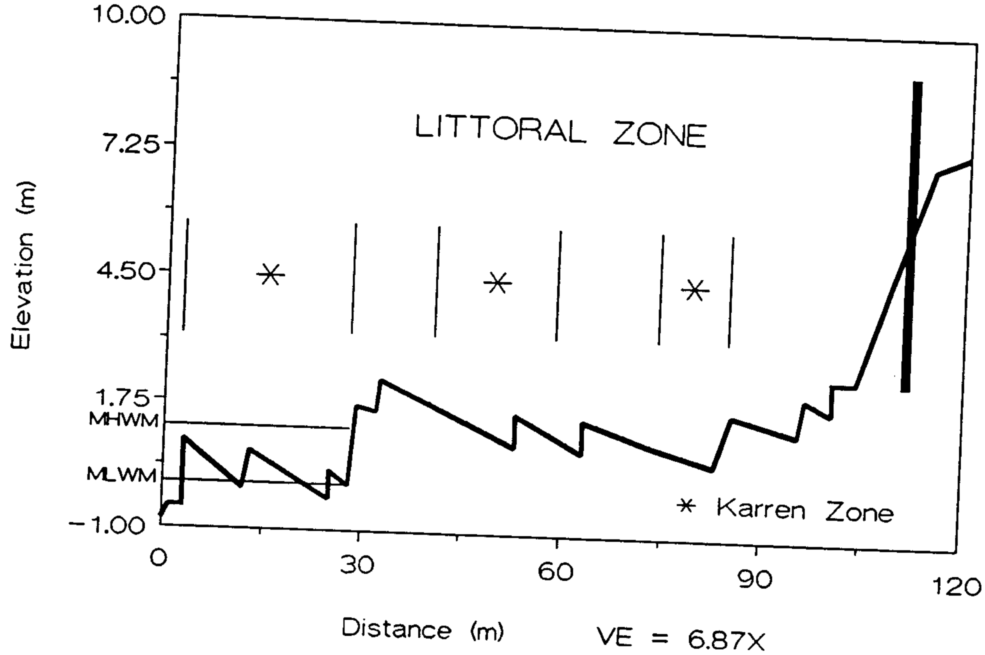
A



B

Figure 4.12 Photographs of the Port au Choix Peninsula. A) Photograph illustrating the shingle-dominated shoreline of the east side of the peninsula. B) Photograph illustrating the more extensive, scarp sloping platform of the NNW littoral zone.

A




B

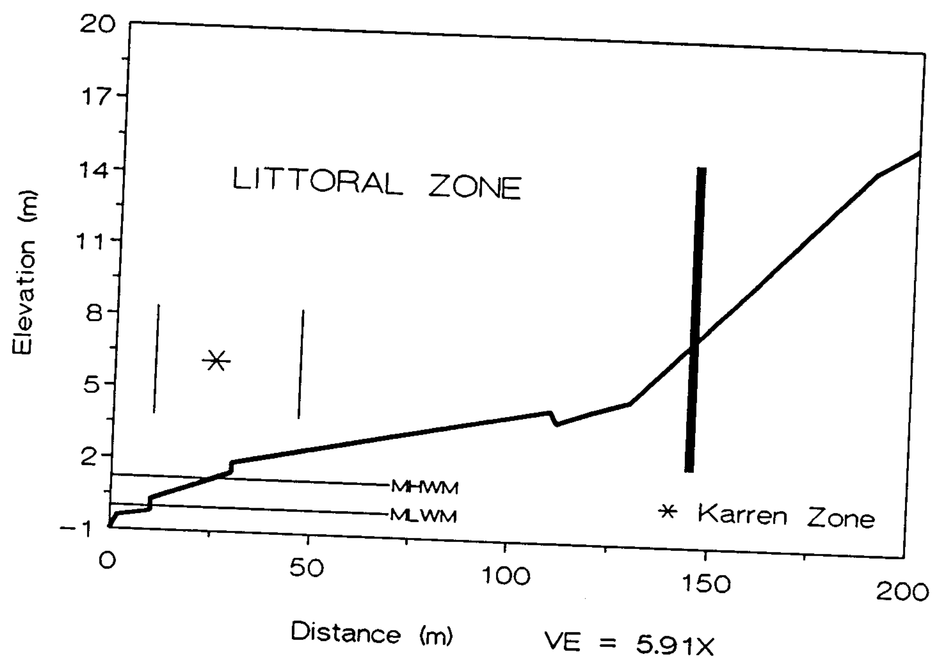



Figure 4.13 Representative profiles of the Pointe Riche Peninsula. A) Profile of the scarp slope platform on the west side of the peninsula, north of the navigation light (Figure 4.3), and B) on the west side, south of the navigation light. Karren zones within the littoral zone are illustrated.

A

B

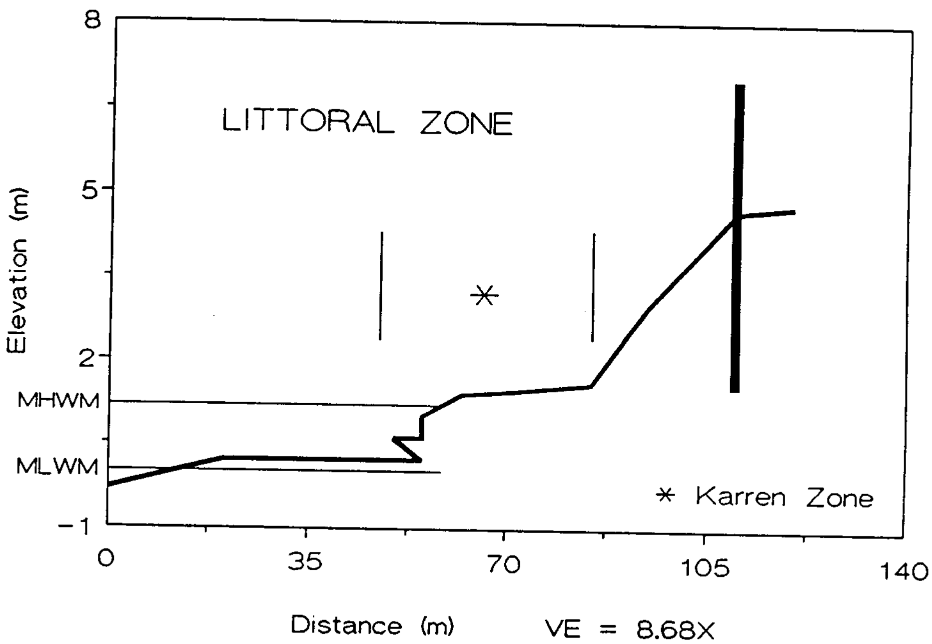
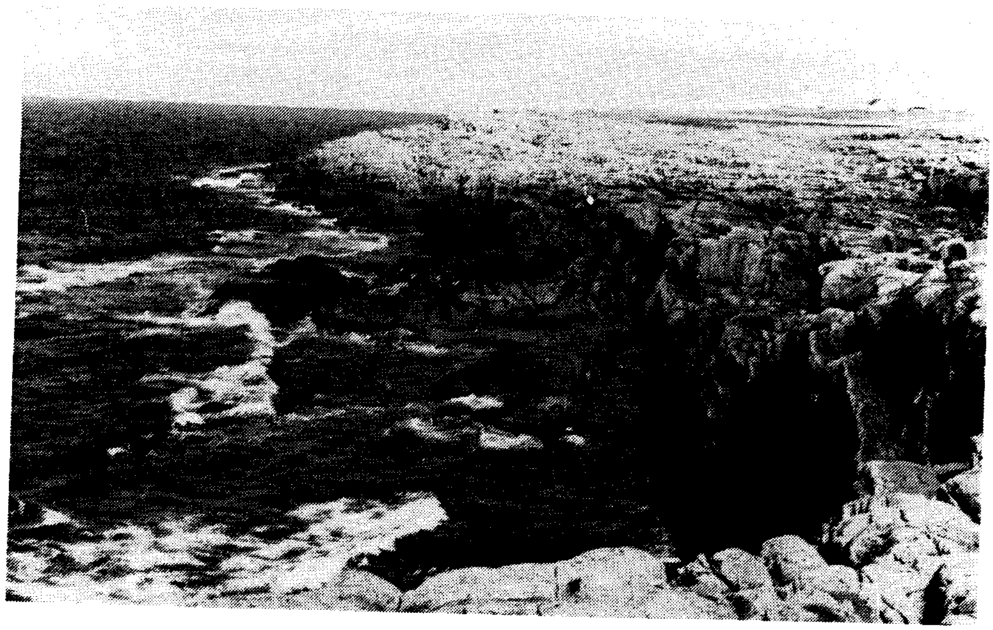



Figure 4.14 Platform morphology of the Ingornachoix Bay shoreline, illustrating the very gentle dip slope of the littoral zone gradient. A) Photo taken at the profile site at low tide. Note the high density, shallow karren pits in the foreground, within the supratidal swash zone. B) Profile of the same area illustrating the location of karren within the littoral zone.

A



B

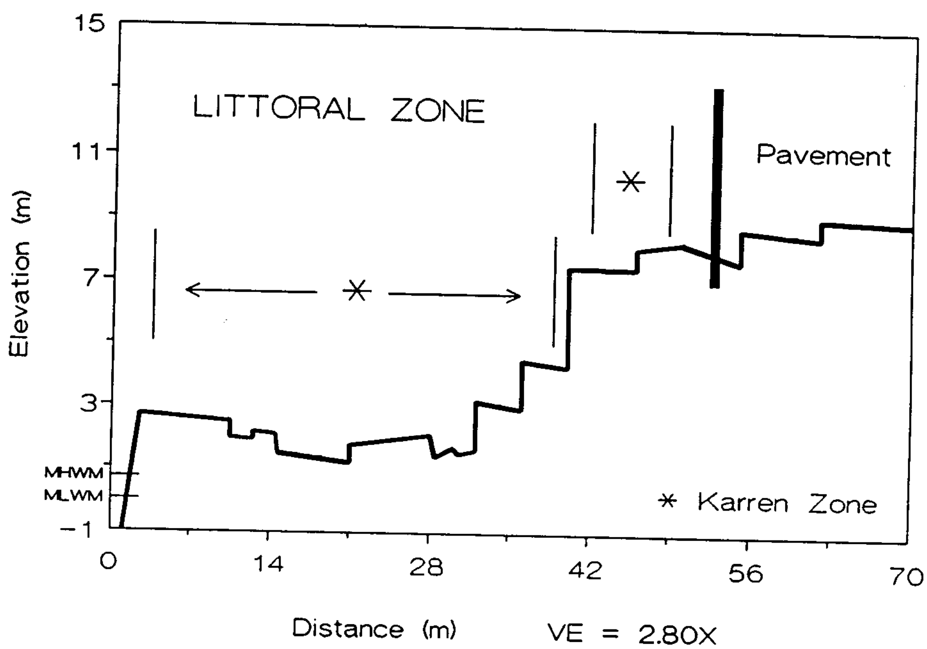



Figure 4.15 Platform development in the Cook's Harbour region. A) Photo of the coastline between Boat Harbour and Cape Norman (Figure 4.4), illustrating the vertical cliffs which often extend into the water. Note the huge expanse of limestone pavement which dominates this region. The asterisk shows the location of the profile in B. B) Profile across a section of developed platform, with karren occurring over most of the onshore littoral zone.

shoreline. An exception occurs towards the southwest end of the study area (Figure 4.4), where there is a narrow intertidal zone (Figure 4.16), but most of the platform is located in the backshore.

There are places where it was not feasible to produce a coastal profile, such as the majority of the east coast of Port au Port East Bay (Figure 4.17) and Daniel's Harbour (Figure 4.18). At these sites the coastal morphology made profile surveying difficult or impossible, but detailed karren notes and quadrat sampling were still made with respect to the MLWM and the position within the littoral zone. For some sites, such as Lower Head (Figure 4.19) and Broom Point (Figure 4.20), of the Cow Head Peninsula region, it was better to produce a small scale sketch map, delineating where the karren occurred with respect to the MLWM and the local lithology over a wider area. These maps allow one to see the spatial extent of karren development better, when the zonal pattern associated with the littoral zone is not as distinct.

Most of the karren at Lower Head occur along the western shore, especially at heights much higher than present sea level, in association with the megaconglomerate of the Cow Head Group (Sec. 3.2.5). This may be the best example of raised littoral karren, initiated during a higher sea level stand before postglacial isostatic rebound occurred. The "alpha boulder section" of Lower Head, much of which is shingle covered, flat and intertidal, refers to the largest clast conglomerate (approx. 50 m wide) of the Cow Head Group, clearly originating outside the depositional environment (James and Stevens, 1986; Figure 4.19). Although not shown in the figure, the alpha boulder includes the grass covered hill and cliff terrain extending to the north. Very little karren are associated with this biohermal facies, except on parts of the Alpha boulder fragment, which has broken off from the rest of the block.

Most of the karren at Broom Point (Figure 4.20) are associated with conglomerate beds of the Broom Point Member of the Cow Head Group. This is especially true for the karren zones along the northern shoreline, where conglomerate rock exists within the swash zone. The remainder of the area is shingle-dominated, or composed of lime mudstone, where karren was present only in the swash zone and at greatly reduced dimensions.

Some profiles were extended up to a distance of 20 to 30 m offshore by divers, as well

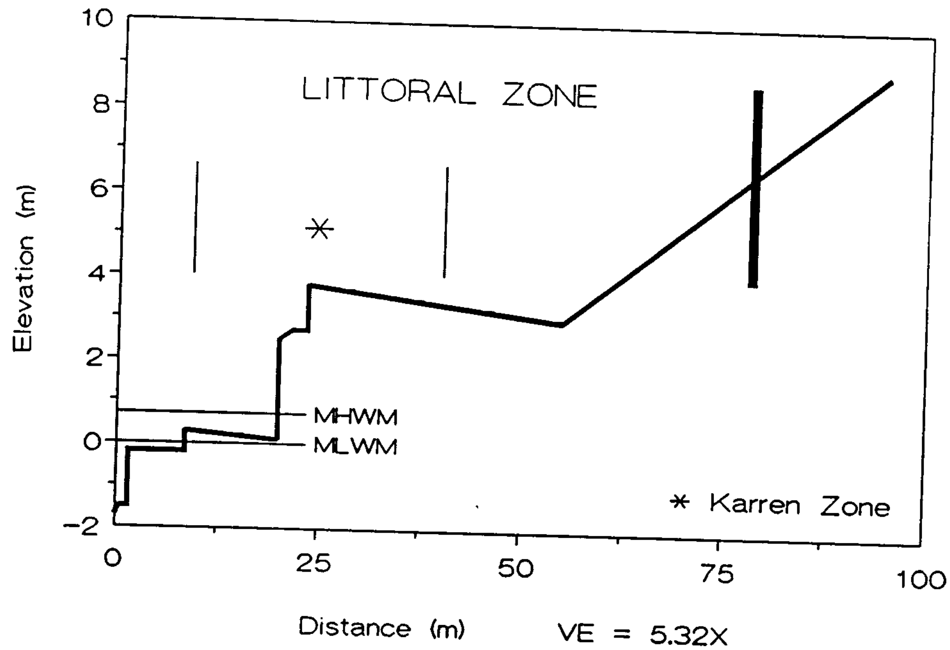



Figure 4.16 Representative profile for the platform morphology at the western end of the Cook's Harbour region, illustrating the presence of a narrow intertidal zone which also host karren.

as offshore surveys, parallel to the shoreline of the study site. In this manner detailed karren observations were made offshore along The Bar and Lower Cove, Port au Port Peninsula, the south and WNW shore of the Cow Head Peninsula and the entire study area of the Pointe Riche Peninsula.

Unfortunately, there was often a strong colonization of seaweed and/or algae cover on the submerged rock, blanketing any karren which may be present underneath. Most of the sites had an increasing amount of sand and shingle (usually cobble-sized) with increasing depth away from the shoreline. Sea urchins (*Strongylocentrotus droebchiensis*) were also in abundance, usually around 10 to 20 per ½ $m^2$ quadrat (Figure 4.21A), and up to 40 per ½ $m^2$ quadrat. There appears to be the same number of sea urchins in relatively exposed sites as in the more sheltered sites.

When carbonate rock was exposed many shallow pits were prevalent, however, and it can

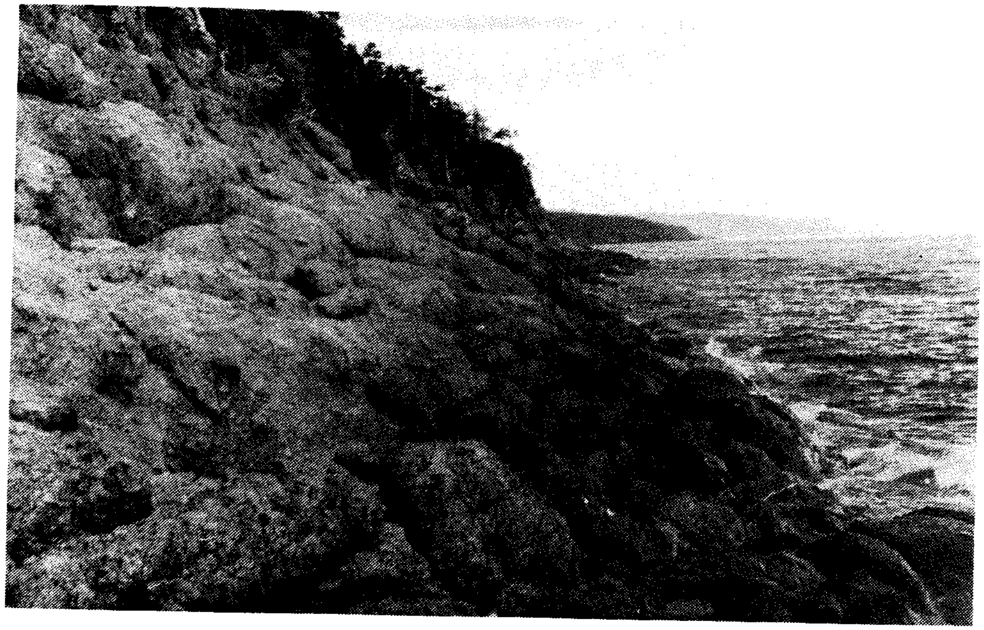


Figure 4.17 Photograph of the rugged coastline along the eastern shore of Port au Port East Bay, where the construction of coastal profiles was not feasible.

be assumed that the main eroding agent for these karren is from the action of the sea urchins (Sec. 2.2.3). Some degree of karren development was present for most sites within the first 3 to 4 m water depth below the MLWM, decreasing rapidly thereafter with the increase in clastic materials. The site with the best development of subtidal karren was adjacent to the south side of the Cow Head Peninsula, corresponding with one of the best sites for onshore littoral karren, with the karren averaging 1 to 7.5 cm in depth, reaching depths anywhere from 10 to 25 cm (Figure 4.21B). There does not appear to be any correlation with pit depth versus water depth, as opposed to the findings of Vajoczki (1993) offshore of Tobermory, Bruce Peninsula, Ontario.

## 4.3 Quadrat Sampling

Quadrat sampling refers to the representative sampling of the karren zones which existed within each coastal profile or study area. It was decided that metre square quadrats would be used,

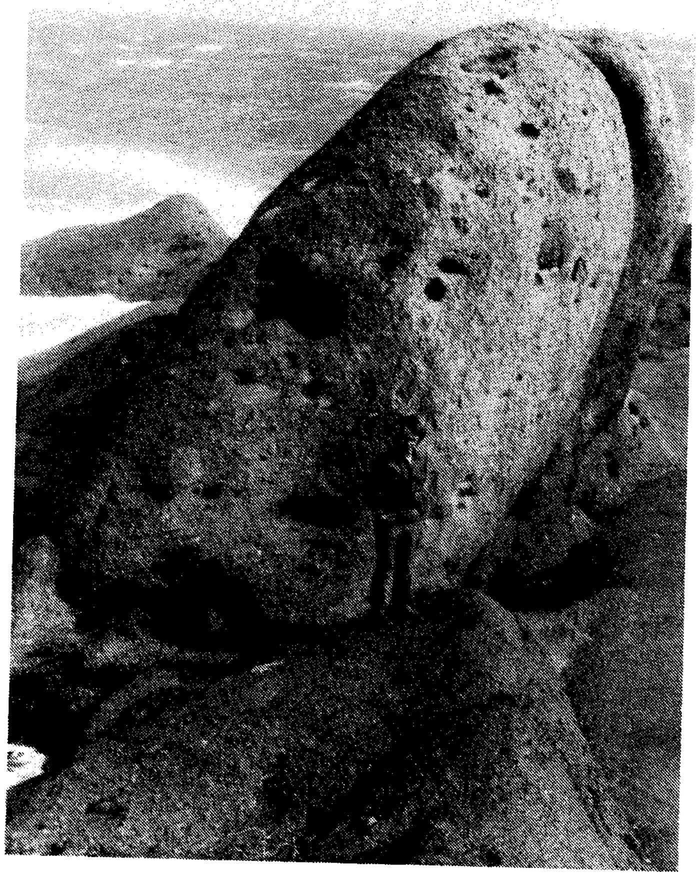


Figure 4.18 Coastal morphology of the limestone rock at Daniel's Harbour. There is very limited platform development at this site, and most of the rock is in the shape not unlike that of pinnacle karst described in Ford and Williams (1989). Karren are evident at all elevations throughout the photograph.

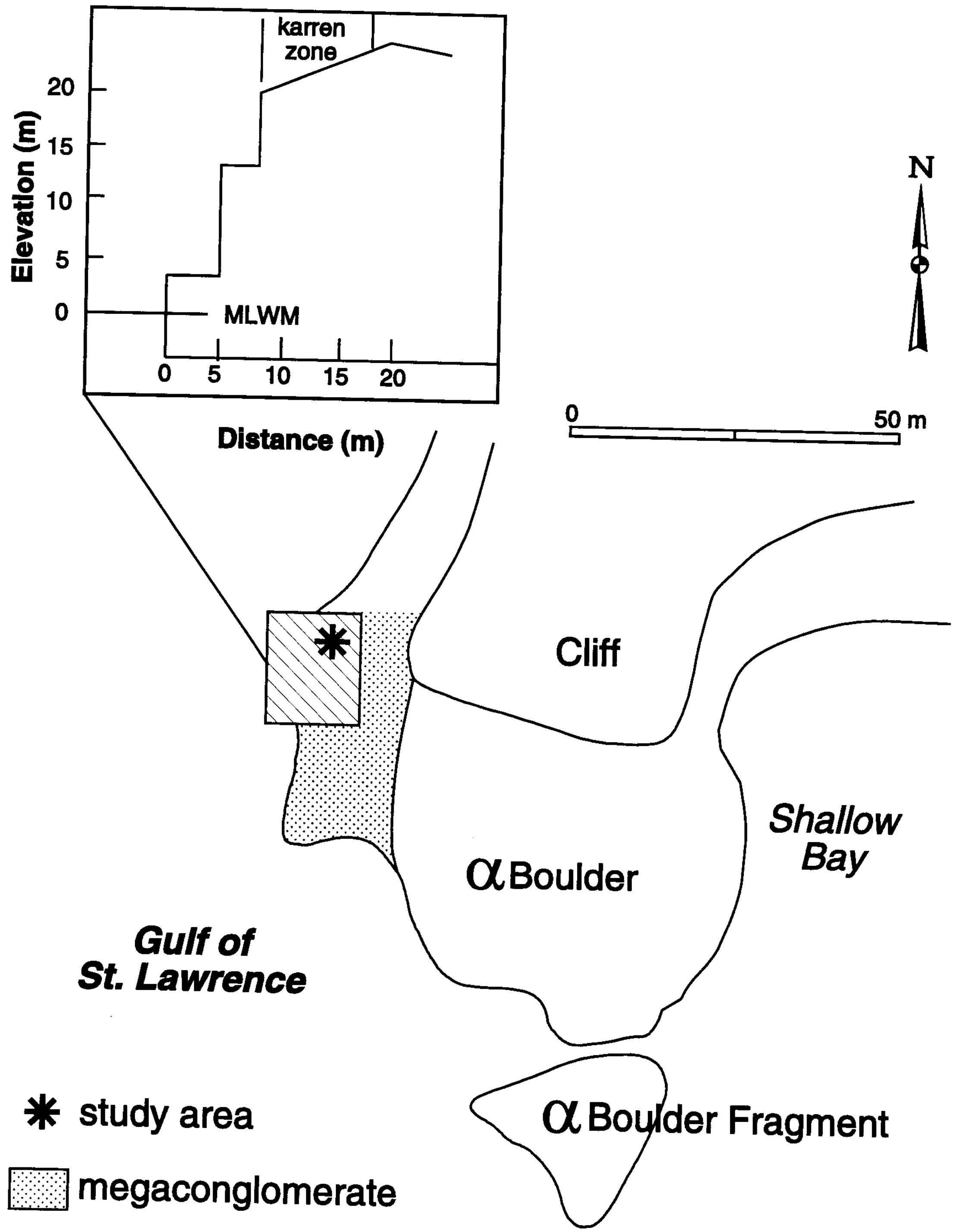



Figure 4.19 Sketch map of Lower Head illustrating the location of the study area, and the occurrence of littoral karren in the backshore. Alpha Boulder and Alpha Boulder fragment are discussed in the text.

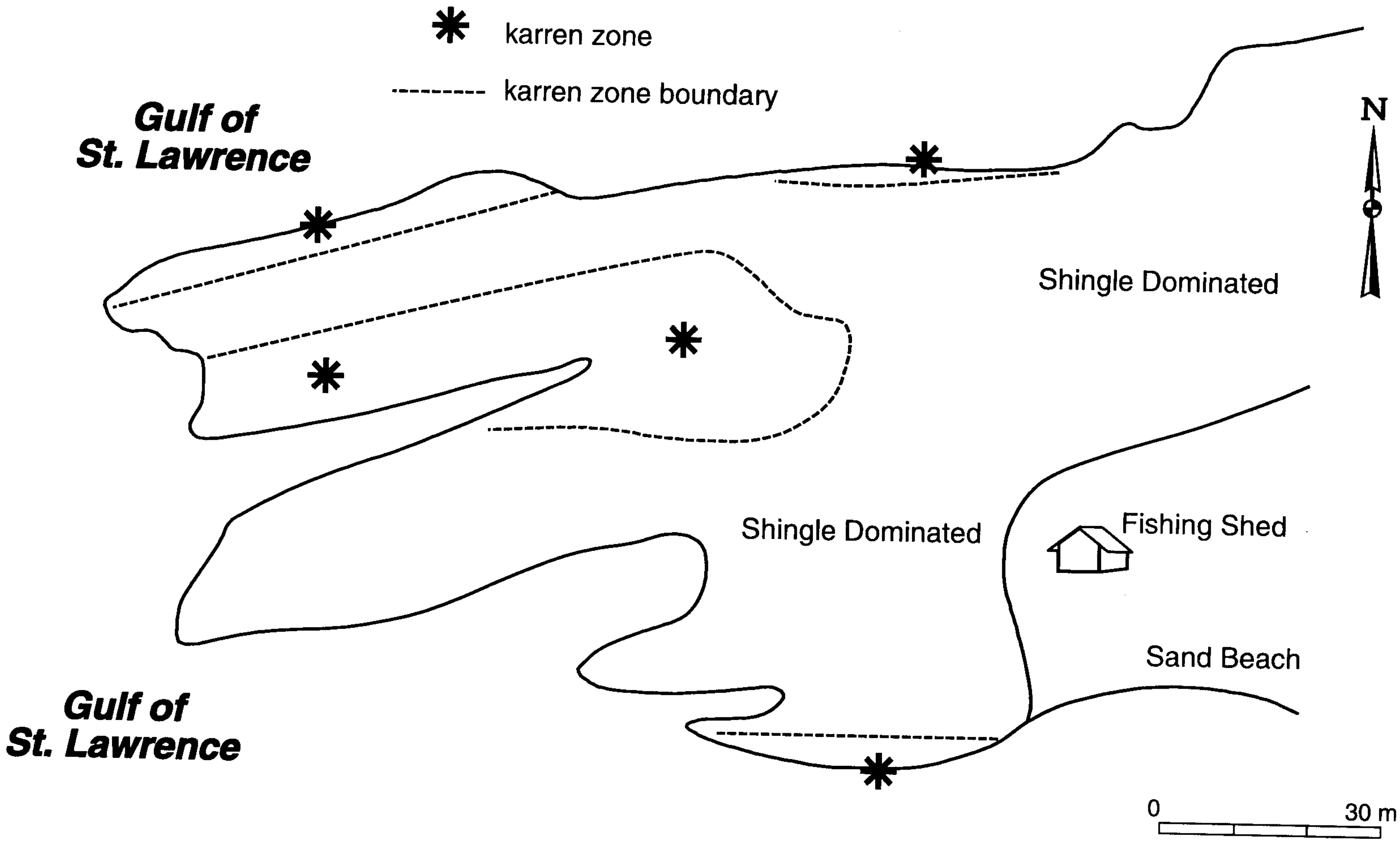



Figure 4.20 Sketch map of Broom Point illustrating the occurrence of karren, with respect to the combined influence of littoral zone location and lithology as discussed in the text.

A

B

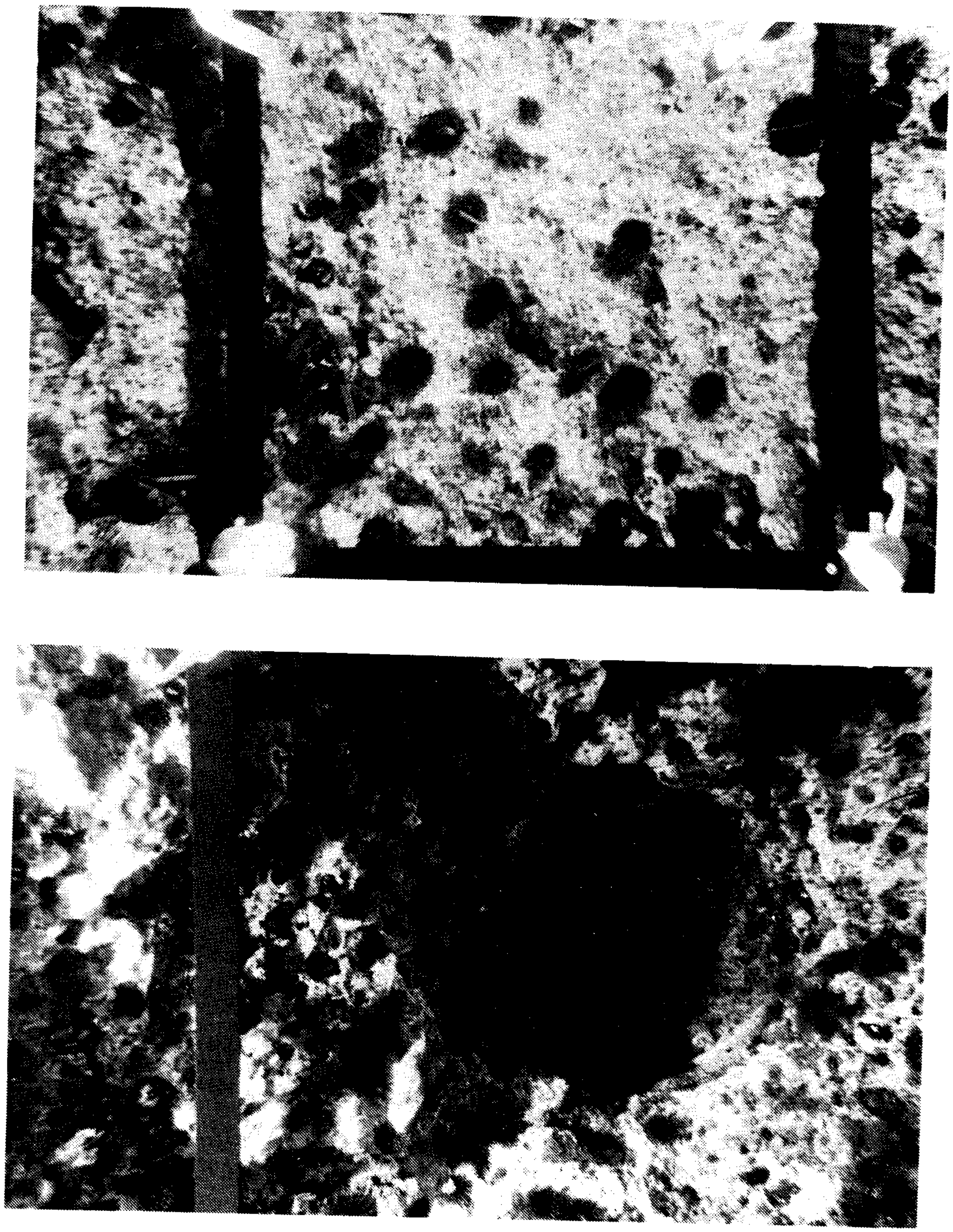


Figure 4.21 Photographs of littoral karren located in the subtidal zone offshore of the Cow Head Peninsula. A) Quadrat sample of *Strongylocentrotus droebchiensis* spp. and scattered shallow pitting approx. 1.5 m water depth. B) Example of karren pit with dimensions 25 x 19 x 10 cm (length by width by depth) approx. 5 m water depth.

following the practice of Ley (1976), to collect sufficient data in the time allowed. The number of quadrats for each profile varied, depending on the amount of karren variation within, and between, onshore littoral zones. Some karren zones required only one quadrat, while others needed several, especially where karren of a given type and scale spanned more than one onshore littoral zone. A total of 162 quadrats were measured throughout the study area, covering the 44 profiles produced, mapped coastal areas, and some isolated sites where the use of quadrats was the only feasible method of sampling the karren (e.g. the east shore of Port au Port East Bay).

Quadrat sampling provides the basis for the morphologic statistical analysis of the karren in Chapter 5. Within each quadrat karren density was determined, as well as the long axis, short axis and microrelief of each pit, noting the maximum and minimum-sized pit. If the density was greater than 30 per $m^2$ quadrat, then only 30 random pits were measured to provide a necessary sample for that quadrat. Only measurable pits were selected and this did not include micropits and poorly defined pits. At times the density was too high to count every single observation (i.e. > 100 pits/$m^2$ ), and a standard density of 100 pits/$m^2$ quadrat was recorded for these quadrats. It was not unusual to have less than 10 pits per $m^2$ quadrat.

The quadrat location on the profile is recorded and correlated to its position within the littoral zone. The karren zones fall within the inter-, supratidal and backshore zones, with at least 20 quadrats representing each one. The intertidal zone is the platform area between the MLWM and the MHWM, and is exposed to both subaerial and subaqueous conditions. The supratidal zone, for this study, is split into a swash zone, relating to the quadrats where the karren are regularly affected by high/rough water wave swash, and a spray zone where the karren are primarily a function of sea spray. The backshore karren are only affected by marine processes of erosion during unusually high spring tides or storm conditions.

Examples of some representative metre square quadrats and/or karren assemblages for each of the four littoral zones are provided in Figures 4.22 through 4.28. Figures 4.22 and 4.23 provide examples of intertidal zone karren, revealing a featureless, to highly micropitted, surface with minimal karren development, except for the presence of splitkarren (fissure-controlled karren; Figure

Figure 4.22 Intertidal zone along the Ingornachoix Bay shoreline. Most of the bare rock surface is featureless or host to a high density of shallow relief pits. Intertidal splitkarren are quite common along this coastline, where length is much greater than maximum width and depth.

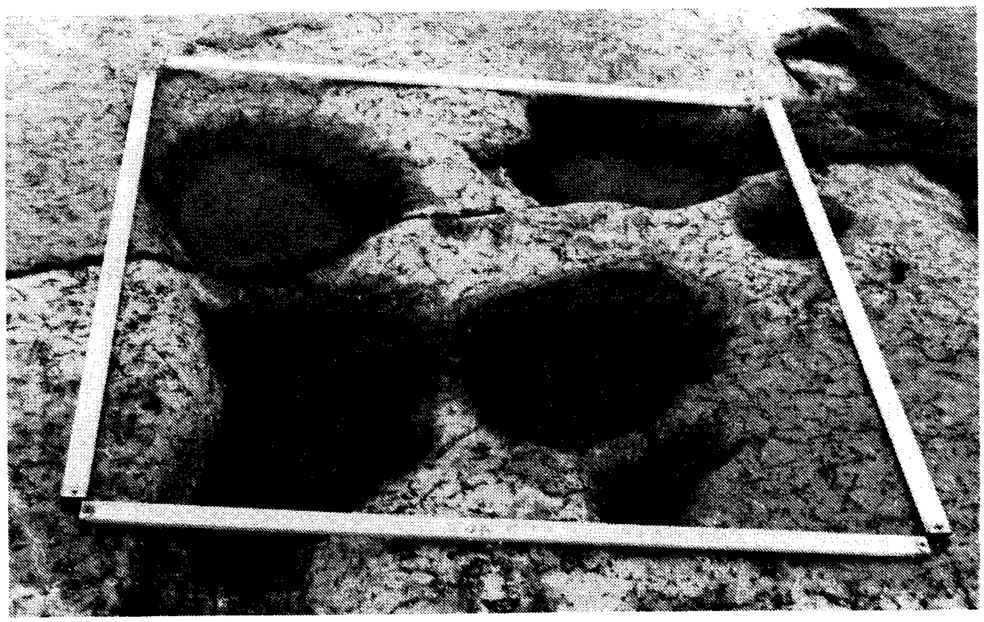
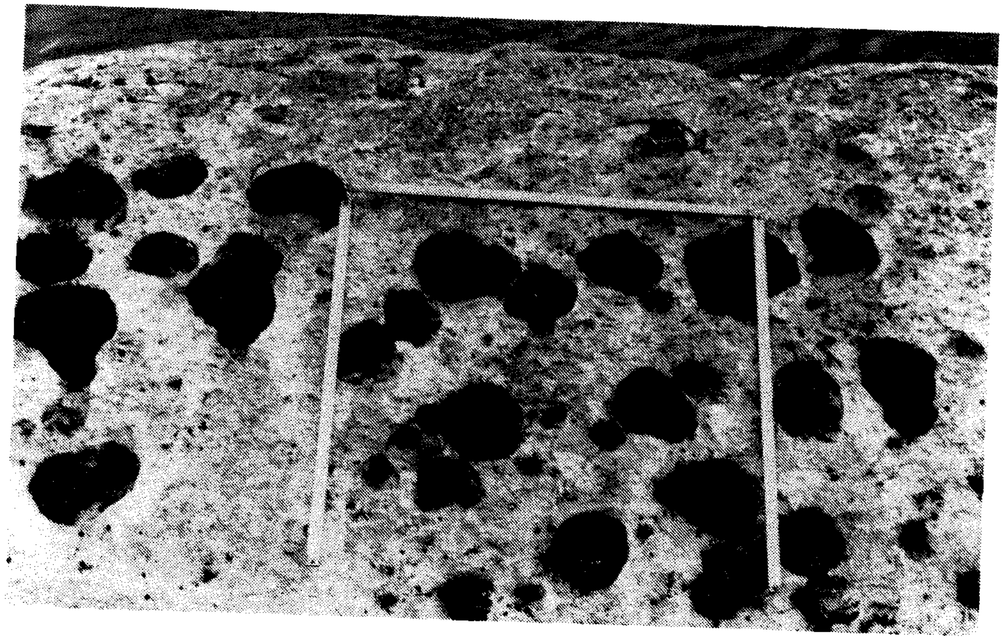


Figure 4.23 Intertidal zone quadrat at the Pointe Riche Peninsula. Again most of the surface is composed of featureless rock, yet also hosts fairly large, flora dominated, karren.

4.22). At the same time it is clear that in some instances the karren are quite significant, comprising the majority of the surface area of the quadrat (Figure 4.23). Karren variation within a single quadrat was greater within the intertidal zone than in the other zones.

The deepest and most spectacular karren occurred in the supratidal swash zone, as evidenced by Figure 4.24 and 4.25, where the karren are of low density and reach up to 1 m diameter and microrelief (e.g. Figure 4.25B). This is opposed to the supratidal spray zone where high density micropitting and much limited karren occur (Figure 4.26), in relation to the predominance of sea spray affecting the rock surface in this zone. Occasionally swash activity does affect the platform areas of the spray zone, producing bigger pits than expected (e.g. large, but shallow pits in Figure 4.26B). Pits also often coalesce together to produce fewer, larger pits.

A



B

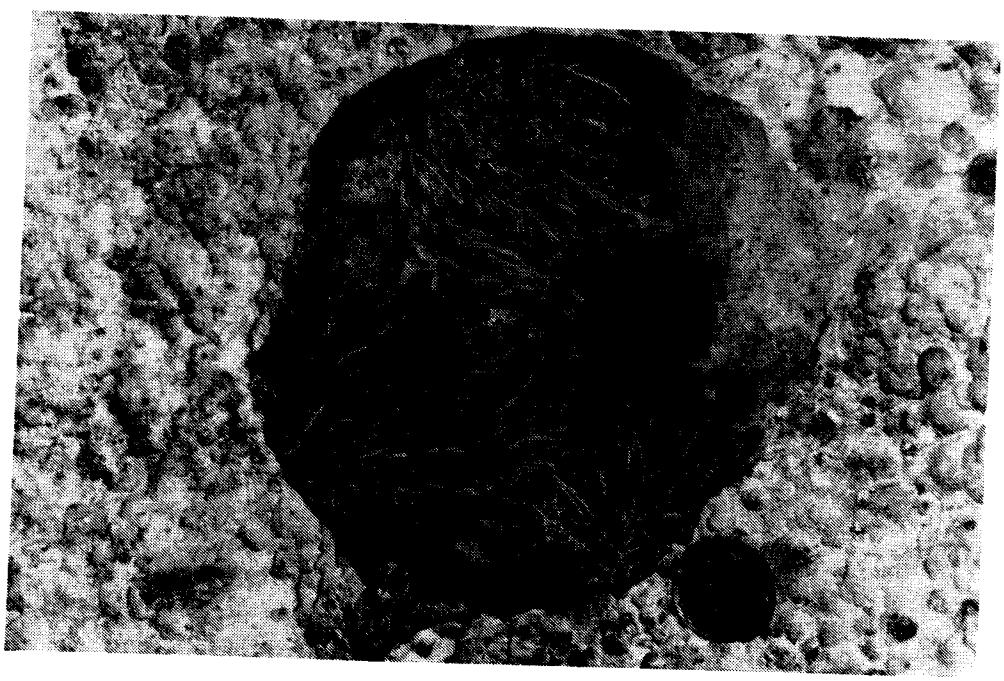


Figure 4.24 Examples of supratidal swash zone karren. A) Well defined karren pits on the east side of The Bar, Port au Port Peninsula, with a strong flora colonization of rockweed species *Fucus vesiculosus and disthicus*. B) Close-up of one karren pit. Note the intense micropitting on the rock surface surrounding the pit.

A

B

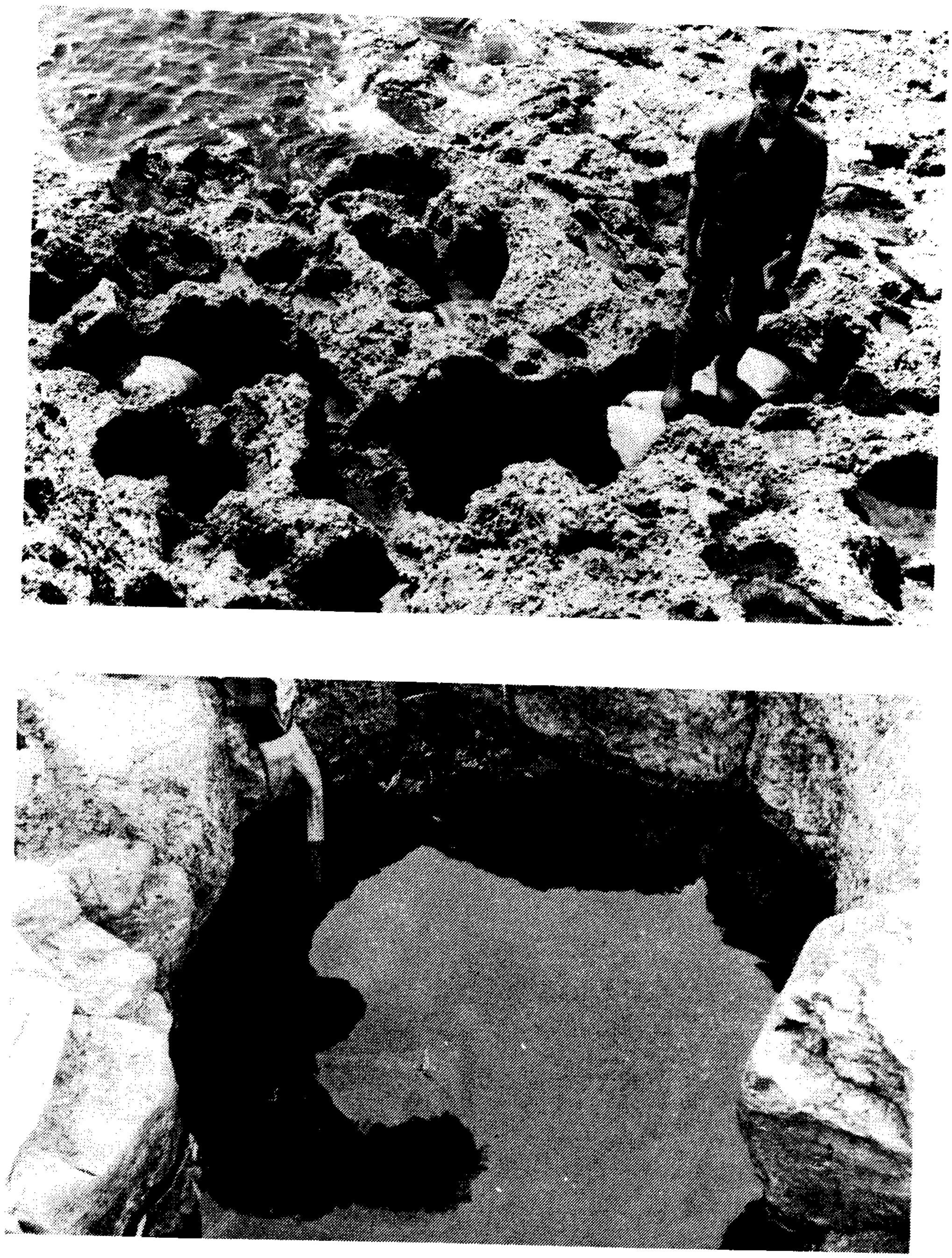


Figure 4.25 Examples of supratidal swash zone karren. A) Large karren pits on the south side of the Cow Head Peninsula. B) Close-up of a karren pit on the platform in the Cook's Harbour area, which measures about 1 m for all dimensions. The pit is distinguished from a pool of water by its tapered floor and circular plan form.

A

B

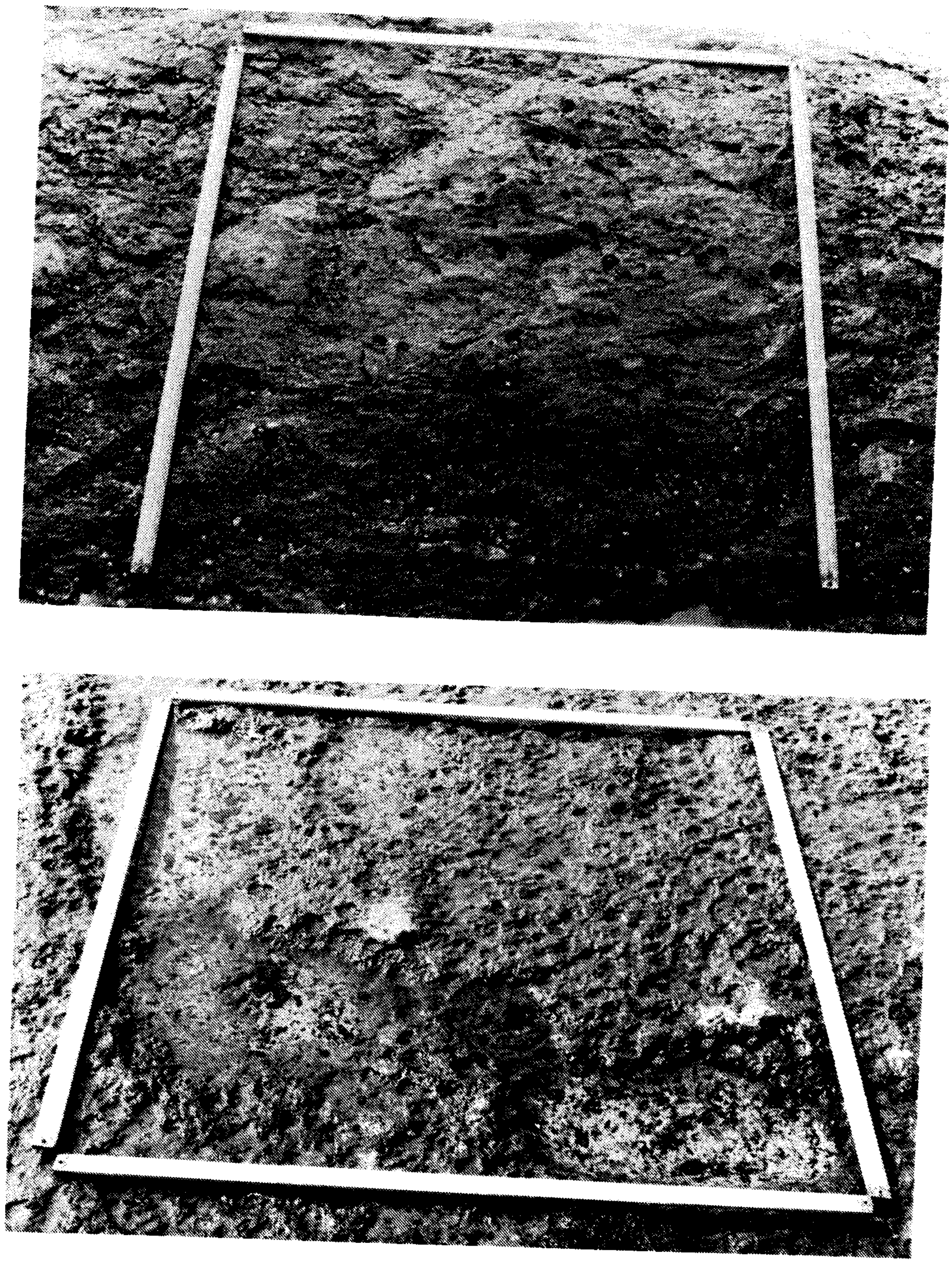


Figure 4.26 Examples of supratidal spray zone karren. A) Spray zone quadrat at the east side of The Bar, Port au Port Peninsula and B) at a platform section in the Cook's Harbour region. Note the general higher density of small, shallow pits, and the lack of larger, more defined pits.

The karren in the backshore are the most variable of the four zones, when quadrats are compared for different sites (Figure 4.27 and 4.28). This is probably due to the varying degrees of storm erosion experienced at the different sites, as well as variations in rock lithology and structure. Karren density in the backshore can be as low as only 1 or 2 pits per $m^2$ quadrat, or range as high as 30 to 40 per $m^2$ quadrat.

There are also sites, such as the New Ferrolle Peninsula (Figure 4.29A) and the northwest side of Long Point, Port au Port Peninsula (Figure 4.29B), where there is little or no karren development, even in the supratidal swash zone. This is due to the adverse lithology of the area reducing the effects of marine dissolution at these sites. The rock at the New Ferrolle Peninsula, as mentioned, is a dolomitic limestone, and the rock on the northwest side of Long Point is a siltstone containing only a small percentage of carbonate within its matrix. The solubility of these rocks is much less than predominantly pure limestone rocks of the Cow Head Peninsula (Figure 4.24A) and the Cook's Harbour region (Figure 4.24B).

## 4.4 Geologic Sampling and Measurements

Rock samples were taken in the field at all sites, usually at least two from each profile, with one taken within a karren zone and one where karren did not occur. One rock sample was taken to represent the inter- and supratidal zone, unless the rock was distinctly different between the two zones. A rock sample was taken from the backshore if the lithology was different from the other zones, or if karren were absent there for that platform. Samples were also usually taken from a karren zone where no profiles were constructed and only karren notes and observations were made (e.g. Daniel's Harbour; Cow Head Peninsula region). Within a study site a sample or two were taken from platform areas with no karren (except micropitting) in any of the three defined littoral zones. Samples were collected using a standard geologic hammer and chisel, with a sledgehammer used for platform sections where it proved difficult to break off a sample. These samples provided a means of establishing the lithology for each site and in producing representative thin sections, in order to determine some of the rock properties which may correlate with karren development. Chip

Figure 4.27 Example of backshore karren at the New Ferrolle Peninsula. The flat expanse of limestone pavement allows for the development of high density, but very poorly defined pits.

samples were also taken to determine the insoluble residue percentage of karren and non-karren areas.

On all of the platforms the general direction and dip of the strata hosting karren were recorded using a Brunton compass. On several scarp sloping platforms the angle of dip varied between scarps, so that the dip of each single scarp was determined. The occurrence of joints (splitkarren and grikes; e.g. Figure 4.22) within the platform was noted, with the dimensions of karren inside these joints recorded in addition to that of regular quadrats. Detailed analysis, however, is focused on circular pits and pans occurring on the open rock surface of the littoral zone.

## 4.5 Water Chemistry Measurements

Water measurements of the inter-, supratidal and backshore pools were undertaken to see

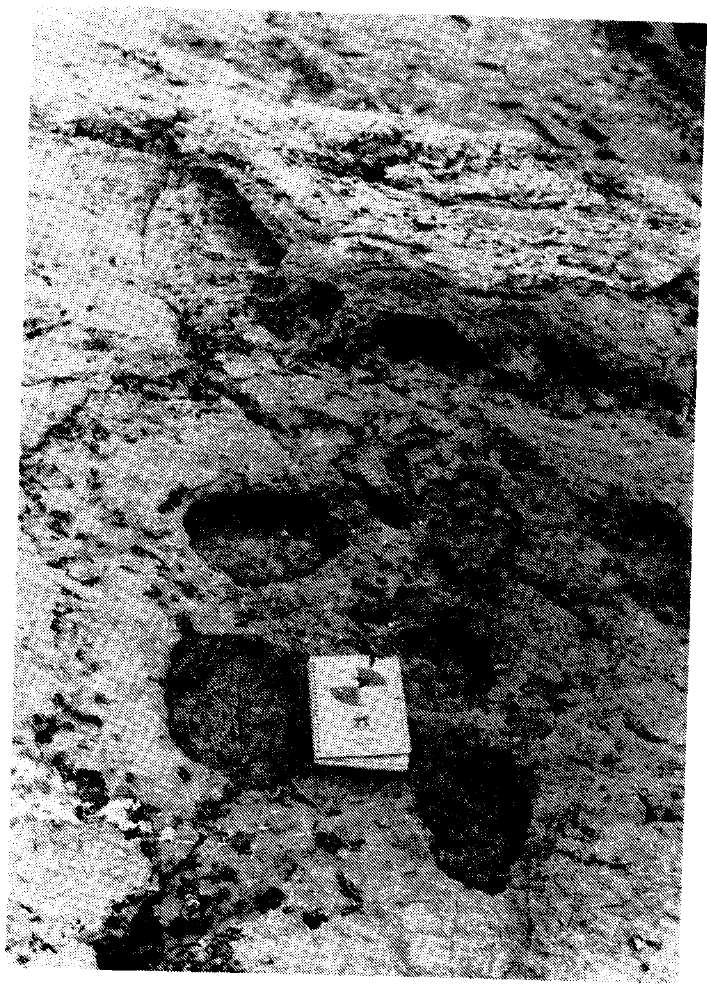


Figure 4.28 Example of backshore karren at the Port au Choix Peninsula. Here the karren are of a much lower density and almost appear to be paleo-pits, with very little evidence of a marine influence.

A

B

Figure 4.29 Examples of sites which host minimal, if any, karren. A) Supratidal swash zone platform at Ferrolle Point on the New Ferrolle Peninsula, revealing zero karren development on this dolomitic limestone rock. B) The occurrence of quite high density, but very small, karren features in the supratidal swash zone on the northeast side of Long Point, Port au Port Peninsula.

if there is any correlation between the degree of karren development and the ocean water chemistry. Measurements were taken across all profiles, or any other areas where there were some variations in the water chemistry of the platform pools. Water temperature, conductivity and salinity were measured using a standard YSI model # 33 S-C-T meter, and pH was measured using a Cole-Palmer Digi-Sense pH meter (model No. 5985-80). The S-C-T meter was calibrated in the lab before and after the field season. The pH meter is calibrated in the field with the use of buffer solutions before each recording. It is imperative that the buffer solutions be brought to the same ambient temperature as the water, in order to reduce any error in the readings as much as possible (Ford and Williams, 1989). The time of day and weather conditions were recorded when all measurements were taken.

At one selected site, along the western dip slope of the Pointe Riche Peninsula, a more detailed programme of water chemistry analysis was performed. Here there existed an excellent range of saline conditions across the platform, thereby creating differences in the abundance of different cations and anions in solution. Seven platform pools, shallow ocean water and terrestrial bog water, at the top of the platform (Figure 4.30), were analyzed in the field for concentrations of total hardness, $Ca^{2+}$ and $Mg^{2+}$ hardness and alkalinity, using a Hach digital titrator (model No. 16900-01). These procedures must be done as soon as possible after collection when the sample is fresh. Water samples from this site were brought back to the lab, kept cool and out of sunlight, to determine the concentration of all other ions in solution, which can be determined with better precision in the lab.

## 4.6 Biological Sampling

Within the metre square quadrats the degree, and type, of biological organism colonization was noted, with variations occurring depending on the location of the quadrat within the littoral zone. All flora and fauna species were identified, as best as possible, in the field using field references by The Audubon Society (1981) and Gosner (1979) as guides.

A sample of each important floral and faunal species encountered was preserved and taken

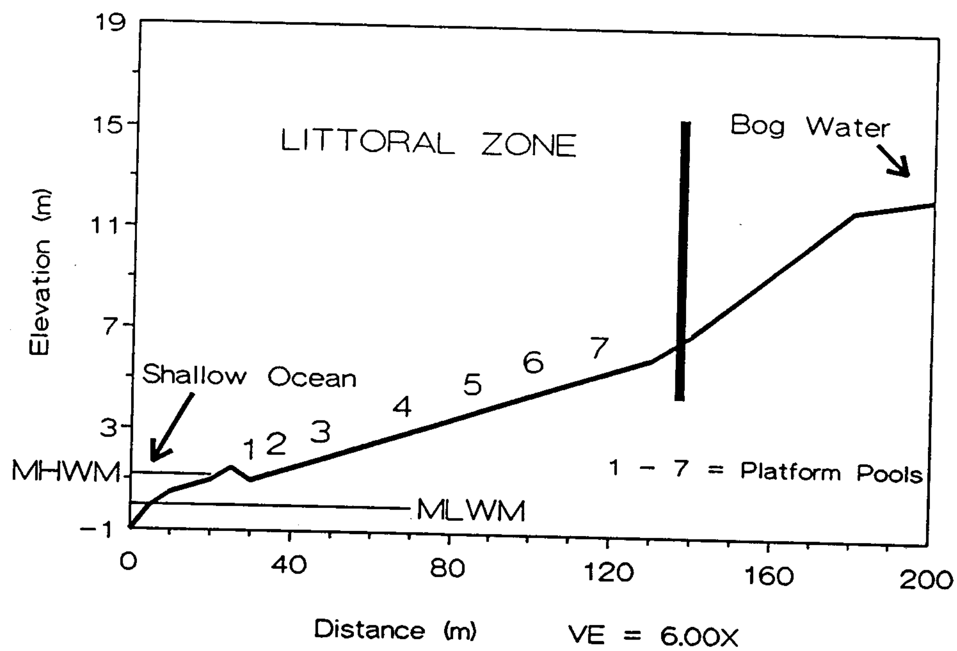



Figure 4.30 Profile across the western dip slope of the Pointe Riche Peninsula, illustrating the location of platform pools, shallow ocean and bog water, which were used for detailed water chemistry sampling and measurements.

back to the lab for confirmation. Floral species were preserved in a 10% formalin (37% concentrate) solution of sea water, enriched with 500 g of calcium carbonate ($CaCO_3$) chips. Faunal species were preserved for three days in this same solution, washed with fresh water and transferred into a 70% ethanol (95% concentrate) and 3% glycerine (99.5% assay concentrate) fresh water solution.

Littoral fauna found along the western shore of Newfoundland are summarized in Table 4.2, littoral flora (seaweed) in Table 4.3 and algae/lichen species in Table 4.4. There is not a huge variety of species, due to the cold ocean climate of the region and the presence of seasonal sea ice. The only species in abundance at all of the sites was the Northern Rock Barnacle, *Semi-balanus balonoides*, often blanketing the entire intertidal zone (Figure 4.31) and the Common Periwinkle, *Littorina littorea* (Figure 4.32). Also colonizing the intertidal zone, but only as clusters within existing pits, notches and joints is the Blue Mussel, *Mytilus edulis* (Figure 4.31and 4.32).

Table 4.2 Littoral fauna distribution along the west coast of Newfoundland, from the Port au Port Peninsula to Cape Norman Point, in the Cook's Harbour region.

| Genus (species) | Common Name | Habitat | Abundance* |
|---|---|---|---|
| *Semi-balanus balanoides* | Northern Rock Barnacle | Entire Intertidal Zone | High |
| *Littorina littorea* | Common Periwinkle | Entire Intertidal Zone | High |
| *Littorina saxatilus* | Rough Periwinkle | Upper Intertidal, Supratidal Zone | High |
| *Strongylocentrotus droebchiensis* | Green Sea Urchin | MLWM and Subtidal | High |
| *Thais lapillus* (Port au Port Peninsula only) | Atlantic Dogwinkle | Entire Intertidal Zone | Moderate |
| *Mytilus edulis* | Blue Mussel | Lower Intertidal, Subtidal Zone | Moderate |
| *Acmaea testudinalis* (Port au Port Peninsula only) | Tortoise-shell Limpet | Mid-lower Intertidal Zone | Low |
| *Gammarus oceanicus* | Scuds | Tidal Pools Only | Low |

* Abundance is a relative term based on the degree of colonization within each zone, estimated by the percentage of the area covered by a species within the metre square quadrats.

High = > 75% cover

Moderate = 25 - 75% cover

Low = < 25% cover or restricted to tidal pools

Table 4.3 Littoral flora (seaweed) distribution along the west coast of Newfoundland, from the Port au Port Peninsula to Cape Norman Point, in the Cook's Harbour region.

| Genus (species) | Common Name | Habitat | Abundance* |
|---|---|---|---|
| *Fucus distichus* and *vesiculosus* | Rockweeds | Intertidal Zone (common in pits) | High |
| *Ascophyllum nodosum* | Knotted Wrack Seaweed | Intertidal Zone (blanket) | High |
| *Chondrus crispus* | Irish Moss | Intertidal Zone | Moderate |
| *Scytosiphon lomentaria* | Sausage Weed | MLWM and Subtidal | Moderate |
| *Chordaria flagelliformis* | Black Whip Weed | MLWM and Subtidal | Moderate |
| *Entermorpha compressa* and *Ulothrix subflaccida* | Hollow Green Seaweeds | Tidal Pools Only | Low |
| *Spongomorpha arcta* and *Cladophora rupestris* | Filamentous Green Seaweeds | Tidal Pools Only | Low |
| *Pilayella littoralis* | Brown Seaweed | Intertidal Zone | Low |

* Abundance is a relative term based on the degree of colonization within each zone, estimated by the percentage of the area covered by a species within the metre square quadrats.

High = > 75% cover

Moderate = 25 - 75% cover

Low = < 25% cover or restricted to tidal pools

Table 4.4 Littoral coralline algae and lichen distribution along the west coast of Newfoundland, from the Port au Port Peninsula to Cape Norman Point, in the Cook's Harbour region.

| Genus (species) | Common Name | Habitat | Abundance* |
|---|---|---|---|
| *Verrucaria* | Black and Green Lichen | Upper Supratidal Zone/Backshore | High |
| *Xanthoria* | Orange Lichen | Upper Supratidal Zone/Backshore | Low |
| *Lithothamnion glaciale* | Rose and White Coralline Algae | Subtidal Zone | High |
| *Prasiola stipitata* | Green Algae (moss-like) | Supratidal Zone | Low |
| *Clatromorphum circumscriptum* | Pink and White Coralline Algae | Tidal Pools Only | Low |
| *Phymatolithon lenormandii* | Speckled Pink Coralline Algae | Tidal Pools Only | Low |
| *Stragularia clavata* | Brown Coralline Algae | Tidal Pools Only | Low |

* Abundance is a relative term based on the degree of colonization within each zone, estimated by the percentage of the area covered by a species within the metre square quadrats.

High = > 75% cover

Moderate = 25 - 75% cover

Low = < 25% cover or restricted to tidal pools

A

B

Figure 4.31 Examples of *Semi-balanus balonoides* and *Mytilus edulis* colonization in the intertidal zone. A) Intertidal platform section on the Pointe Riche Peninsula. Clusters of white are *Semi-balanus balonoides* and the dark blue are clusters of *Mytilus edulis*. B) Small, lower intertidal notch on the Ingornachoix Bay shoreline, represented in the profile in Figure 4.14B, strongly colonized by *Mytilus edulis* with *Semi-balanus balonoides* attached to the wall above the notch.

Figure 4.32 Exposed intertidal step at Gargamelle Cove revealing scattered colonization of *Littorina littorea*, as well as a cluster of *Mytilus edulis* and a few *Strongylocentrotus droebchiensis* species.

*Strongylocentrotus droebchiensis*, as mentioned, dominate the subtidal environment (Figure 4.21a), but are occasionally exposed at the MLWM at low tide (Figure 4.32).

The most dominant floral species are the rockweeds *Fucus distichus* and *vesiculosus*, which often flourish within karren pits of the mid-upper intertidal zone and the supratidal swash zone (Figure 4.24). *Ascophyllum nodosum* usually blankets the entire surface within the intertidal zone, especially in depression areas with water (Figure 4.33). Generally only lichen species colonize the surface of the upper supratidal and, occasionally, backshore zones, except for platform pools containing seaweed species *Entermorpha compressa, Ulothrix subflaccida* and *Spongomorpha arcta.*

There is not a clear biological zonation, especially within the intertidal zone. This contrasts with the karren studies at Galway Bay (Williams, 1971; Lundberg, 1974; Trudgill, 1987), and is probably due to the harsher marine environment present along the west coast of Newfoundland, as well as the microtidal range and often very narrow intertidal zone. Most species which inhabit the intertidal zone of western Newfoundland colonize the entire area, although numbers and size usually decrease toward the high tide line. Intertidal organisms are capable of adapting to both subaerial and subaqueous conditions on a diurnal basis, while subtidal species must remain submerged in standard ocean salinity levels for survival. Supratidal species are capable of surviving high salinity tidal pools, associated with almost constant subaerial conditions and increased evaporation. Very few species are capable of adapting to this area of the littoral zone.

It should be stressed that most of these species do not appear to be active rock borers. For the most part they colonize existing hollows and pits within the rock, for protection from wave and wind action. There is little evidence, in the rock samples brought back to the lab, that bioerosion occurs at all (Aitken, Pers. Comm., 1992). The only exceptions are found with rock continually submerged in pools of water. Here there are a number of filamentous, microscopic red, green and blue-green algae which can bore into carbonate rock (Sec. 2.2.3B); some pitting is present in rock samples taken from these pools, but at a scale too small to be considered for this study. There are also several coralline algae species associated with these pools (Table 4.4), but they do not erode

Figure 4.33 Thick blanket of *Ascophyllum nodosum* in a water-filled depression area of the upper intertidal zone on the Cow Head Peninsula. *Ascophyllum nodosum* are especially common in areas like this where the platform rock is quite broken and scattered.

into the rock, for doing so would be detrimental to their very structure (Bird, Pers. Comm., 1992).

It is possible that pre-existing karren pits are enhanced by the presence of rockweed species. Some of the best defined pits possess rockweed within them (Figures 4.24). As these rockweeds grow and expand, their roots become denser and stronger, weakening the rock and making it more susceptible to erosion from wave swash and turbulence. Thus, some larger pits may be indirectly related to the growth of the rockweeds, as well as the combined action of filamentous algae species within the rock strata.

There does appear to be direct bioerosion offshore in the subtidal zone. Off the northwest shore of the Pointe Riche Peninsula a loose rock sample, filled with small boreholes, was brought to shore by divers (Figure 4.34). The morphology of the boreholes are characteristic of those produced from the Red Nose clam species, *Hiatella arctica* (Aitken, Pers. Comm., 1992). Time did not allow for a detailed study of this rock sample to confirm the species of origin of these boreholes.

It is the view of the author that bioerosion is minimal along the shore of western Newfoundland. This is due to the cold climate of the region and the seasonal sea ice, possibly destroying organisms on an annual basis, as well as the low porosity, highly crystalline limestone rock, which is diagenetically more mature than that typically found in the tropics. Because bioerosion is not a significant factor in developing the karren along the coast of western Newfoundland, it is not considered a part of the quantitative analysis of the inter- and intrasite karren variation for the study regions.

A

B

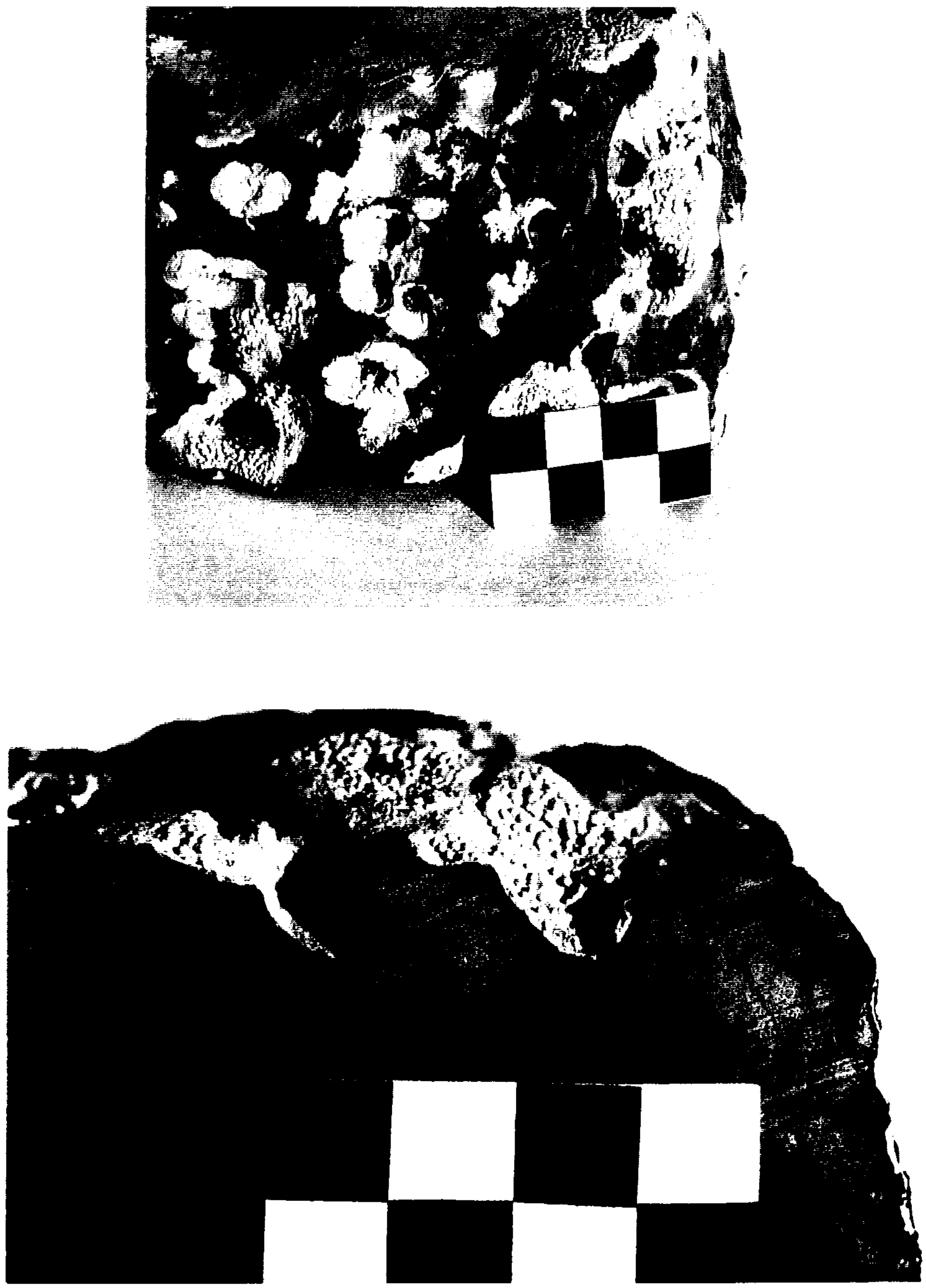


Figure 4.34 Rock sample taken from offshore of the Pointe Riche Peninsula. A) Plan view of several small boreholes believed to be cause by *Hiatella arctica*. Pink to whitish crusts on the rock are the coralline algae species, *Lithothamnion glaciale*. B) Close-up, cross sectional view of two boreholes. Each scale division equals one cm.

# CHAPTER 5

# ANALYSIS AND RESULTS

## 5.1 Introduction

This chapter will attempt to quantify any variations in karren density and morphology (diameter and microrelief), which exist along the west coast of Newfoundland. This includes intrasite karren analysis and an examination of trends in karren development along a coastal profile, and the different littoral zones, in relation to the tidal range. Intersite statistical comparisons of the study sites, both within and between the four major regions, are undertaken to verify any intersite karren variation that may exist.

Geology appears to be the most important factor in controlling karren development (Sec. 2.2.4). Rock samples taken in the field from all sites are classified and selected properties are correlated with variations in karren development. The amount and direction of platform dip, on sections of rock hosting karren, are analyzed to examine any structural control on the karren.

Finally, the analysis becomes more process-oriented. Degree of exposure and available energy for a region, established in Section 3.5.1, are correlated with karren morphology and density. This will give an indication of the importance of increased wave energy-driven erosion on the karren. The role of offshore and onshore gradients are examined in relation to potentially affecting the karren. Results of water property measurements, recorded in the platform rock pools, are presented for conductivity, salinity and pH, and are then correlated with variations in karren morphology. All of the statistics presented in this chapter were calculated using the SPSS/PC+ Version 5.0 (1992) computer system.

## 5.2 Statistical Analysis of Karren Morphology and Density

### 5.2.1 Descriptive Statistical Analysis

Before the karren observations are separated into the different littoral zones, to establish any intrasite karren variation, an overall descriptive statistical summary is provided. This enables one to readily see the distribution of the data involved and dispersion around the mean. Table 5.1 lists the mean ($\bar{x}$), standard deviation ($\sigma_x$) skewness (*Sk*) and kurtosis ($K$) for karren long and short axis, diameter, microrelief and density, measured within the metre square quadrats described in Section 4.3.

It is clear from the significantly high skewness and kurtosis values that the distributions are not normal for any of the karren measurements presented except density. Instead, there is somewhat of a resemblance to a Poisson distribution as revealed in histograms of diameter (Figure 5.1A) and microrelief (Figure 5.1B). This is because about 72% of karren microrelief measurements are less than 5 cm and about 67% have diameters less than 10 cm. Average diameter is more than double that of average microrelief, and there is a width to depth ratio of about 2:1. It should be noted that the range of data is over 100 cm, but the high percentage of observations at the lower end of the scale warranted the narrow interval widths used in Figure 5.1. Thus, the last interval is open-ended in order to exhaust all of the data, at the same time providing a suitable number of classes to analyze the data.

Class intervals are expanded for density since these data are more uniformly distributed (Figure 5.1C). The highest percentage of quadrats (37%) have densities less than 10 pits/m$^2$, and over half (61.7%) have less than 20/m$^2$. Less than 20% of the quadrats used in the study had densities of at least 50 pits/m$^2$. Again, these density values do not include the numerous, very high density micropits, often evident on the rock surface surrounding larger, more defined pits (Sec. 4.3; Figure 4.24).

Descriptive statistics were then produced for the karren in each littoral zone defined in Section 4.3, to assess if there is any zonal pattern of karren development. Table 5.2 lists the same descriptive statistical parameters used in Table 5.1, for the karren morphologic measurements within

Table 5.1 Descriptive statistical summary for littoral karren measurements existing along the west coast of Newfoundland.

| Karren Measurement | Descriptive Measure | | | | |
|---|---|---|---|---|---|
| | $\bar{x}$ (cm) | $\sigma_x$ (cm) | *Sk* | *K* | *N* |
| Long Axis | 11.06 | 11.69 | 2.81 | 15.01 | 2520* |
| Short Axis | 8.28 | 8.79 | 3.69 | 30.24 | 2520 |
| Diameter | 9.70 | 8.41 | 4.22 | 38.43 | 2520 |
| Microrelief | 4.19 | 5.31 | 7.67 | 111.76 | 2496+ |
| Density | 27.48 (per $m^2$ quadrat) | 33.10 (per $m^2$ quadrat) | 1.53 | 0.79 | 162** |

* refers to the number of individual karren observations recorded within all metre square quadrats, regardless of location within the littoral zone

** refers to the total number of quadrats used to sample karren in the study

+ the number of microrelief observations are less than that for the other measurements, as there were times when biological colonization by *Mytulis edulis* (e.g. Figure 4.31A) prevented a proper microrelief measure of those pits

the inter-, supratidal swash and spray zones and the backshore. Table 5.3 provides a zonal statistical summary for density. Note that the number of observations are not close to being uniform across the zones. This, in itself, is an indication of the differential karren development that is evident at all sites. The backshore zone usually lacks karren, however, it appears that when they do occur they are, on average, the largest, deepest and most variable between sites. If spray zone data are excluded, there is an increase in karren size toward the backshore and a noticeable decrease in density. Spray zone karren were the most consistent over the study areas, with the lowest standard deviation values for all morphologic measurements.

A
B
C

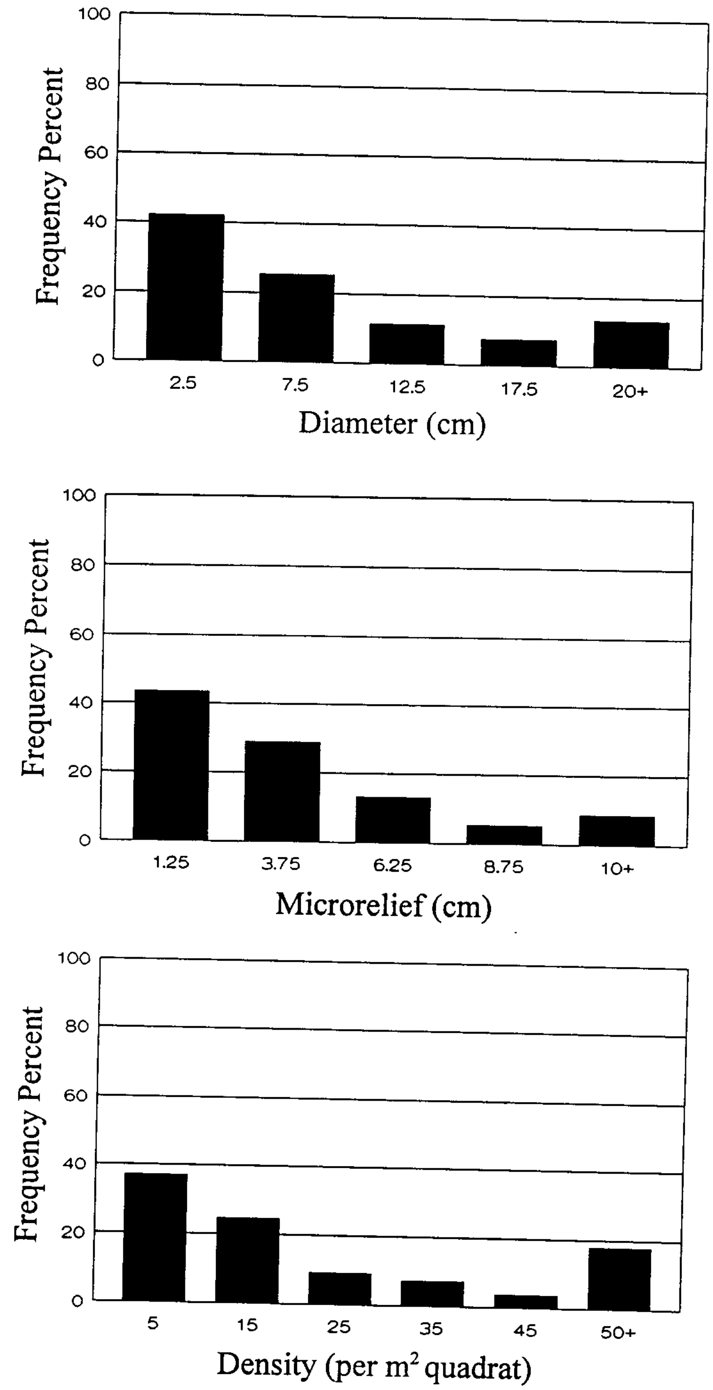



Figure 5.1 Frequency histograms illustrating general variations in karren A) diameter, B) microrelief and C) density. X-axis represents the mid-point of each class interval.

Table 5.2 Descriptive statistical summary for karren long axis, short axis diameter and microrelief for each littoral zone.

| Zone | Morphologic Dimension | Descriptive Measure | | | | |
|---|---|---|---|---|---|---|
| | | $\bar{x}$ (cm) | $\sigma_x$ (cm) | *Sk* | *K* | *N** |
| **Intertidal** | Long Axis | 9.41 | 9.82 | 2.49 | 8.11 | 956 |
| | Short Axis | 6.96 | 6.56 | 2.17 | 5.77 | 956 |
| | Diameter | 8.17 | 8.02 | 2.19 | 5.63 | 956 |
| | Microrelief | 3.00 | 2.92 | 2.97 | 11.70 | 930** |
| **Supratidal Swash** | Long Axis | 13.81 | 11.88 | 1.86 | 5.73 | 791 |
| | Short Axis | 10.40 | 9.09 | 2.67 | 16.45 | 791 |
| | Diameter | 12.10 | 10.33 | 2.13 | 9.48 | 791 |
| | Microrelief | 5.64 | 6.21 | 6.74 | 88.80 | 791 |
| **Supratidal Spray** | Long Axis | 4.78 | 4.59 | 2.92 | 11.11 | 598 |
| | Short Axis | 3.55 | 3.23 | 3.39 | 14.93 | 598 |
| | Diameter | 4.17 | 3.84 | 3.09 | 12.69 | 598 |
| | Microrelief | 2.20 | 1.80 | 3.75 | 23.65 | 598 |
| **Backshore** | Long Axis | 16.24 | 17.74 | 3.05 | 15.35 | 175 |
| | Short Axis | 12.43 | 14.20 | 3.86 | 25.03 | 175 |
| | Diameter | 14.34 | 15.85 | 3.39 | 19.55 | 175 |
| | Microrelief | 5.90 | 8.24 | 6.63 | 60.61 | 175 |

* refers to the number of individual karren observations recorded within all metre square quadrats for each zone

** the number of microrelief observations are less than that for the other measurements, as there were times when biological colonization by *Mytulis edulis* (e.g. Figure 4.31A) prevented a proper microrelief measure of those pits

Table 5.3 Descriptive statistical summary of karren density for each littoral zone.

| | Descriptive Measure | | | | |
|---|---|---|---|---|---|
| Zone | $\bar{X}$ (per m$^2$ quadrat) | $\sigma_x$ (per m$^2$ quadrat) | *Sk* | *K* | *N** |
| Intertidal | 39.92 | 37.59 | 0.838 | -1.01 | 47 |
| Supratidal Swash | 14.65 | 17.81 | 3.60 | 15.21 | 70 |
| Supratidal Spray | 56.72 | 40.82 | 0.042 | -1.96 | 25 |
| Backshore | 7.29 | 6.31 | 2.18 | 6.45 | 24 |

* refers to the number of quadrats used to sample karren within each zone

These karren measurement distributions are organized into frequency histograms for diameter (Figure 5.2), microrelief (Figure 5.3) and density (Figure 5.4), with the number of classes and interval widths used in Figure 5.1. The use of frequency percent allows for proper comparison between the four zones. Intertidal and spray zone karren are quite small in comparison to the swash and backshore zones. Over 40% of the intertidal karren have diameters less than 5 cm and over 50% have depths less than 2.5 cm. At least 70% of spray zone karren have diameters less than 5 cm and depths less than 2.5 cm. These distributions resemble a Poisson distribution, while swash and backshore data are more uniformly distributed. The swash and backshore zones also have the highest percentage of observations in the first or second histogram interval, but at least 20% of the karren, in both zones, have diameters 20 cm or greater, and 14.6% possess a microrelief of at least 10 cm.

The much smaller karren in the intertidal and spray zones allow for significantly higher densities than in the swash and backshore zone, although the intertidal zone also has the most uniform distribution than any other zone (Sec. 4.3). Almost 32% of intertidal and 50% of spray

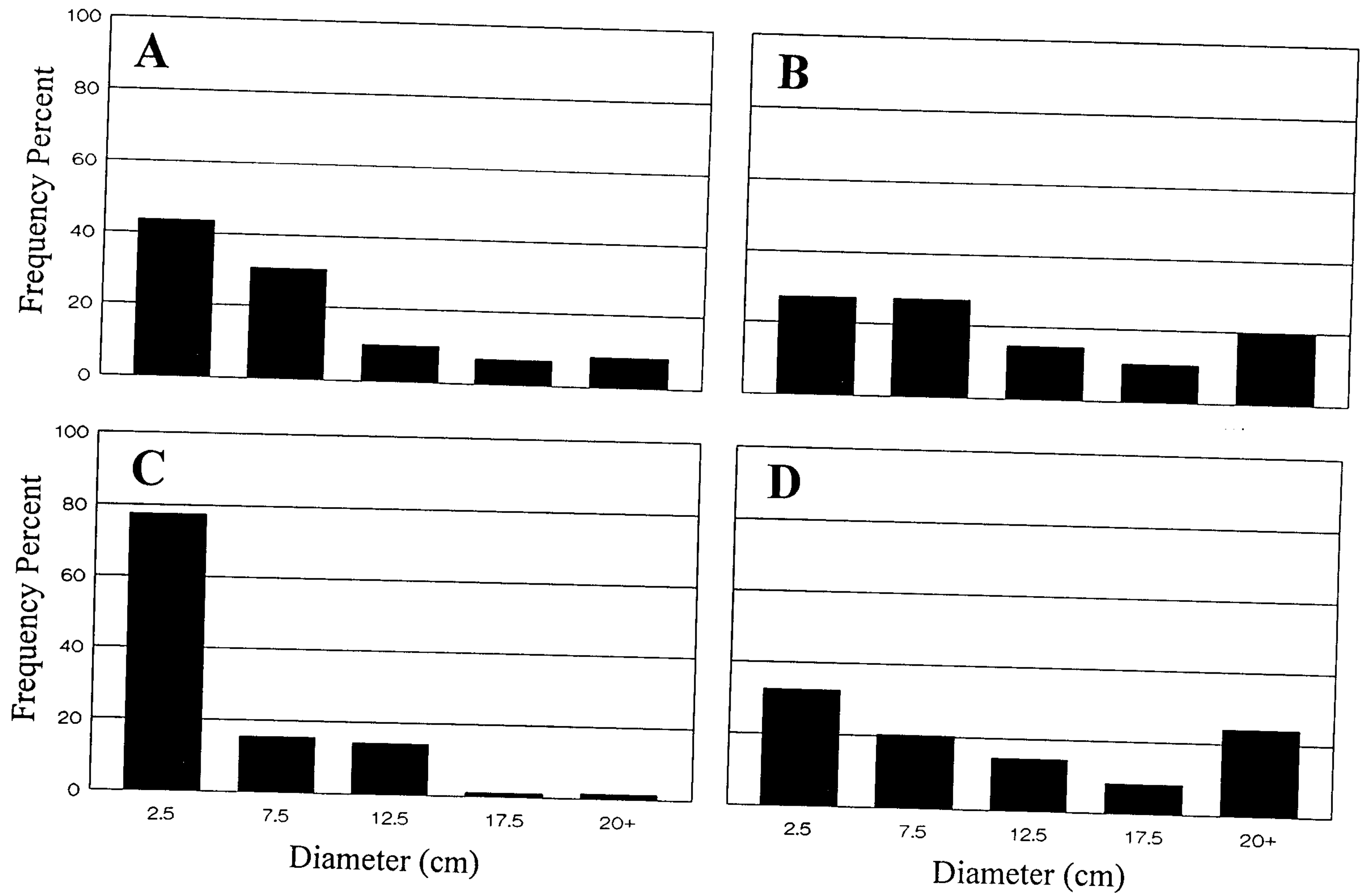



Figure 5.2 Frequency histograms illustrating variations in karren diameter within the littoral zone; A) intertidal, B) supratidal swash, C) supratidal spray and D) backshore. Again note the high percentage of observations less than 10 cm depth for the inter- and supratidal spray zones. X-axis represents the mid-point of each class interval.

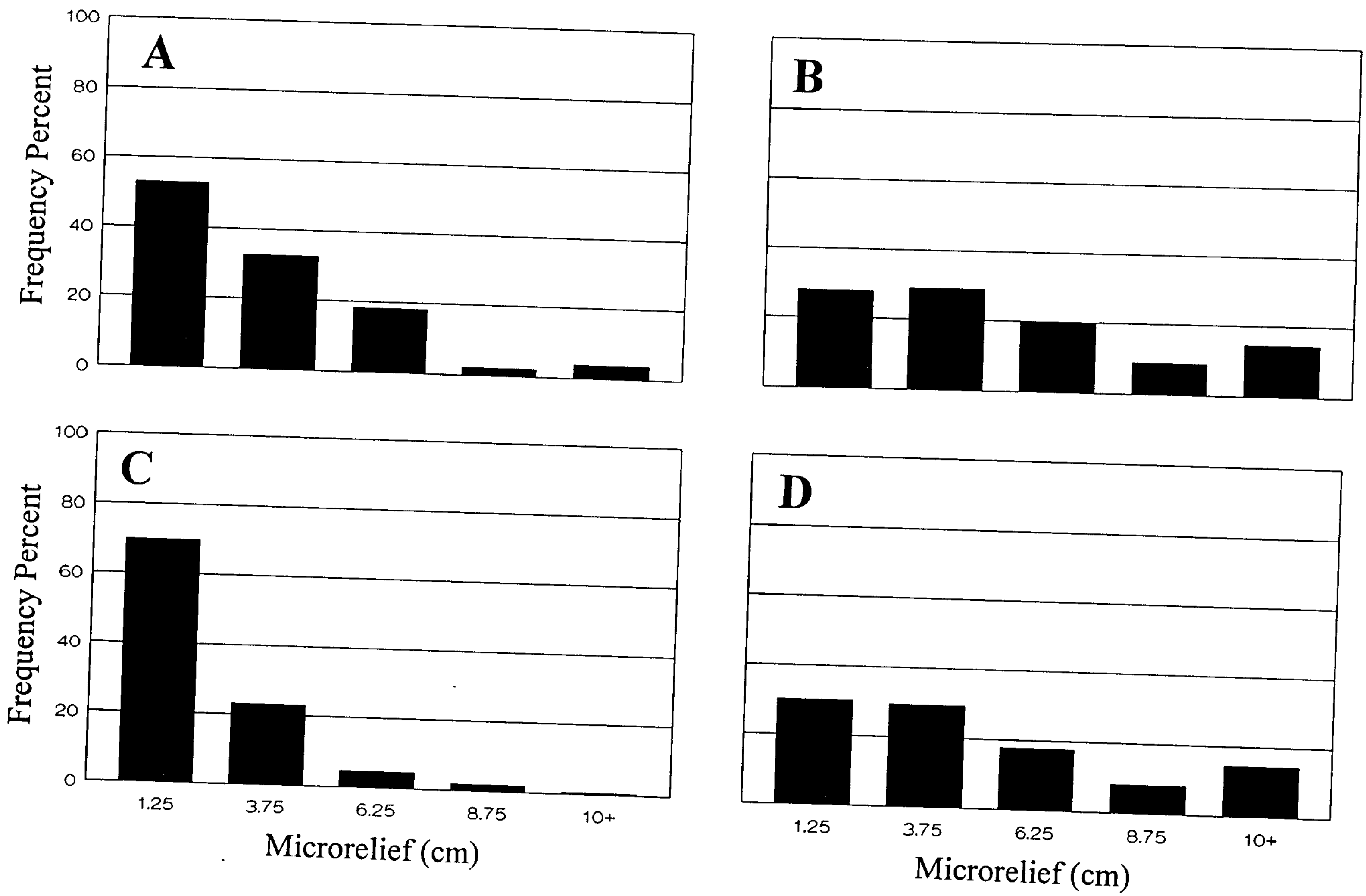



Figure 5.3 Frequency histograms illustrating variations in karren microrelief within the littoral zone; A) intertidal, B) supratidal swash, C) supratidal spray and D) backshore. Again note the high percentage of observations less than 10 cm depth for the inter- and supratidal spray zones. X-axis represents the mid-point of each class interval.

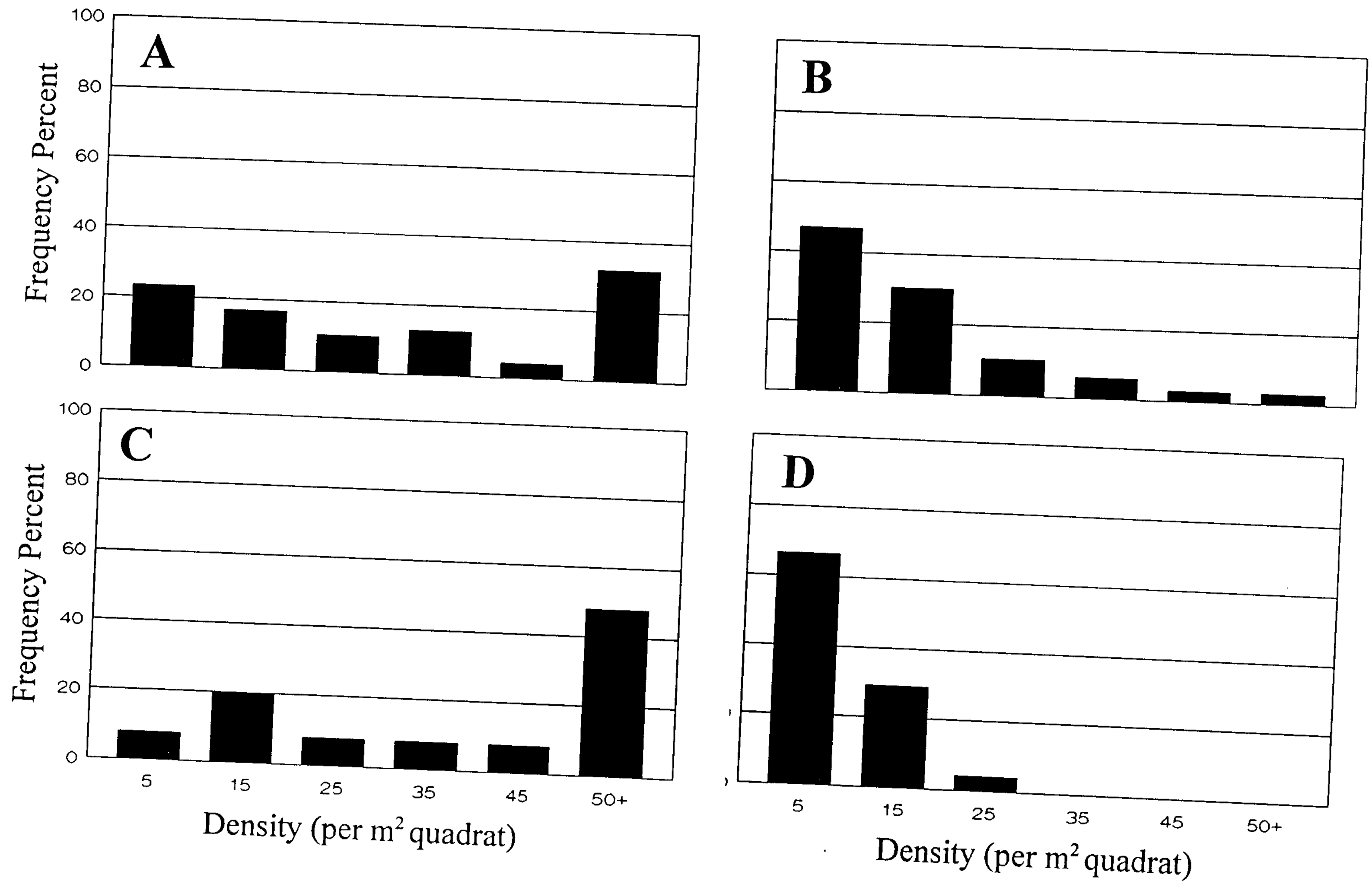



Figure 5.4 Frequency histograms illustrating variations in karren density within the littoral zone; A) intertidal, B) supratidal swash, C) supratidal spray and D) backshore. The reverse pattern to diameter and microrelief occurs here, where a high percentage of observations fall within the first two class intervals (density less than 20 pits/$m^2$) for the supratidal swash and backshore zones. X-axis represents the mid-point of each class interval.

zone quadrats have densities greater than 50 pits/m$^2$, while these percentages are drastically reduced for swash (5%) and backshore zone (0%) quadrats.

It is stressed that these data are presented only to illustrate general trends. Because the data possess extremely high skewness (normal = 0) and kurtosis (normal = 3) values, especially for microrelief, then standard, normal parametric hypothesis testing between zones and sites cannot be implemented. The mean and standard deviation do not properly define the nature of the distributions as they are presented here, because there is a strong asymmetry to the left of the mean (positively skewed). Thus, non-parametric tests must be used, which are not affected by skewed frequency distributions (Griffith and Amrhein, 1991).

A non-parametric way of summarizing the data is presented in Table 5.4 using percentiles. Percentiles determine the values above and below which a certain number of observations fall (SPSS/PC+, 1992). Table 5.4 provides percentile values for the 25th, 50th (median) and 75th percentile for each morphologic karren measurement. For example, the median provides the value in the distribution above and below which exactly half of the observations fall, and it is not affected by extreme data values. Note that the median values for all measurements are smaller than the corresponding mean, due to the existence of positive skewness. The amount of variation between the four zones becomes clear, as the median values for the intertidal and spray zone diameters and depths are much lower than those for the swash and backshore. This disparity becomes greater at the 75th percentile, where 75% of the observations for intertidal and spray zone diameter and microrelief, in almost all cases, fall below a value at least half that for the swash and backshore 75th percentile value.

### 5.2.2 Intrasite Statistical Analysis

A) Correlations With Height Above The MLWM

An attempt will now be made to quantify the apparent zonal patterns of karren development. Correlations between karren diameter, microrelief and density on the one hand, and height above the MLWM on the other were investigated. A statistical correlation (Pearson's *r*) of two variables

Table 5.4 Percentile variations in karren morphology and density across the littoral zone.

| Zone | Karren Measurement | Percentile 25 | 50 | 75 | *N** |
|---|---|---|---|---|---|
| **Intertidal** | Long Axis (cm) | 3.00 | 6.00 | 12.00 | 956 |
| | Short Axis (cm) | 2.50 | 4.50 | 8.63 | 956 |
| | Diameter (cm) | 2.79 | 4.5 | 8.63 | 956 |
| | Microrelief (cm) | 1.00 | 2.00 | 3.60 | 930** |
| | Density (per $m^2$ quadrat) | 10.00 | 25.00 | 100.00 | 47+ |
| **Supratidal Swash** | Long Axis (cm) | 5.00 | 10.00 | 19.95 | 791 |
| | Short Axis (cm) | 4.00 | 7.10 | 15.00 | 791 |
| | Diameter (cm) | 4.50 | 8.73 | 17.00 | 791 |
| | Microrelief (cm) | 2.00 | 4.00 | 7.00 | 791 |
| | Density (per $m^2$ quadrat) | 5.00 | 10.00 | 18.00 | 70 |
| **Supratidal Spray** | Long Axis (cm) | 2.30 | 3.00 | 5.40 | 598 |
| | Short Axis (cm) | 2.00 | 2.40 | 4.00 | 598 |
| | Diameter (cm) | 2.10 | 2.80 | 4.63 | 598 |
| | Microrelief (cm) | 1.00 | 1.50 | 2.50 | 598 |
| | Density (per $m^2$ quadrat) | 13.00 | 40.00 | 100.00 | 25 |
| **Backshore** | Long Axis (cm) | 4.75 | 9.50 | 23.00 | 175 |
| | Short Axis (cm) | 3.85 | 8.00 | 17.00 | 175 |
| | Diameter (cm) | 4.23 | 8.85 | 19.25 | 175 |
| | Microrelief (cm) | 2.00 | 4.00 | 6.75 | 175 |
| | Density (per $m^2$ quadrat) | 3.00 | 5.00 | 11.50 | 24 |

* refers to the number of individual karren observations recorded within all metre square quadrats for each zone

** the number of microrelief observations are less than that for the other measurements, as there were times when biological colonization by *Mytulis edulis* (e.g. Figure 4.31A) prevented a proper microrelief measure of those pits

+ refers to the number of quadrats used to sample karren within each zone does not establish which is the independent or dependent variable; instead it only measures the strength and direction of a relationship between two variables (Shaw and Wheeler, 1985). In an initial study the *r* values were very low for all three relationships (i.e. *r* approx. 0.02), because data are combined from different sites and there is remarkable karren variation within each zone from one site to the next. At least 30 profiles would have to be constructed at each site to overcome this difficulty, which time and coastal morphologic constraints (e.g. Sec. 4.2) did not allow.

Thus, the data was aggregated by producing averages of karren diameter, microrelief and density, for each zone in each of the four primary study regions (Tables 5.5 to 5.7). This was done by combining data for sites and/or profiles which were in close proximity to one another, possibly minimizing the effects of other factors (e.g. geologic variations) involved in karren development. Hopefully this would also produce a normal distribution in the variables, necessary to use a parametric measure such as the Pearson *r*. The spray zone was excluded in this spatial analysis, because it would obviously skew any relationship which exists here.

An average height for the quadrats above the MLWM, involved in the karren measurements listed in Tables 5.5 to 5.7, was produced from the constructed littoral profiles. There is some intersite variation in quadrat location, however, especially when comparing supratidal swash and backshore zone quadrats, depending on the platform morphology and exposure to the open marine environment. Some swash and backshore quadrats for more exposed heights, are higher than those for more sheltered sites. For example, the backshore quadrat at Lower Head is about 20 m above the present MLWM (Figure 4.19). Thus, it is significantly higher than any other backshore karren measurement and is removed from this spatial analysis. The swash zone quadrat locations for the Cook's Harbour region are at a similar height, on average, to those in the backshore of the Pointe Riche and Port au Choix Peninsula (Table 5.6 and 5.7). This is due to the fact that the Cook's Harbour region is significantly more exposed than the Port au Choix Peninsula region (Figure 3.9), which would appear to increase the height of the swash zone above the MLWM. At the same time, the platform morphology, especially for the Pointe Riche Peninsula (Figure 4.13), allows for the backshore karren to develop at a reduced height above the MLWM, especially since waves arriving

Table 5.5 Average karren diameter, microrelief and density for the intertidal zone quadrats from the major sites of western Newfoundland.

| Site (*N*)* | Diameter (cm) | Micro-relief (cm) | Density (per m$^2$ quadrat) | Height Above MLWM (m) |
|---|---|---|---|---|
| **Port au Port Peninsula** | | | | |
| Port au Port Peninsula South Coast Sites (3) | 6.21 | 3.04 | 33.33 | 1.00 |
| The Bar/Long Point (7) | 12.68 | 6.30 | 17.57 | 0.94 |
| Port au Port East Bay (2) | 8.81 | 4.48 | 25.00 | 0.75 |
| **Cow Head Peninsula Region** | | | | |
| Cow Head Peninsula (1) | 18.59 | 8.38 | 4.00 | 1.00 |
| Broom Point (1) | 8.18 | 3.83 | 6.00 | 0.80 |
| **Port au Choix Peninsula Region** | | | | |
| Port au Choix Peninsula (7) | 6.08 | 1.90 | 26.71 | 0.90 |
| Pointe Riche Peninsula (8) | 13.87 | 3.79 | 15.63 | 0.90 |
| Ingornachoix Bay (17) | 5.98 | 2.04 | 52.54 | 0.50 |
| **Cook's Harbour Region (1)** | 3.51 | 1.44 | 100.00 | 0.50 |

* refers to the number of quadrats for each aggregated site

Table 5.6 Average karren diameter, microrelief and density for the supratidal swash zone quadrats from the major sites of western Newfoundland.

| Site (*N*)* | Diameter (cm) | Micro-relief (cm) | Density (per $m^2$ quadrat) | Height Above MLWM (m) |
|---|---|---|---|---|
| **Port au Port Peninsula** | | | | |
| Port au Port Peninsula South Coast Sites (4) | 9.46 | 4.00 | 13.88 | 1.50 |
| The Bar/Long Point (17) | 10.75 | 5.46 | 16.36 | 1.36 |
| Port au Port East Bay (3) | 8.45 | 4.56 | 10.67 | 1.30 |
| **Cow Head Peninsula Region** | | | | |
| Cow Head Peninsula (7) | 17.81 | 9.98 | 9.86 | 1.70 |
| Broom Point (3) | 17.21 | 10.24 | 11.00 | 1.70 |
| Belldowns Island (1) | 5.52 | 3.03 | 40.00 | 1.20 |
| Stearing Island (1) | 18.46 | 8.58 | 13.00 | 1.80 |
| Daniel's Harbour (1) | 17.68 | 10.90 | 10.00 | 2.05 |
| **Port au Choix Peninsula Region** | | | | |
| Port au Choix Peninsula (5) | 11.92 | 3.06 | 12.25 | 1.77 |
| Pointe Riche Peninsula (6) | 15.87 | 4.93 | 9.00 | 1.65 |
| Ingornachoix Bay (14) | 16.87 | 5.83 | 8.72 | 1.86 |
| **Cook's Harbour Region (8)** | 24.56 | 12.20 | 25.67 | 2.70 |

* refers to the number of quadrats for each aggregated site

Table 5.7 Average karren diameter, microrelief and density for the backshore zone quadrats from the major sites of western Newfoundland.

| Site (*N*)* | Diameter (cm) | Micro-relief (cm) | Density (per $m^2$ quadrat) | Height Above MLWM (m) |
|---|---|---|---|---|
| **Cow Head Peninsula Region** | | | | |
| Cow Head Peninsula (1) | 19.58 | 8.33 | 3.00 | 8.00 |
| Broom Point (1) | 11.15 | 4.39 | 7.00 | 2.35 |
| Lower Head (1) | 9.90 | 7.51 | 12.00 | 20.00 |
| Daniel's Harbour (1) | 9.78 | 5.13 | 4.00 | 4.60 |
| **Port au Choix Peninsula Region** | | | | |
| New Ferrolle Peninsula (2) | 6.47 | 4.87 | 18.00 | 4.12 |
| Port au Choix Peninsula (5) | 18.96 | 5.37 | 7.00 | 2.90 |
| Pointe Riche Peninsula (5) | 16.60 | 3.66 | 6.60 | 2.40 |
| Ingornachoix Bay (2) | 24.35 | 12.94 | 2.50 | 5.04 |
| **Cook's Harbour Region (6)** | 22.79 | 14.60 | 15.56 | 4.80 |

* refers to the number of quadrats for each aggregated site

at an oblique angle to the shore are not taken into account. Note that there were no backshore quadrats for any of the Port au Port Peninsula sites.

Scattergraphs of karren diameter, microrelief and density correlated with height above the MLWM are represented in Figure 5.5. The resultant *r* values are quite low, indicating a weak association between these variables. The distributions were subjected to a normality test using skewness ($\sqrt{b_1}$) and kurtosis ($b_2$; Table 5.8). The distribution can be considered normal if the sample $\sqrt{b_1}$ is less than the upper limit of $\sqrt{b_1}$ defined by the sample size. The sample $b_2$ must fall within the lower and upper limit of $b_2$ for that sample size. It is preferable if the 10% significance level is used to determine if a parametric procedure can be implemented (Sachs, 1982). Here all of the sample $\sqrt{b_1}$ values, and the density and height $b_2$ values, are significantly outside of the range defined by a normal distribution, therefore revealing a positively skewed data distribution.

It is for this reason that the data for all four variables are log-transformed, since many positively skewed distributions can have a measure of normality imposed upon them in this way (Shaw and Wheeler, 1985). The $\sqrt{b_1}$ values for the variables now fall within the normal limits defined for that sample size, except density and height (Table 5.8A), which are marginally outside of the acceptable range of normality. The $b_2$ sample values all fall within the defined range of normality for the sample size (Table 5.8B).

Scattergraphs for the log-transformed data are presented in Figure 5.6, and even though the variables now possess a log-normal distribution, there is still not a significant increase in the strength of the associations. Although the correlations are statistically significant ($r > r$ critical), the $r^2$ (coefficient of determination) values are all below 50% (Table 5.9). The $r^2$ measures the proportion of the variance explained by the correlation of the two variables (Shaw and Wheeler, 1985). For example, the highest $r^2$ is 0.44 for the density/height correlation. This means that 44% of the variance in density and height, at these sites, is explained by the association of these two variables, leaving 56% explained by other variables. This is not a very high $r^2$ value, especially with the trends presented in Section 5.2.1. This reinforces the importance of other variables (i.e. marine, geologic), which are affecting

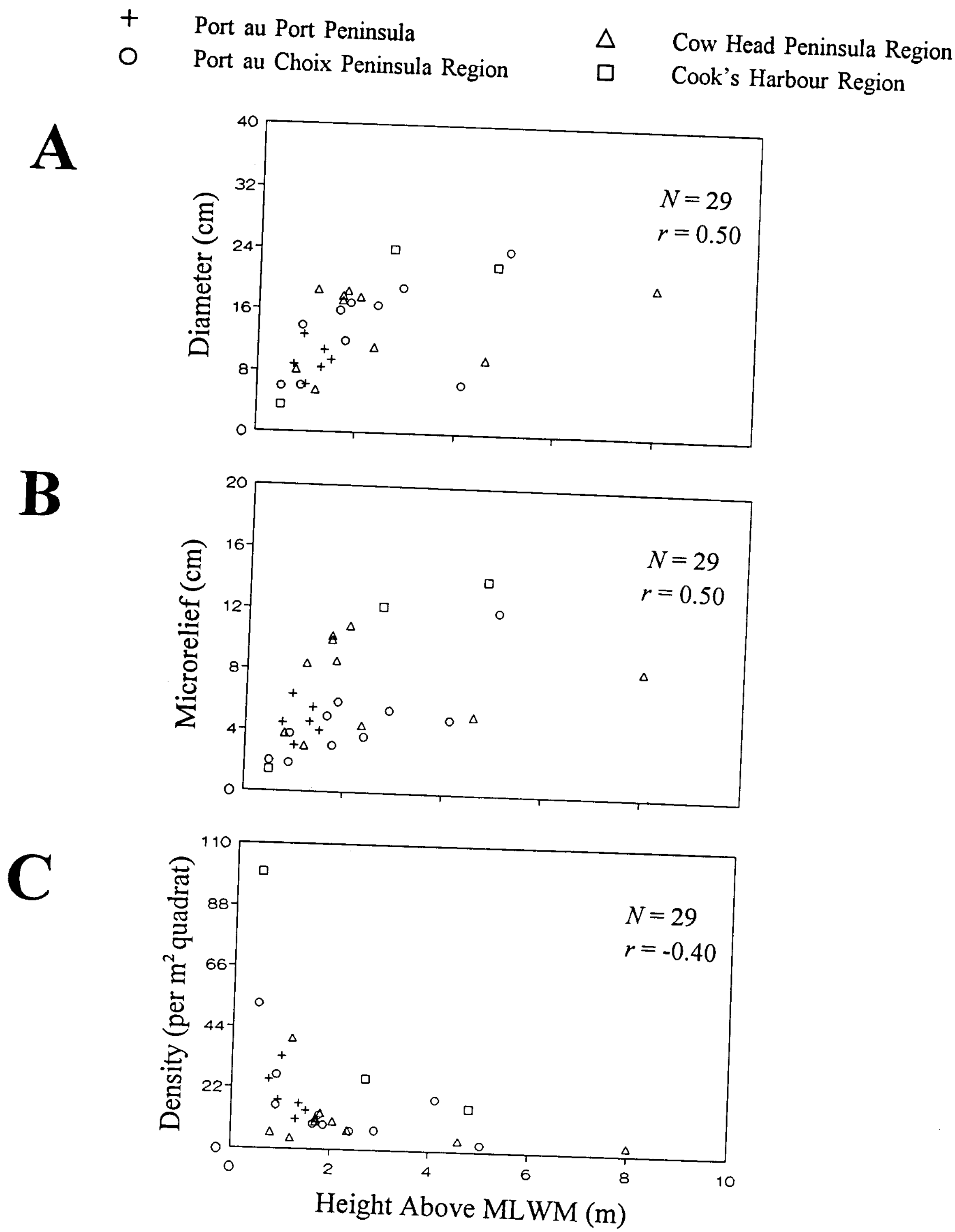



Figure 5.5 Scattergraphs of average karren A) diameter, B) microrelief and C) density correlated with height above the MLWM.

Table 5.8 Normality testing for variables diameter, microrelief, density and height for normal and log-transformed distributions. A) $\sqrt{b_1}$ (skewness) and B) $b_2$ (kurtosis).

# A

| Skewness | Sample $\sqrt{b_1}$ | $\sqrt{b_1}$ (10%)* | Sample log $\sqrt{b_1}$ | $\sqrt{b_1}$ (10%)* | $N$ |
|---|---|---|---|---|---|
| Diameter | 0.75 | 0.51 | 0.37 | 0.51 | 29 |
| Microrelief | 0.91 | 0.51 | 0.44 | 0.51 | 29 |
| Density | 1.73 | 0.51 | 0.53 | 0.51 | 29 |
| Height | 1.38 | 0.51 | 0.56 | 0.51 | 29 |

* upper limits of $\sqrt{b_1}$ values are from Table 71, p. 326 in Sachs (1982)

# B

| Kurtosis | Sample $b_2$ | Lower Limit $b_2$ (10%)* | Upper Limit $b_2$ (10%)* | Sample log $b_2$ | Lower Limit $b_2$ (10%)* | Upper Limit $b_2$ (10%)* | $N$ |
|---|---|---|---|---|---|---|---|
| Diameter | 1.89 | 2.10 | 3.68 | 2.46 | 2.10 | 3.68 | 29 |
| Microrelief | 2.71 | 2.10 | 3.68 | 2.62 | 2.10 | 3.68 | 29 |
| Density | 13.90 | 2.10 | 3.68 | 3.26 | 2.10 | 3.68 | 29 |
| Height | 7.08 | 2.10 | 3.68 | 2.80 | 2.10 | 3.68 | 29 |

* lower and upper limits of $b_2$ values are from Table 71, p. 326 in Sachs (1982)

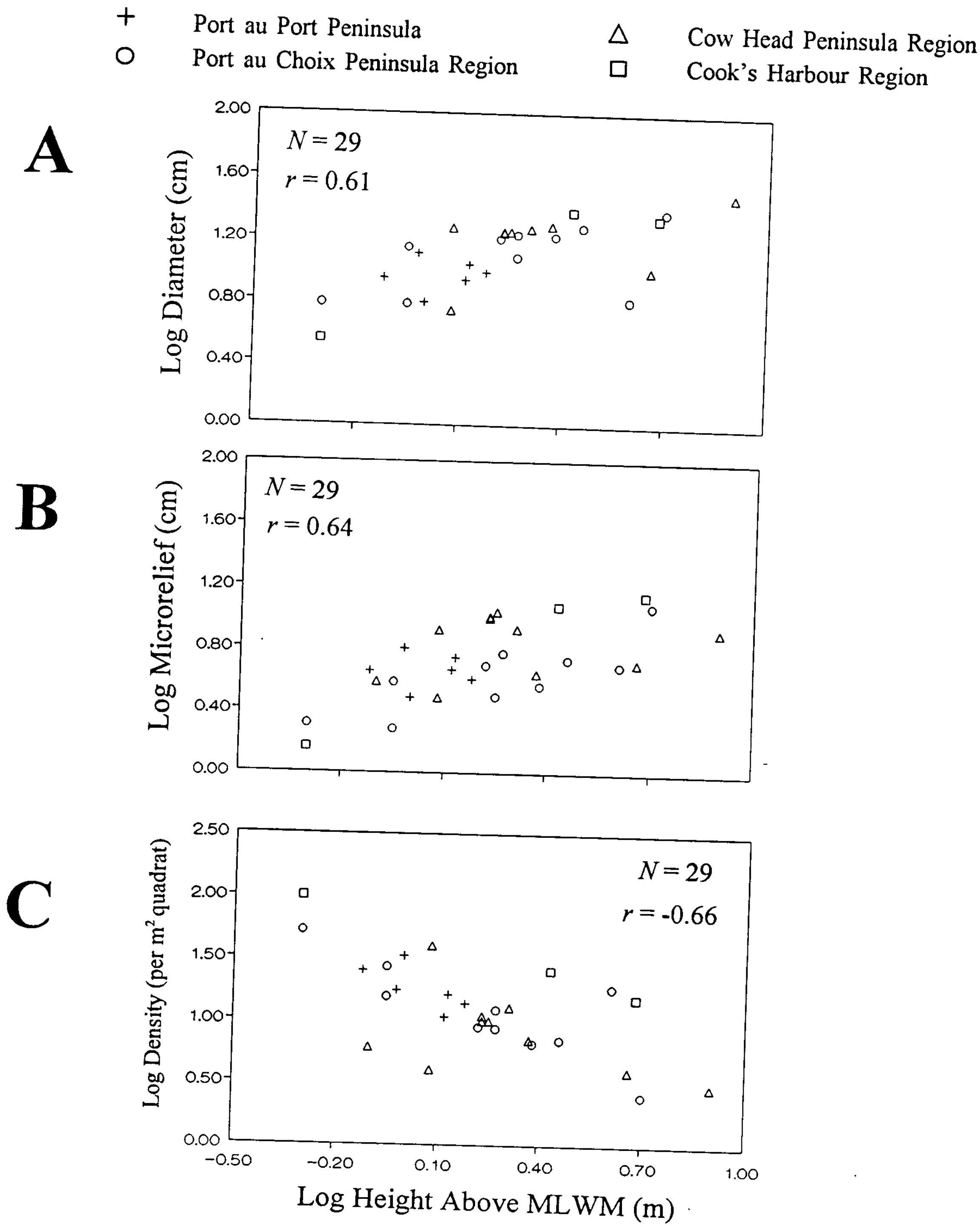



Figure 5.6 Scattergraphs of log-transformed data for average karren A) diameter, B) microrelief and C) density correlated with height above the MLWM.

Table 5.9 Significance testing of the $r$ value for diameter, microrelief and density correlations with height above the MLWM for log-normal correlations.

| Correlation | $r$ | $r$ critical (0.05)* | $r^2$ | $N$ |
|---|---|---|---|---|
| Diameter : Height | 0.61 | 0.37 | 0.37 | 29 |
| Microrelief : Height | 0.64 | 0.37 | 0.41 | 29 |
| Density : Height | -0.66 | 0.37 | 0.44 | 29 |

* critical values of the Pearson $r$ are from Appendix VIII, p. 353 in Shaw and Wheeler (1985)

the development of littoral karren in addition to quadrat height above the MLWM.

B) Regression Analysis: Karren Development With Height Above the MLWM

The analysis of diameter, microrelief and density correlations were taken a step further. The variables were run through a regression model, with height above the MLWM established as the independent variable and diameter, microrelief and density as dependent variables. This then statistically defines how much of the variation in karren development is controlled by variations in height above the MLWM. This time, though, backshore data from Daniel's Harbour, and the Cow Head and New Ferrolle Peninsula are removed from the analysis, as they are noticeable outliers to the general trend in the data (especially for diameter and microrelief; Figure 5.5).

The log-linear relationship of diameter with height is given in Figure 5.7A, defined by the equation

$$Y = 0.96 + 0.6974X \pm 0.138 \qquad (5.1)$$

which defines the change in diameter ($Y$) with a change in height ($X$), bounded by confidence limits provided by the standard error of the estimate (0.138; $SE$). However, since this equation is

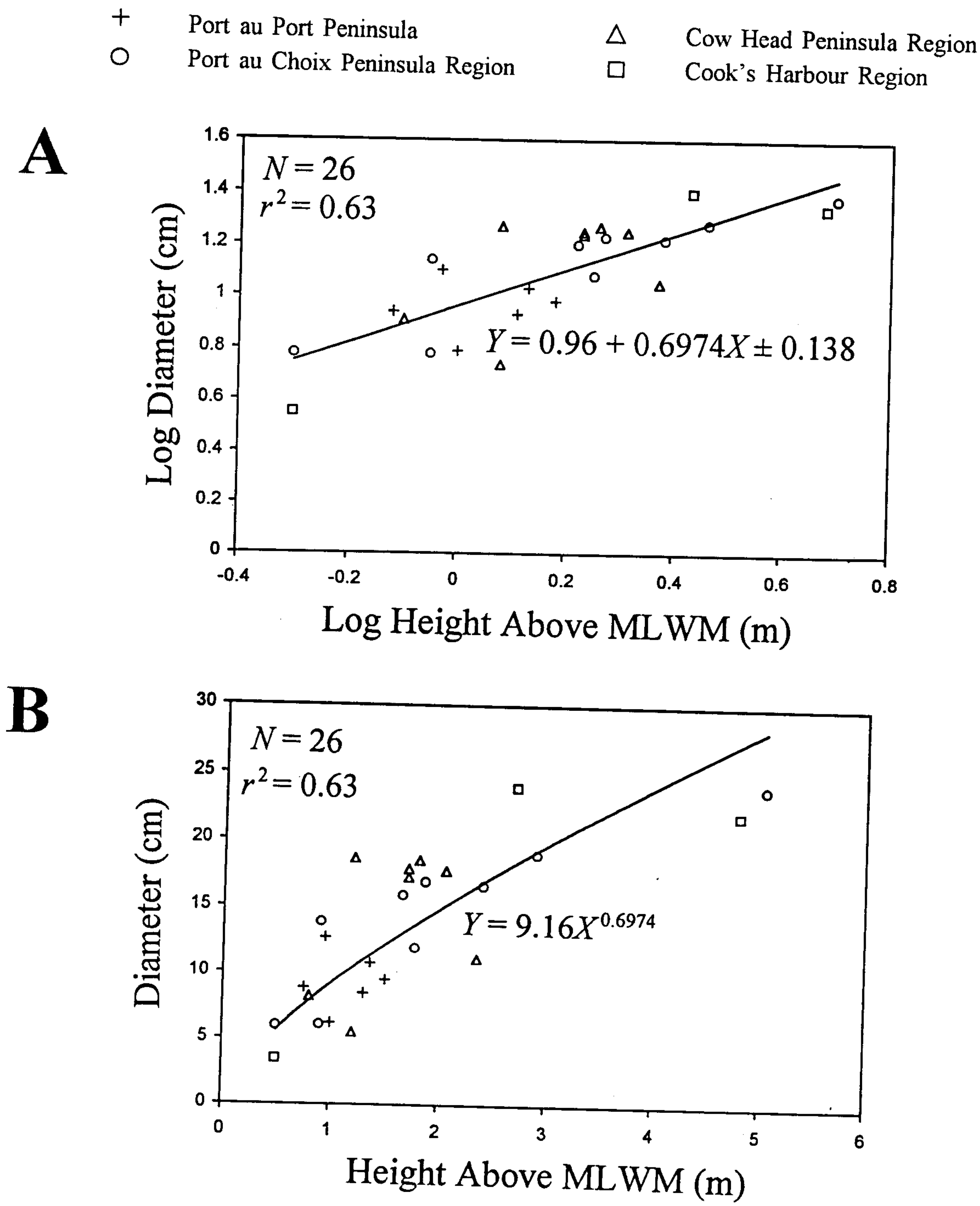



Figure 5.7 A) Log-linear relationship between height above the MLWM ($X$) and average karren diameter ($Y$). B) Curve fit through the original data. Backshore data are excluded for Daniel's Harbour and the New Ferrolle and Cow Head Peninsula.

based on log-transformed data, it must be converted into anti-log from in order to interpret the original data so that

$$Y = 9.16X^{0.6974} \tag{5.2}$$

This equation can be fitted through the original data (Figure 5.7B), predicting that at a height of 1 m above the MLWM, karren diameter can be expected to be 9.16 cm. Diameter increases with increasing height above the MLWM, but at a decreasing rate, as the power coefficient is less than 1.0 (0.6974).

The $r^2$ is calculated to be 0.63 or 63%, which means that 63% of the variance in karren diameter is explained by height above the MLWM, leaving 37% unexplained by other variables. This value represents the adjusted $r^2$, which is a more realistic measure of the goodness of fit for reduced sample sizes (SPSS Base Systems User's Guide, 1992) using the following formula

$$r^2_a = r^2 - \frac{p\,(1 - r^2)}{N - p - 1} \tag{5.3}$$

where $p$ = the number of independent variables in the equation
$N$ = the number of observations in the sample

Thus, the adjusted $r^2$ is usually somewhat lower (often only 2-3%) than simply squaring the Pearson $r$. This regression $r^2$ is significantly improved from that in Table 5.9 ($r^2$ = 0.37), which illustrates how much the three removed outliers skewed the distribution of the data. All three of these backshore outliers have much smaller karren dimensions, with respect to height above the MLWM, than the regression model here predicts, again due to other reasons not accounted for. Considering the strength of the trends in karren development presented in Section 5.2.1, an $r^2$ of 0.63 is still somewhat lower than expected, revealing that the aggregation of sites does not significantly minimize the effects of other factors. The defined relationship, however, is normally distributed and the *F* statistic (41.23) is statistically significant at both the 0.05 (41.23 > 4.26) and 0.01 (41.23 > 7.82) levels of significance (Shaw and Wheeler, 1985, p.349-350).

The distribution of residuals is analyzed in an attempt to account for the unexplained variance between diameter and height. Residual values are calculated for each observation in the data set, and represent the difference between the actual diameter value, (*y*), with those expected from the proposed regression equation (Shaw and Wheeler, 1985). Observations which deviate the most from the proposed relationship are then easy to spot, and may provide clues as to other variables involved in explaining the observed trends in karren diameter. The log-normal *SE* is used to define homogenous residual categories (Table 5.10), in a similar manner that the standard deviation is used for a univariate analysis; the *SE* measures the extent of scatter around a regression line, just like the standard deviation measures the extent of scatter around a mean (Kuz, Pers. Comm., 1993). Observations within category 3 ( -½ *SE* to +½ *SE* ) are considered to be predicted fairly accurately by the defined relationship. Any residuals less than -½ *SE* reveal a site where average karren diameter, for that zone, is considered to be significantly overestimated by the regression model, and any residuals greater than +½ *SE* are significantly underestimated.

From examination of Table 5.10, there appear to be nine sites with karren zones where average karren diameter is significantly less than the model predicts. This is especially true for the supratidal swash zone of Belldowns Island, in the Cow Head Peninsula region. The karren at this island is located adjacent to Cow Head Harbour (Figure 4.2), which is a very sheltered area and protected from the open marine environment, thus, greatly limiting the wave energy acting upon the shore. It is also possible that the carbonate rock at this island is not very conducive to karren development (i.e. high insoluble residue percent), thereby limiting karren diameter more than expected for this littoral zone.

There are ten sites which have karren zones with diameters much greater than the model predicts. Here the interaction of geology and the marine environment appear to enhance the development of karren, much more than expected for the heights above the MLWM at which they are located. This may be the reason that the intertidal karren located at the Cow Head and Pointe

Table 5.10 Residual categories for log-normal karren diameter as determined by the standard error of the estimate (*SE*) from the regression equation.

| Category | Site | Zone | Residual Value |
|---|---|---|---|
| **Category 1** | | | |
| < -1½ *SE* (< -0.207) | Belldowns Island | Supratidal | -0.27517 |
| **Category 2** | Port au Port Peninsula - South Coast | Intertidal | -0.16880 |
| -½ *SE* to -1½ *SE* | Port au Port Peninsula - South Coast | Supratidal | -0.10881 |
| (-0.069 to -0.207) | Port au Port Peninsula - East Bay | Supratidal | -0.11450 |
| | Broom Point | Supratidal | -0.17340 |
| | Port au Choix Peninsula | Intertidal | -0.14607 |
| | Ingornachoix Bay | Backshore | -0.07156 |
| | Cook's Harbour Region | Intertidal | -0.20664 |
| | Cook's Harbour Region | Backshore | -0.09457 |
| **Category 3** | Port au Port Peninsula - Bar/Long Pt. | Supratidal | -0.02361 |
| -½ *SE* to +½ *SE* | Broom Point | Intertidal | 0.01845 |
| (-0.069 to 0.069) | Daniel's Harbour | Supratidal | 0.06817 |
| | Ingornachoix Bay | Intertidal | 0.02475 |
| | Port au Choix Peninsula | Supratidal | -0.05855 |
| | Port au Choix Peninsula | Backshore | -0.00653 |
| | Pointe Riche Peninsula | Backshore | -0.00694 |
| **Category 4** | Port au Port Peninsula. - Bar/Long Pt. | Intertidal | 0.15997 |
| ½ *SE* to 1½ *SE* | Port au Port Peninsula - East Bay | Intertidal | 0.07022 |
| (0.069 to 0.207) | Cow Head Peninsula | Supratidal | 0.12806 |
| | Broom Point | Supratidal | 0.11318 |
| | Stearing Island | Supratidal | 0.12631 |
| | Ingornachoix Bay | Supratidal | 0.07727 |
| | Pointe Riche Peninsula | Supratidal | 0.08701 |
| | Cook's Harbour Region | Supratidal | 0.11749 |
| **Category 5** | Cow Head Peninsula | Intertidal | 0.25217 |
| > 1½ *SE* (> 0.207) | Pointe Riche Peninsula | Intertidal | 0.21210 |

Riche Peninsula are much larger than expected. There is only one intertidal zone quadrat for the entire Cow Head Peninsula, due to its platform morphology, and it is at a very exposed shoreline of the peninsula, which may help to explain an average karren diameter of over 18 cm at that location.

The log-linear relationship between microrelief and height above the MLWM is presented in Figure 5.8A and defined by the equation

$$Y = 0.58 + 0.7484X \pm 0.186 \tag{5.4}$$

When transformed back to the original data, the relationship is defined by the power equation in Figure 5.8B.

$$Y = 3.81X^{0.7484} \tag{5.5}$$

Thus, at a height of 1 m above the MLWM karren microrelief can be expected to be 3.81 cm. Karren microrelief, as with diameter, also increases with increasing height, but at a decreasing rate. The adjusted $r^2$ is only 0.50 (50%) which is somewhat lower than that for diameter, primarily due to the small microrelief pits at the backshore of the Port au Choix and Pointe Riche Peninsula, as for some reason these sites favour the development of large, shallow pits. However, the $F$ statistic (26.19) is statistically significant at both the 0.05 (4.26) and 0.01 (7.82) levels of significance. A separate regression was run with these two sites removed from the analysis, and the $r^2$ was exactly the same as that for diameter (0.63).

The distribution of the residuals are again analyzed, in an attempt to reveal the sites which have karren zones not conforming to the relationship predicted by the regression model (Table 5.11). There are nine sites in Table 5.11 where karren microrelief is significantly smaller than expected. This includes almost all of the Port au Choix Peninsula region, where most of the sites have a negative residual value (except for the intertidal zone of the Pointe Riche Peninsula at 0.03208).

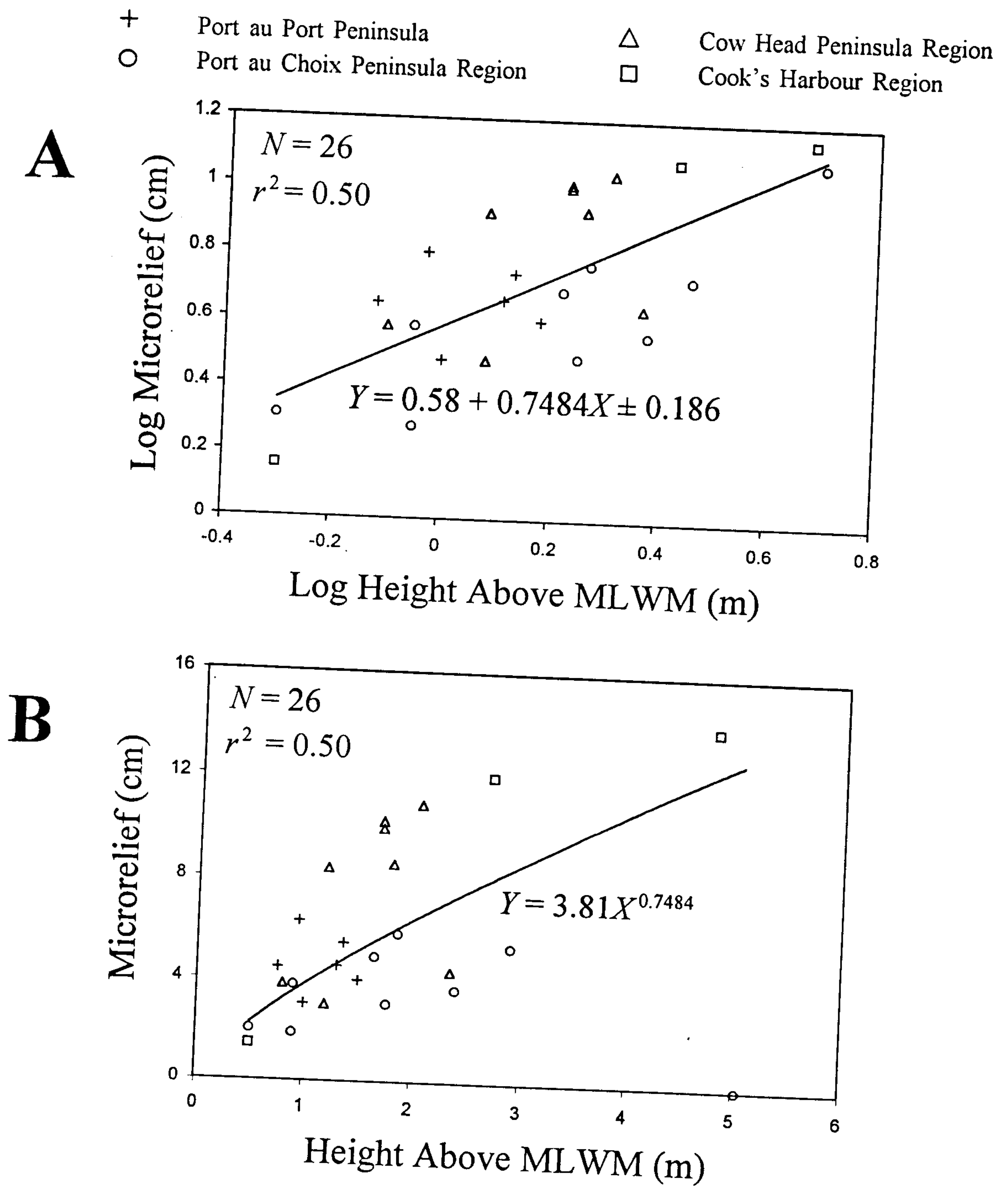



Figure 5.8 A) Log-linear relationship between height above the MLWM ($X$) and average karren microrelief ($Y$). B) Curve fit through the original data. Backshore data are excluded for Daniel's Harbour and the New Ferrolle and Cow Head Peninsula.

Table 5.11 Residual categories for log-normal karren microrelief as determined by the standard error of the estimate (*SE*) from the regression equation.

| Category | Site | Zone | Residual Value |
|---|---|---|---|
| **Category 1** | Port au Choix Peninsula | Supratidal | -0.28066 |
| < -1½ *SE* (< -0.279) | Pointe Riche Peninsula | Backshore | -0.30187 |
| **Category 2** | Port au Port Peninsula - South Coast | Intertidal | -0.09793 |
| -½ *SE* to -1½ *SE* | Port au Port Peninsula - South Coast | Supratidal | -0.11053 |
| (-0.093 to -0.279) | Belldowns Island | Supratidal | -0.15862 |
| | Broom Point | Backshore | -0.21604 |
| | Port au Choix Peninsula | Intertidal | -0.26781 |
| | Port au Choix Peninsula | Backshore | -0.19688 |
| | Cook's Harbour Region | Intertidal | -0.19716 |
| | Port au Port Peninsula - Bar/Long Pt. | Supratidal | 0.05645 |
| **Category 3** | Port au Port Peninsula - East Bay | Supratidal | -0.00711 |
| -½ *SE* to +½ *SE* | Broom Point | Intertidal | 0.07492 |
| (-0.093 to 0.093) | Pointe Riche Peninsula | Intertidal | 0.03208 |
| | Pointe Riche Peninsula | Supratidal | -0.05072 |
| | Ingornachoix Bay | Intertidal | -0.04589 |
| | Ingornachoix Bay | Supratidal | -0.01683 |
| | Ingornachoix Bay | Backshore | -0.02731 |
| | Cook's Harbour Region | Backshore | 0.05550 |
| | Port au Port Peninsula - Bar/Long Pt. | Intertidal | 0.23865 |
| **Category 4** | Port au Port Peninsula - East Bay | Intertidal | 0.16398 |
| ½ *SE* to 1½ *SE* | Cow Head Peninsula | Supratidal | 0.24586 |
| (0.093 to 0.279) | Broom Point | Supratidal | 0.25743 |
| | Stearing Island | Supratidal | 0.16164 |
| | Daniel's Harbour | Supratidal | 0.22331 |
| | Cook's Harbour Region | Supratidal | 0.18273 |
| **Category 5** | | | |
| > 1½ *SE* (> 0.279) | Cow Head Peninsula | Intertidal | 0.28318 |

Only one of these sites, the intertidal zone of the Port au Choix Peninsula, has both diameter and microrelief greatly overestimated by the model, illustrating that this entire region must be affected by geologic factors which favour the development of large, yet shallow pits.

There are eight sites which have much higher microrelief values than expected for the corresponding height above the MLWM. This again includes the intertidal zone quadrat of the Cow Head Peninsula, which was already discussed, several supratidal swash zone quadrats at other sites in the Cow Head Peninsula region and the Cook's Harbour region, and two intertidal karren zones at the Port au Port Peninsula. Most of the swash zone quadrats were located at very exposed coastlines, thereby possibly enhancing karren microrelief, and the intertidal rock at the Port au Port Peninsula, though not very exposed, may possess rock properties more favourable to karren development than the intertidal zone of other sites.

When a regression was performed for karren density, the $r^2$ drastically dropped to 0.25 (25%), which is significantly lower than the original $r^2$ for all 29 sites ($r^2 = 0.44$). This shows that there are different outliers involved with skewing the general trend in karren density. Upon viewing Figure 5.5C it is clear that, in addition to the New Ferrolle Peninsula, all three karren zones at the Cook's Harbour region possess densities which are much higher than those at the other sites (especially the intertidal zone). Thus, a regression was run with these sites removed from the analysis, and the backshore sites of the Cow Head Peninsula and Daniel's Harbour included. The resultant log-linear relationship is shown in Figure 5.9A and defined by the equation,

$$Y = 1.24 - 0.9574X \pm 0.216 \tag{5.6}$$

and is then transformed back to the original data set (Figure 5.9B).

$$Y = 17.30X^{-0.95743} \tag{5.7}$$

This means that at a height at 1 m above the MLWM, karren density can be expected to be 17.30

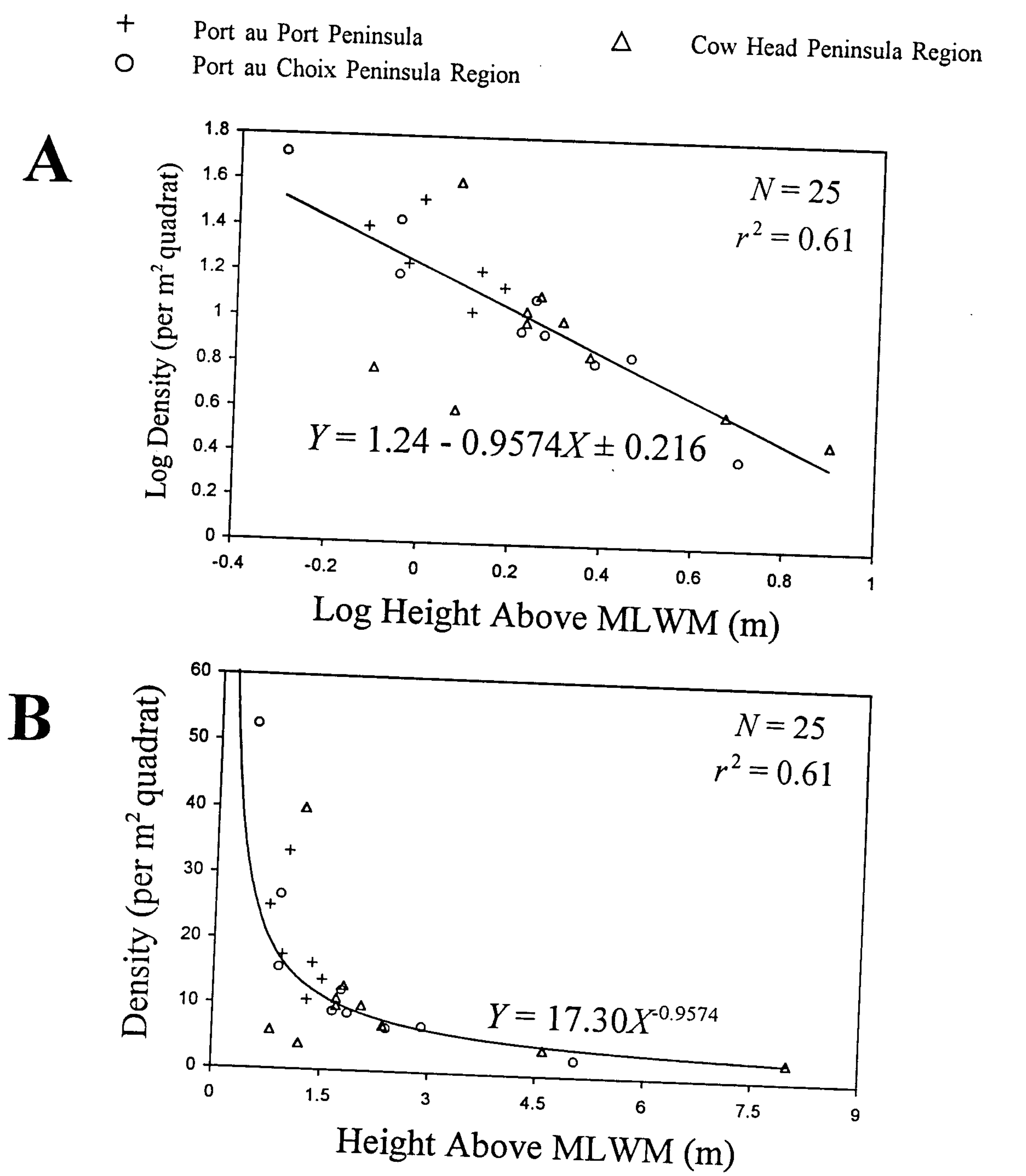



Figure 5.9 A) Log-linear relationship between height above the MLWM ($X$) and average karren density ($Y$). B) Curve fit through the original data. Data are excluded for the New Ferrolle Peninsula and the Cook's Harbour region.

pits/$m^2$. An inverse relationship exists here as density decreases with increasing height above the MLWM, but at a decreasing rate. The adjusted $r^2$ is 0.61 (61%) for the newly defined data set and the $F$ statistic (35.79) is statistically significant at both the 0.05 (4.26) and 0.01 (7.82) levels of significance.

The distribution of residuals are again analyzed and separated into the previously defined categories (Table 5.12). It is interesting in that only eight of the sites in this analysis have karren densities which are significantly under- or overestimated by the regression model. These sites have density values which are either, much higher or lower than one would expect for that particular zone, again due to the combination of geology and local environmental conditions. Usually sites which have diameter overestimated (e.g. Belldowns Island, S. Coast, Port au Port Peninsula), have corresponding densities which are underestimated by the model, although this is not always the case. One clear reason for much higher densities in some of the swash and backshore zones, especially the Cook's Harbour region, is due to the existence of dolomite, or dolomitic rock, which hosts high density, small pitting due to its much reduced solubility (Section 2.4).

## C) Explanation of the Proposed Intrasite Trends in Karren Development

It is difficult to explain these trends in karren development across the littoral zone, strictly in terms of location with respect to the local tidal regime. Karren within the intertidal zone are subjected to 12 hours of subaerial and subaqueous exposure every day. Supratidal swash karren are continually subaerially exposed, except when temporarily submerged by daily high water/rough water swash. Backshore karren are only submerged by swash from waves during storm conditions.

With this in mind it appears that karren diameter and microrelief increase with increased subaerial exposure, reducing the number of pits and karren density over a given area of the platform. Although the highest average karren dimensions are associated with the backshore, karren are more abundant and consistently spectacular in the supratidal swash zone. This zone receives a combination of maximum swash energy and subaerial exposure on a more regular basis than the backshore and intertidal zones. There must be some connection between littoral karren development

Table 5.12 Residual categories for log-normal karren density as determined by the standard error of the estimate (*SE*) from the regression equation.

| Category | Site | Zone | Residual Value |
|---|---|---|---|
| **Category 1** | Cow Head Peninsula | Intertidal | -0.56041 |
| < -1½ *SE* (< -.324) | Broom Point | Intertidal | -0.55291 |
| **Category 2** -½ *SE* to -1½ *SE* (-0.108 to -0.324) | Pointe Riche Peninsula | Supratidal | -0.16781 |
| **Category 3** | Port au Port Peninsula - Bar/Long Pt. | Intertidal | -0.01924 |
| -½ *SE* to +½ *SE* | Port au Port Peninsula - Bar/Long Pt. | Supratidal | 0.10366 |
| (-0.108 to 0.108) | Port au Port Peninsula - East Bay | Intertidal | 0.04004 |
| | Port au Port Peninsula - East Bay | Supratidal | -0.10102 |
| | Port au Port Peninsula - South Coast | Supratidal | 0.07270 |
| | Cow Head Peninsula | Supratidal | -0.02377 |
| | Cow Head Peninsula | Backshore | 0.10348 |
| | Broom Point | Supratidal | 0.02375 |
| | Broom Point | Backshore | -0.03791 |
| | Daniel's Harbour | Supratidal | 0.06020 |
| | Daniel's Harbour | Backshore | -0.00168 |
| | Port au Choix Peninsula | Supratidal | 0.08727 |
| | Port au Choix Peninsula | Backshore | 0.04953 |
| | Pointe Riche Peninsula | Intertidal | -0.08813 |
| | Pointe Riche Peninsula | Supratidal | -0.07581 |
| | Pointe Riche Peninsula | Backshore | -0.05471 |
| | Ingornachoix Bay | Supratidal | -0.03972 |
| **Category 4** | Port au Port Peninsula - South Coast | Intertidal | 0.14458 |
| ½ *SE* to 1½ *SE* | Stearing Island | Supratidal | 0.12007 |
| (0.108 to 0.324) | Port au Choix Peninsula | Intertidal | 0.14458 |
| | Ingornachoix Bay | Intertidal | 0.19400 |
| **Category 5 > 1½ *SE*** (> 0.324) | Belldowns Island | Supratidal | 0.43959 |

and degree of subaerial exposure, but further process work would be required at all sites to verify if any such relationship does exist.

These findings contrast with those found at Galway Bay, the Bristol Channel and Vancouver Island, B.C., where maximum karren development occurred in the mid-intertidal zone (Sec. 2.3). This is probably due to the differing nature of the tidal regimes in these regions as compared to western Newfoundland. The mean tidal range for Vancouver Island is about 2.7 m (mesotidal) and over 4 m for Galway Bay and the Bristol Channel (macrotidal). The horizontal extent of platform rock within the intertidal zone for western Newfoundland is usually very limited (Sec. 4.2), so that most of the maximum swash energy is released at the supratidal swash zone. At these other temperate karren regions the intertidal zone probably spans much greater distances, allowing a higher magnitude of erosion to be concentrated within this zone. Also, the Galway Bay karren models are directly correlated with biological colonization within the intertidal zone (Sec. 2.3.2), and bioerosion is not a primary factor of karren genesis for western Newfoundland (Sec. 4.6).

### 5.2.3 Intersite Statistical Comparisons

A) Regional Non-parametric Comparisons

This section will attempt to verify that there are variations in karren development between different sites and regions for western Newfoundland. Morphologic data are used to compare degrees of karren development between the regions. Non-parametric methods of comparison are used, as the data do not have to be normally distributed and there are a number of very small samples used in the testing.

The best non-parametric testing technique to be used here is the Kruskal-Wallis test of ordinal data. To apply this technique there must be at least three groups involved in the comparison, each of which must contain at least three observations (Shaw and Wheeler, 1985). The karren data for the different sites defined in Chapter 4, are presented for average density (Table 5.13), diameter (Table 5.14) and microrelief (Table 5.15). There is essentially only one site in the Cook's Harbour

Table 5.13 Diameter comparisons between the four karren regions of western Newfoundland, for the inter-, supratidal swash and backshore zones. The data is presented in the form prepared for the Kruskal-Wallis test.

| Study Sites (*N*)* | Intertidal Zone | | Supratidal Swash Zone | | Backshore Zone | |
|---|---|---|---|---|---|---|
| | Average Diameter (cm) | Rank | Average Diameter (cm) | Rank | Average Diameter (cm) | Rank |
| Port au Port Peninsula: South Coast Sites (7) | 6.21 | 4 | 9.46 | 3 | ----- | ----- |
| The Bar/Long Point (20) | 12.68 | 7 | 10.75 | 4 | ----- | ----- |
| Port au Port East Bay (5) | 8.81 | 6 | 8.45 | 2 | ----- | ----- |
| Cow Head Peninsula (9) | 18.59 | 9 | 17.81 | 11 | 19.58 | 9 |
| Broom Point (4) | 8.18 | 5 | 17.21 | 9 | 11.15 | 5 |
| Belldowns Island (1) | ----- | ----- | 5.52 | 1 | ----- | ----- |
| Stearing Island (1) | ----- | ----- | 18.46 | 12 | ----- | ----- |
| Lower Head (1) | ----- | ----- | ----- | ----- | 9.90 | 4 |
| Daniel's Harbour (2) | ----- | ----- | 17.68 | 10 | 9.78 | 3 |
| Port au Choix Pen. (16) | 6.08 | 3 | 11.92 | 5 | 18.96 | 8 |
| Pointe Riche Pen. (19) | 13.87 | 8 | 15.87 | 7 | 16.60 | 7 |
| Ingornachoix Bay (33) | 5.98 | 2 | 16.87 | 8 | 24.35 | 10 |
| New Ferrolle Pen. (1) | ----- | ----- | ----- | ----- | 6.47 | 1 |
| W. Cape Norman (4) | ----- | ----- | 36.42 | 14 | 16.00 | 11 |
| Cape Norman (4) | ----- | ----- | 12.16 | 6 | 8.54 | 2 |
| E. Cape Norman (7) | 3.51 | 1 | 27.21 | 13 | 47.54 | 6 |
| *H* Statistic | ------ | | 6.04 | | 0.33 | |
| Critical *H* (0.05)** | ------ | | 7.82 | | 5.99 | |

* number in brackets refers to the number of total quadrats at each site (excl. spray zone)

** critical values of the Kruskal-Wallis test statistic *H* are from Appendix III (chi-square), p. 340 in Shaw and Wheeler (1985)

Table 5.14 Microrelief comparisons between the four karren regions of western Newfoundland, for the inter-, supratidal swash and backshore zones. The data is presented in the form prepared for the Kruskal-Wallis test.

| | Intertidal Zone | | Supratidal Swash Zone | | Backshore Zone | |
|---|---|---|---|---|---|---|
| Study Sites (*N*)* | Average Diameter (cm) | Rank | Average Diameter (cm) | Rank | Average Diameter (cm) | Rank |
| Port au Port Peninsula: South Coast Sites (7) | 3.04 | 4 | 4.00 | 4 | ----- | ----- |
| The Bar/Long Point (20) | 6.30 | 8 | 5.46 | 7 | ----- | ----- |
| Port au Port East Bay (5) | 4.48 | 7 | 4.56 | 5 | ----- | ----- |
| Cow Head Peninsula (9) | 8.38 | 9 | 9.98 | 10 | 8.33 | 9 |
| Broom Point (4) | 3.83 | 6 | 10.24 | 11 | 4.39 | 3 |
| Belldowns Island (1) | ----- | ----- | 3.03 | 3 | ----- | ----- |
| Stearing Island (1) | ----- | ----- | 8.58 | 9 | ----- | ----- |
| Lower Head (1) | ----- | ----- | ----- | ----- | 7.51 | 8 |
| Daniel's Harbour (2) | ----- | ----- | 10.90 | 12 | 5.13 | 5 |
| Port au Choix Pen. (16) | 1.90 | 2 | 3.06 | 2 | 5.37 | 6 |
| Pointe Riche Pen. (19) | 3.79 | 5 | 4.93 | 6 | 3.66 | 2 |
| Ingornachoix Bay (33) | 2.04 | 3 | 5.83 | 8 | 12.94 | 10 |
| New Ferrolle Pen. (1) | ----- | ----- | ----- | ----- | 4.87 | 4 |
| W. Cape Norman (4) | ----- | ----- | 28.06 | 14 | 6.36 | 7 |
| Cape Norman (4) | ----- | ----- | 2.38 | 1 | 3.41 | 1 |
| E. Cape Norman (7) | 1.44 | 1 | 20.25 | 13 | 37.88 | 11 |
| *H* Statistic | ------ | | 2.83 | | 0.14 | |
| Critical *H* (0.05)** | ------ | | 7.82 | | 5.99 | |

* number in brackets refers to the number of total quadrats at each site (excl. spray zone)

** critical values of the Kruskal-Wallis test statistic *H* are from Appendix III (chi-square), p. 340 in Shaw and Wheeler (1985)

Table 5.15 Density comparisons between the four karren regions of western Newfoundland, for the inter-, supratidal swash and backshore zones. The data is presented in the form prepared for the Kruskal-Wallis test.

| | Intertidal Zone | | Supratidal Swash Zone | | Backshore Zone | |
|---|---|---|---|---|---|---|
| Study Sites (*N*)* | Average Density (per m$^2$ quadrat) | Rank | Average Density (per m$^2$ quadrat) | Rank | Average Density (per m$^2$ quadrat) | Rank |
| Port au Port Peninsula: South Coast Sites (7) | 33.33 | 7 | 13.88 | 11 | ----- | ----- |
| The Bar/Long Point (20) | 17.57 | 4 | 16.36 | 12 | ----- | ----- |
| Port au Port East Bay (5) | 25.00 | 5 | 10.67 | 7 | ----- | ----- |
| Cow Head Peninsula (9) | 4.00 | 1 | 9.86 | 5 | 3.00 | 3 |
| Broom Point (4) | 6.00 | 2 | 11.00 | 8 | 7.00 | 6.5 |
| Belldowns Island (1) | ----- | ----- | 40.00 | 13 | ----- | ----- |
| Stearing Island (1) | ----- | ----- | 13.00 | 10 | ----- | ----- |
| Lower Head (1) | ----- | ----- | ----- | ----- | 12.00 | 9 |
| Daniel's Harbour (2) | ----- | ----- | 10.00 | 6 | 4.00 | 4 |
| Port au Choix Pen. (16) | 26.71 | 6 | 12.25 | 9 | 7.00 | 6.5 |
| Pointe Riche Pen. (19) | 15.63 | 3 | 9.00 | 4 | 6.60 | 5 |
| Ingornachoix Bay (33) | 52.54 | 8 | 8.72 | 3 | 2.50 | 2 |
| New Ferrolle Pen. (1) | ---- | ----- | ----- | ----- | 18.50 | 10 |
| W. Cape Norman (4) | ----- | ----- | 6.00 | 2 | 2.33 | 1 |
| Cape Norman (4) | ----- | ----- | 68.00 | 14 | 34.60 | 11 |
| E. Cape Norman (7) | 100.00 | 9 | 3.00 | 1 | 9.72 | 8 |
| *H* Statistic | ------ | | 2.68 | | 0.18 | |
| Critical *H* (0.05)** | ------ | | 7.82 | | 5.99 | |

* number in brackets refers to the number of total quadrats at each site (excl. spray zone)

**critical values of the Kruskal-Wallis test statistic *H* are from Appendix III (chi-square), p. 340 in Shaw and Wheeler (1985).

region, so it was divided into three areas based on profile locations with respect to Cape Norman (Figure 4.4). Dashed lines indicate sites where karren did not exist for that zone. Note that there was no test performed for intertidal zone karren comparisons, as the number of observations within the Cow Head Peninsula and Cook's Harbour regions do not comply to the requirements of the Kruskal-Wallis test.

The procedure, from Shaw and Wheeler (1985), involves ranking the data from the smallest to largest observation, with a rank of 1 representing the smallest value. Observations with the same value are given an average of the ranks had the tie not occurred. For example, the only instance of a tie here was with backshore density. Average density for Broom Point and the Port au Choix Peninsula is 7 pits/m$^2$. Had the tie not occurred one would have been given a rank of 6 and the other a rank of 7. Thus, since they are tied both are given an average rank of 6.5, with the next highest observation given a rank of 8. The test statistic ($H$) is then calculated using the equation,

$$H = \frac{12}{n_s(n_s + 1)} \sum_{i=1}^{k} \frac{R_i^2}{n_i} - 3(n_s + 1) \tag{5.8}$$

where $n_s$ = total number of observations
$n_i$ = number within each group
$R_i$ = rank sums for each group
$k$ = number of groups

If ties consume at least 25% of the data then a correction must be applied to the $H$ statistic, with $H$ being divided by $C$, where

$$C = 1 - \frac{(T^3 - T)}{n_s^3 - n_s} \tag{5.9}$$

where $T$ = number of ties
$n_s$ = number of observations

Greater inter-group differences will produce a larger $H$ value, revealing regional differences in the data. All of the $H$ statistics presented in Tables 5.13 to 5.15 are very small, except for supratidal swash diameter variations. None of these $H$ values fall within the rejection region for hypothesis testing (i.e. greater than critical $H$ values determined by the individual group sizes), indicating that karren data do not differ significantly between the four primary study regions. It had been anticipated that there would be significant karren variation between these regions, due to the contrasting coastal environments and lithologies.

## B) Non-parametric Comparisons Within the Major Regions

A scan of the data in Tables 5.13 to 5.15 reveals that there are significant data variations within each region. This is especially true for the Cook's Harbour region. This amount of internal variation overrides any variation between the regions. Thus, intersite statistical comparisons for each of the littoral zones have been conducted within each region.

The data were again prepared for the Kruskal-Wallis test. It was found that this method worked well for comparisons in the Port au Port Peninsula supratidal swash zones, the backshore zone in the Cow Head Peninsula region, and Port au Choix Peninsula region inter-and supratidal swash zones. None of the $H$ statistics here fall within the rejection region of critical $H$, except for the intertidal zone of the Port au Choix Peninsula region (Table 5.16). That is, both karren density and diameter within this region, for the intertidal zone, are considered to be statistically different beyond that of random variation. Microrelief variations in this region are borderline significant, although the $H$ statistic would fall within the rejection region for a 0.10 significance level ($5.02 > 4.60$). It should be noted that when there are more than five observations in each group, as is the case here, then the test statistic is distributed as chi-square with $k - 1$ degrees of freedom (Shaw and Wheeler, 1985).

Often, however, at this scale of comparison the required number of groups and observations for the Kruskal-Wallis test was not possible. Thus, other intersite comparisons were tested using the two-sample Mann-Whitney statistical test. As described in Shaw and Wheeler (1985), the Mann-

Table 5.16 Variations in intertidal zone karren density, diameter and microrelief within the Port au Choix Peninsula region. The data is presented in the form prepared for the Kruskal-Wallis test.

| Region | Average Density (per $m^2$ quadrat) | Mean Rank | Average Diameter (cm) | Mean Rank | Average Micro-relief (cm) | Mean Rank |
|---|---|---|---|---|---|---|
| **Port au Choix Peninsula Region: Intertidal ($N$)*** | | | | | | |
| Pointe Riche Pen. (8) | 15.63 | 7.25 | 13.87 | 18.63 | 3.79 | 18.29 |
| Port au Choix Pen. (7) | 26.71 | 10.43 | 6.08 | 10.86 | 1.90 | 11.07 |
| Ingornachoix Bay (11) | 73.23 | 19.40 | 5.98 | 10.55 | 2.04 | 10.86 |
| $H$ Statistic | 13.51 | | 7.18 | | 5.02 | |
| Critical $H$ (0.05)** | 5.99 | | 5.99 | | 5.99 | |

* number in brackets refers to the number of quadrats at each site
** critical values of the Kruskal-Wallis test statistic $H$ are from Appendix III, p. 340 in Shaw and Wheeler (1985)

Whitney procedure of statistical variation is very similar to that for the Kruskal-Wallis test. Data for the observations within the two groups are ranked, allowing the test statistic ($U$) to be calculated using the following equation,

$$U = n_1 n_2 + \frac{n_1(n_1 + 1)}{2} - R_1 \tag{5.10}$$

where

$n_1$ = size of small group
$n_2$ = size of larger group
$R_1$ = sum of ranks in smaller group

The Mann-Whitney test is unusual in that low test statistics are required to fall within the rejection region. The rejection region is determined by the probability of *U*, which will vary depending on the *U* statistic and the size of the two groups involved (see Shaw and Wheeler, 1985, p. 135). If the probability of *U* is less than the level of significance (e.g. 0.05 here), then there are statistically significant differences between the two sites involved.

Intersite statistical comparisons, which were proven to be statistically different beyond that of random variation, are provided in Table 5.17 through 5.19. These tables reveal a number of sites which possess differential karren development. For example, average intertidal zone karren diameter and microrelief for the Cow Head Peninsula are significantly different than that for Broom Point. Average backshore karren diameter and microrelief, for the profile constructed near the navigation light at Cape Norman, are significantly lower than that for the rest of the region. Note that the group sizes are larger than eight for the Mann-Whitney comparisons in the Cook's Harbour region. Thus, the *U* statistic is now directly compared to a critical *U* value, in the same manner as for the Kruskal-Wallis test procedure, but the test statistic *U* must still be less than critical *U* to fall within the rejection region. Some intersite comparisons (Cook's Harbour region swash diameter and density and Port au Port Peninsula intertidal density) are presented as being statistically significant, even though the *U* probability values are slightly higher than the proposed level of significance. They would, however, be statistically significant at the 0.10 significance level.

These results verify that there is considerable karren variation between different sites, and at times, from one profile to another *within* the same site. Reasons for these variations will now be examined.

## 5.3 Geologic Analysis

### 5.3.1 Petrological Classification and Description of Western Newfoundland Carbonate Rocks

In order to determine the potential control that geology possesses on the development of littoral karren, it is best to classify the carbonate rocks into different types or categories, and then

Table 5.17 Mann-Whitney testing of statistically significant intersite karren variations. Data includes density variations between the intertidal zones of the Port au Port Peninsula, and the supratidal swash zones of the Cook's Harbour region.

| Region | Average Density (per $m^2$ quadrat) | Mean Rank |
|---|---|---|
| **Port au Port Peninsula (*N*)*** | | |
| The Bar/Long Point (7) | 17.57 | 5.14 |
| Rest of the Region (5) | 30.00 | 8.40 |
| *U* Statistic = 8.00 | + Probability of *U* (0.05) = 0.074 | |
| **Cook's Harbour Region (*N*)** | | |
| Cape Norman (3) | 68.00 | 6.50 |
| Rest of the Region (5) | 3.60 | 3.30 |
| *U* Statistic = 1.50 | ++ Probability of *U* (0.05) = 0.054 | |

* number in brackets refers to the number of quadrats at each site

+ probabilties for the Mann-Whitney test statistic *U* are from Appendix Vb, p. 343 in Shaw and Wheeler (1985)

++ probabilties for the Mann-Whitney test statistic *U* are from Appendix Va, p. 342 in Shaw and Wheeler (1985)

correlate the occurrence of karren with each rock type and its associated properties. A basic classification for carbonate rocks is provided in Figure 5.10, between limestone (calcite), dolomite and various percentages of impure carbonate rocks. Limestone can be further classified into different types, on the basis of grain size, composition and perceived facies (Ford and Williams, 1989). The most widely used limestone classification systems, that of Folk (1959) and Dunham (1962), are based on this premise of relating rock fabric to the deposition of the limestone.

The classification used for the rocks in this study is that of Embry and Klovan (1971), which is essentially an extension of Dunham's system (Figure 5.11). This classification is based on

Table 5.18 Mann-Whitney testing of statistically significant intersite karren variations. Data includes supratidal swash and backshore zone diameter and microrelief comparisons within the Cook's Harbour region.

| Region | | Dimension (cm) | Mean Rank |
|---|---|---|---|
| **Supratidal Swash Average Diameter (*N*)*** | | | |
| | Cape Norman (3) | 12.16 | 2.67 |
| | Rest of the Region (5) | 41.37 | 5.60 |
| | *U* Statistic = 2.00 | + Probability of *U* (0.05) = 0.071 | |
| **Backshore Average Diameter (*N*)**** | | | |
| | Cape Norman (17) | 8.54 | 13.21 |
| | Rest of the Region (18) | 31.77 | 22.53 |
| | *U* Statistic = 71.50 | ++ Critical *U* (0.05) = 102 | |
| **Supratidal Swash Average Microrelief (*N*)*** | | | |
| | Cape Norman (3) | 2.38 | 2.33 |
| | Rest of the Region (5) | 25.44 | 5.80 |
| | *U* Statistic = 1.00 | + Probability of *U* (0.05) = 0.036 | |
| **Backshore Average Microrelief (*N*)**** | | | |
| | Cape Norman (17) | 3.41 | 10.71 |
| | Rest of the Region (18) | 22.12 | 24.89 |
| | *U* Statistic = 29.00 | ++ Critical *U* (0.05) = 102 | |

* number in brackets refers to the number of quadrats at each site

** number in brackets refers to the number of individual karren pits at each site

+ probabilties for the Mann-Whitney test statistic *U* are from Appendix Va, p. 342 in Shaw and Wheeler (1985)

++ critical values of the Mann-Whitney test statistic *U* are from Appendix Vd, p. 345 in Shaw and Wheeler (1985)

Table 5.19 Mann-Whitney testing of statistically significant intersite karren variations. Data includes intertidal zone diameter and microrelief variations between the Cow Head Peninsula and Broom Point.

| Region | Dimension (cm) | Mean Rank |
|---|---|---|
| **Average Diameter (*N*)*** | | |
| Cow Head Peninsula (4) | 18.59 | 8.50 |
| Broom Point (6) | 8.18 | 3.50 |
| *U* Statistic = 0.00 | + Probability of *U* (0.05) = 0.005 | |
| **Average Microrelief (*N*)** | | |
| Cow Head Peninsula (4) | 8.38 | 7.50 |
| Broom Point (6) | 3.83 | 3.00 |
| *U* Statistic = 0.00 | Probability of *U* (0.05) = 0.005 | |

* number in brackets refers to the number of individual karren pits at each site

\+ probabilties for the Mann-Whitney test statistic *U* are from Appendix Va, p. 342 in Shaw and Wheeler (1985)

grain size and differentiates between rocks which are matrix-supported, grain-supported or biologically bound. The biologically bound, or autochthonous, component refers to *in situ* reef growth and sedimentation, and does not apply to the rocks in this study. Instead the various allochthonous categories provided in Figure 5.11 represent the environment of deposition for the rocks taken from western Newfoundland. Even though most of the major rock formations are defined in the literature as being autochthonous (Sec. 3.2), they were not organically bound during deposition and, in fact, these rocks may have experienced some transport from the site of deposition.

Rock samples taken from the field were classified with the aid of polished hand specimens, viewed under a binocular microscope, and several representative thin sections. The different types

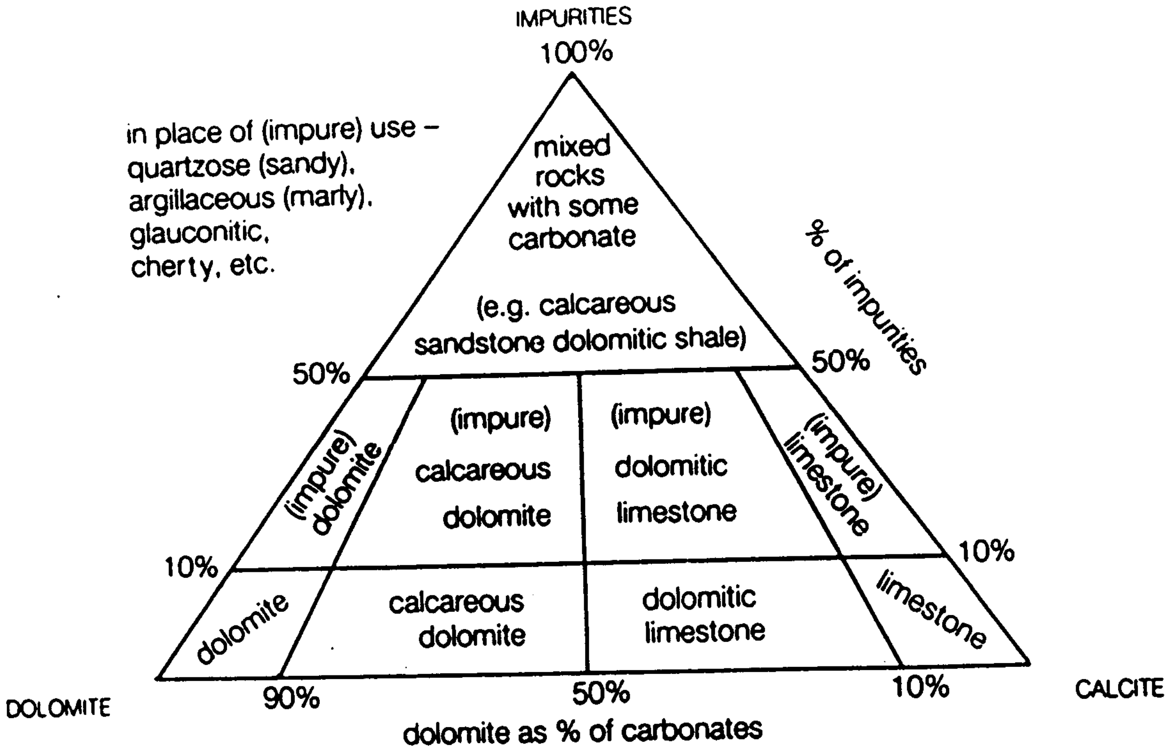



Figure 5.10 A bulk compositional classification of carbonate rocks (from Ford and Williams, 1989 p. 10, modified after Leighton and Pendexter, 1962, p. 51).

of carbonate rocks are presented in Table 5.20, along with a regional distribution of occurrence and a brief description of composition. More detailed notes for each individual rock sample/thin section are provided in Appendix A. In addition to the various limestones existing at the different sites, there are also some occurrences of dolomite and calcareous siltstones, both of which provide a good lithologic comparison to limestone in terms of karren development. Chert is mentioned only due to its close association with the significantly more pure limestone at those sites, as there are no karren directly associated with chert. It was not often easy to determine the rock type for the samples, since these classification systems are based on original depositional fabrics, which can be greatly modified by processes such as pressure dissolution and compaction (Tucker and Wright, 1990).

Thin section pictures of the matrix-supported mudstone and wackestone are provided in

<table>
<tr><td colspan="6">Allochthonous limestones original components not organically bound during deposition</td><td colspan="3">Autochthonous limestones original components organically bound during deposition</td></tr>
<tr><td colspan="4">Less than 10% > 2 mm components</td><td colspan="2">Greater than 10% > 2 mm components</td><td rowspan="4">By organisms which act as baffles</td><td rowspan="4">By organisms which encrust and bind</td><td rowspan="4">By organisms which build a rigid framework</td></tr>
<tr><td colspan="3">Contains lime mud (< .03 mm)</td><td>No lime mud</td><td rowspan="3">Matrix supported</td><td rowspan="3">> 2 mm component supported</td></tr>
<tr><td colspan="2">Mud supported</td><td colspan="2" rowspan="2">Grain supported</td></tr>
<tr><td>Less than 10% grains (> .03 mm < 2 mm)</td><td>Greater than 10% grains</td></tr>
<tr><td>Mudstone</td><td>Wackestone</td><td>Packstone</td><td>Grainstone</td><td>Floatstone</td><td>Rudstone</td><td>Bafflestone</td><td>Bindstone</td><td>Framestone</td></tr>
</table>

Figure 5.11 The Embry and Klovan modification of Dunham's (1962) classification of carbonate rocks (from Embry and Klovan, 1971, p. 736)

Figure 5.12. The differentiation between these two rocks is best seen in thin section, with mudstone possessing a much lower percentage of visible allochems than wackestones. Both of these rock types are deposited in low-energy environmental settings (i.e. deep water), so that most of the mud is not winnowed away by wave action. These rocks appear to be most often associated with the Table Head Group, St. George Group and the Codroy Group rock formations.

Hand specimen photos of a packstone (Figure 5.13) and grainstone (Figure 5.14) rock reveal grain-supported rocks associated with higher-energy environments of deposition. Packstone rocks are the most difficult to identify, as they sometimes contain a fair amount of micritic material, which can make it appear to be a wackestone. There were very few packstones found in the study areas, and most that did exist possessed a grain texture that is representative of two different rock

Table 5.20 Petrological classification, distribution and description of the major carbonate rock types found within the four study regions.

| Rock Type | Regional Distribution* | Comments |
|---|---|---|
| **Mudstone** | Port au Port East Bay, Ship Cove, Lower Cove, Broom Point, Port au Choix Peninsula, Ingornachoix Bay, Pointe Riche Peninsula and Cook's Harbour Region | Very fine grained rocks composed predominantly of a micritic matrix. Most visible allochems in these rocks are peloids or pellets, visible only in thin section. |
| **Wackestone** | Long Point, The Bar, Three Rock Point, Port au Port East Bay, Ship Cove, Port au Choix Peninsula, Ingornachoix Bay and Pointe Riche Peninsula | Generally more spar cement than mudstone rocks. A greater presence of peloids and occasional bioclasts. |
| **Packstone** | The Bar, Lower Cove, Daniel's Harbour and Port au Choix Peninsula | Grain-supported rock containing peloids and bioclasts and varying amounts of micrite. |
| **Grainstone** | The Bar, Lower Cove and Port au Choix Peninsula | Grain-supported rock most often composed of aggregate grains cemented with spar. |
| **Floatstone** | Lower Cove, Port au Port East Bay, Lower Head and Stearing Island | Matrix-supported rock, but with large percentage of visible peloids and bioclasts. |
| **Rudstone** | Lower Cove, Port au Port East Bay, Cow Head Peninsula, Broom Point and Port au Choix Peninsula | Grain-supported rock with large peloids and allochems cemented with spar. |
| **Dolomite** | Jerrys Nose, Port au Choix Peninsula, New Ferrolle Peninsula and Cook's Harbour Region | Limited karren development, due to reduced solubility of the rock. |
| **Calcareous Siltstone** | Long Point, The Bar and Port au Choix Peninsula | Limited karren development, due to higher silt content. |
| **Chert (non-carbonate)** | Cow Head Peninsula and Pointe Riche Peninsula | A very hard, insoluble rock ; no karren development. |

* refers to sites within the major regions where that rock type occurs at least once

A

B

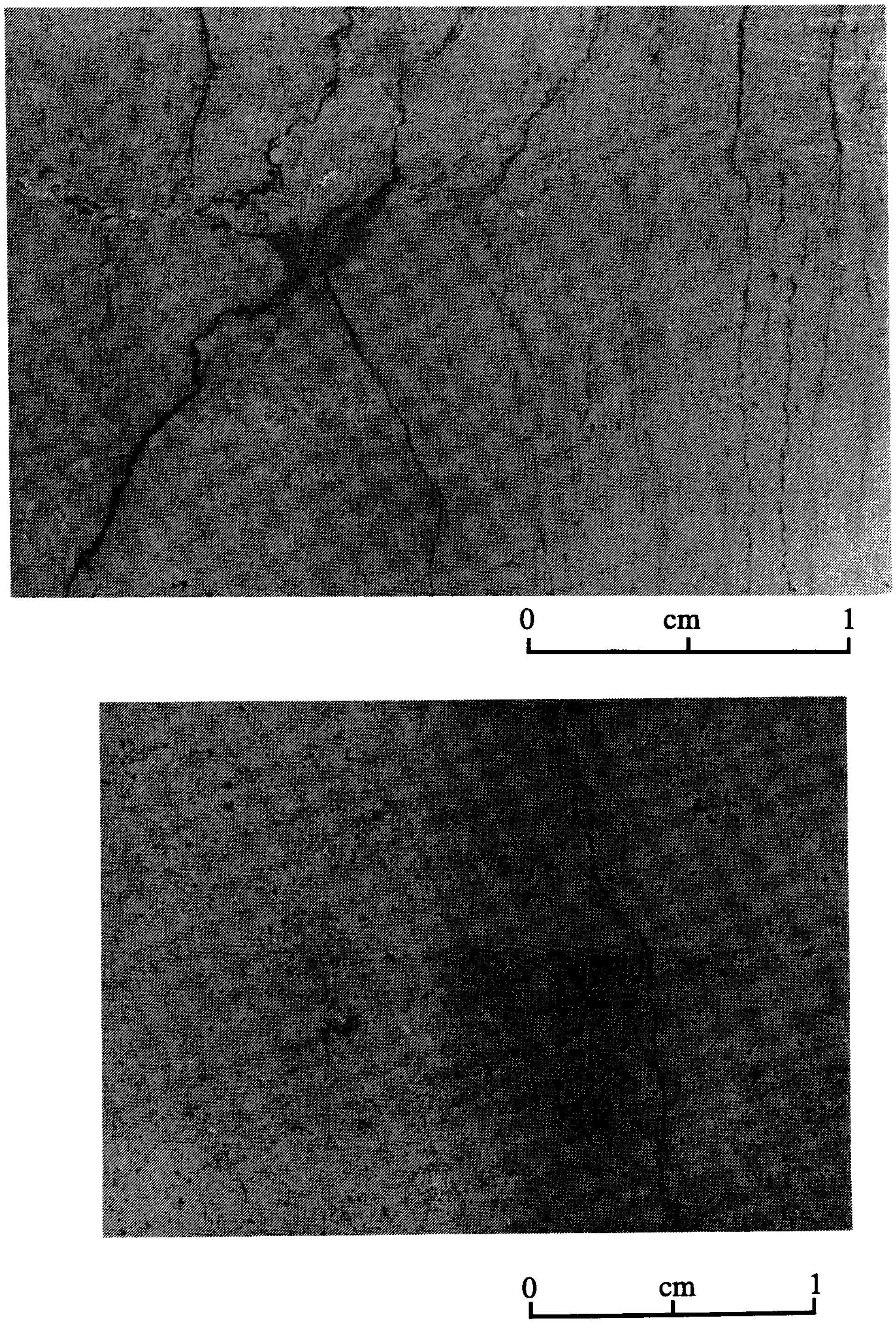



Figure 5.12 Thin section photographs of A) mudstone and B) wackestone as defined by the Embry and Klovan (1971) limestone classification system.

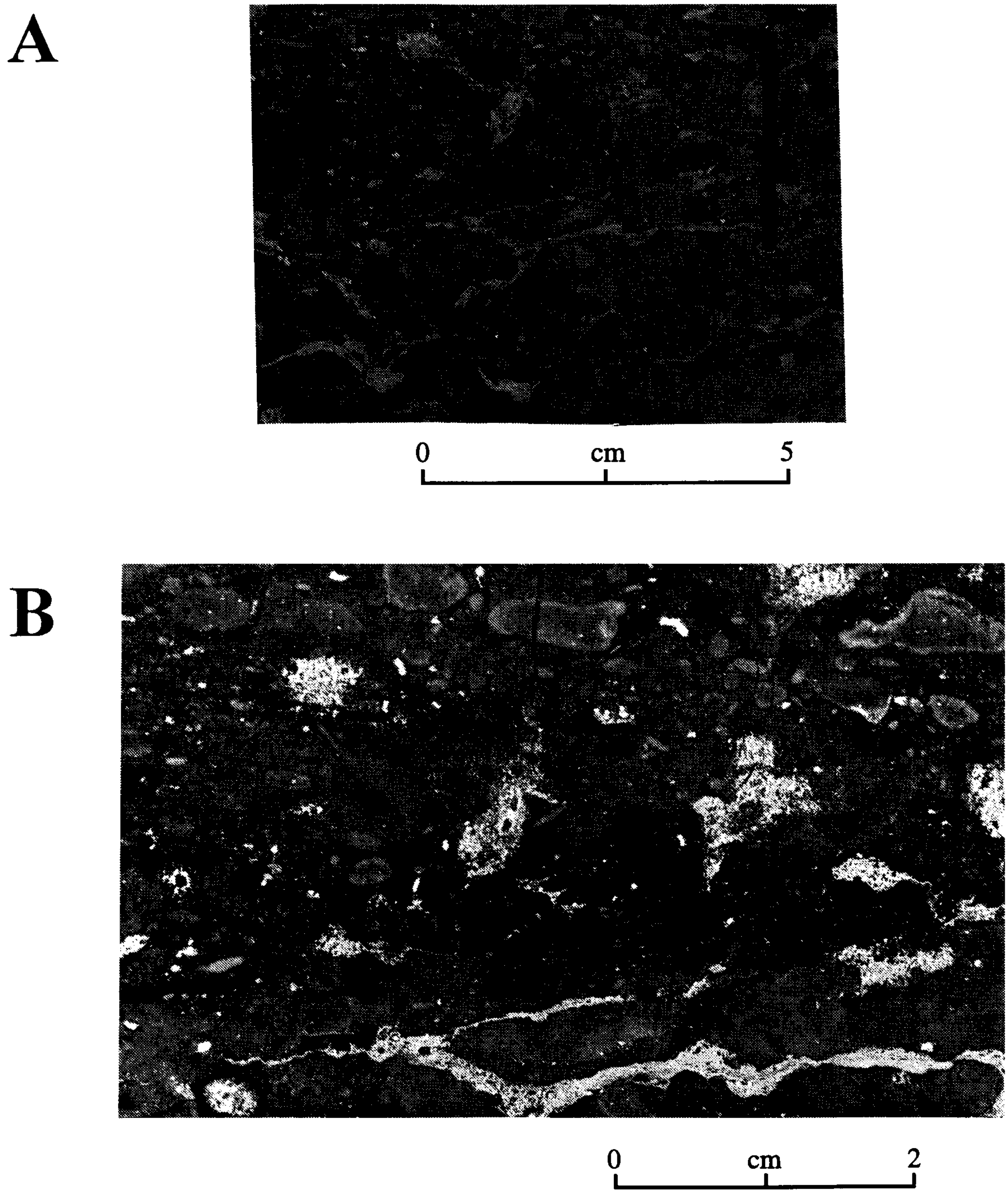



Figure 5.13 Hand specimen photographs of a packstone as defined by the Embry and Klovan (1971) limestone classification system. A) Photo of entire rock face, illustrating the gradation from a packstone texture (top), to a matrix-supported wackestone. B) closeup of the packstone texture as outlined in A.

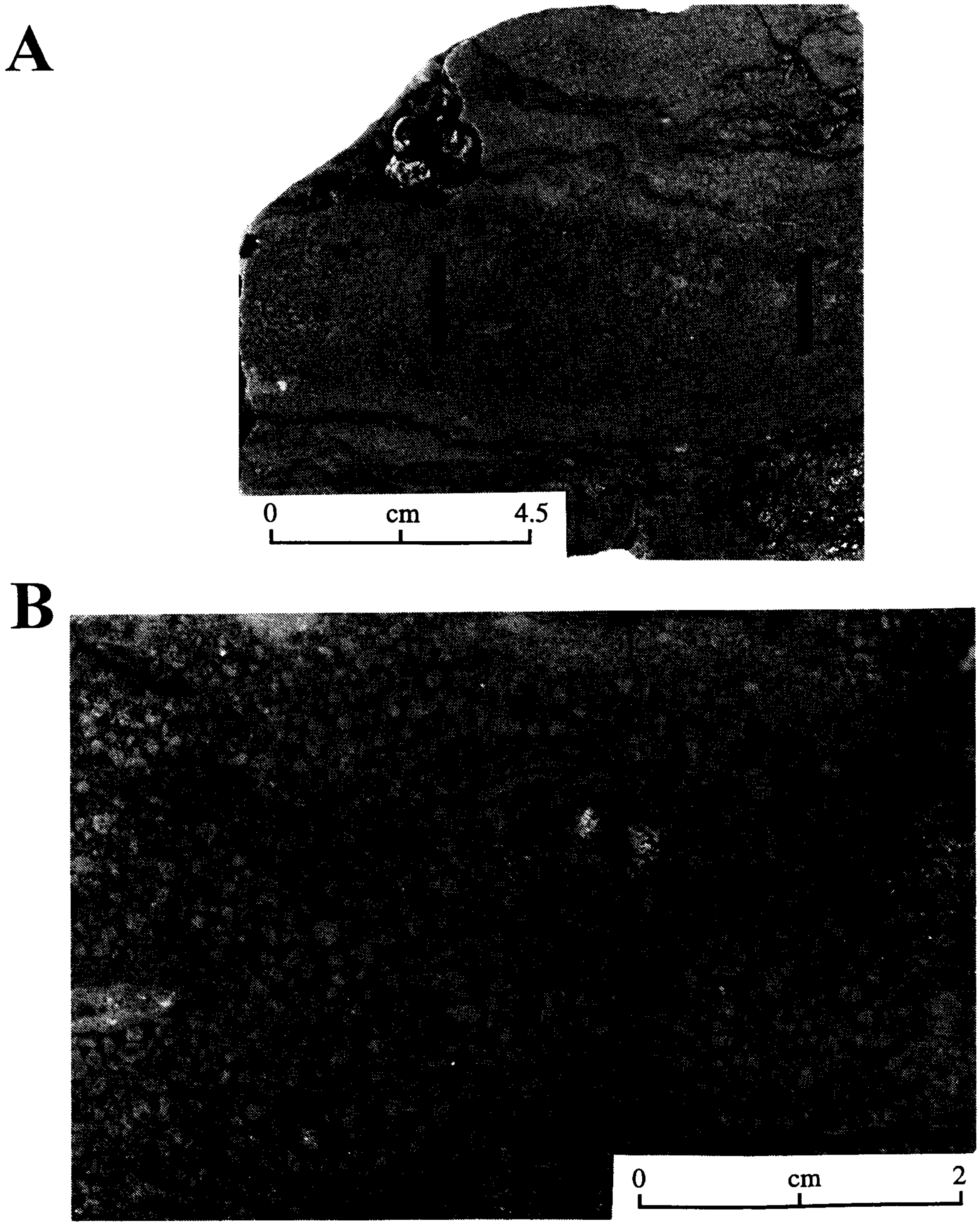



Figure 5.14 Hand specimen photographs of a grainstone as defined by the Embry and Klovan (1971) limestone classification system. A) Photo of entire rock face. B) closeup of the grainstone texture as outlined in A.

types (e.g. Figure 5.13A) and, thus, were classified under both. The distribution of both of these grain-supported rocks reveals what were probably predominantly high-energy environments of deposition at The Bar and Lower Cove, on the Port au Port Peninsula, and the Port au Choix Peninsula.

Most rudstone (Figure 5.15A) and floatstone (Figure 5.15B) samples were from the Cow Head Group of deep-water conglomerates, where most of the rock is composed of a mixture of large clasts. These clasts are often composed of bioclasts, aggregate grains and varying sizes of peloids (micritic grains). Matrix-supported floatstones (best represented by facies B in Sec. 3.2.5) make it appear as though the clasts 'float' in the matrix, which must have had mud introduced into the matrix at some point during the turbidite deposition of these rocks, and was not subsequently winnowed out.

The composition of dolomite (Figure 5.16A) and calcareous siltstones (Figure 5.16B) is best seen in thin section. Dolomite contains characteristic euhedral, rhomb-shaped crystals and often co-exists with calcite. Most limestone samples possess some percentage of dolomite crystals, since most dolomite forms by replacing earlier calcite deposition (Ford and Williams, 1989). Karren development is very limited with this rock type, due to the presence of $Mg^{2+}$ cations reducing rock solubility (Sec. 2.2.2). Siltstones are fine-grained terrigenous rocks and require high-powered magnification to be properly viewed. Since these sediments are insoluble, the rock is much less prone to erosion and the development of karren (Sec. 2.2.4).

### 5.3.2 Rock Type and Karren Development

The effects of the different rock types on karren development are now analyzed. Table 5.21 presents the average karren diameter, microrelief and density associated with the major carbonate rocks discussed in the previous section. As expected, usually only small scale, high density karren occur in dolomite rock formations along the coast, regardless of the littoral zone in which they occur. Microrelief is also quite shallow for karren in calcareous siltstones, although intertidal and supratidal swash diameters are comparable to the more pure limestones. It should be noted, however

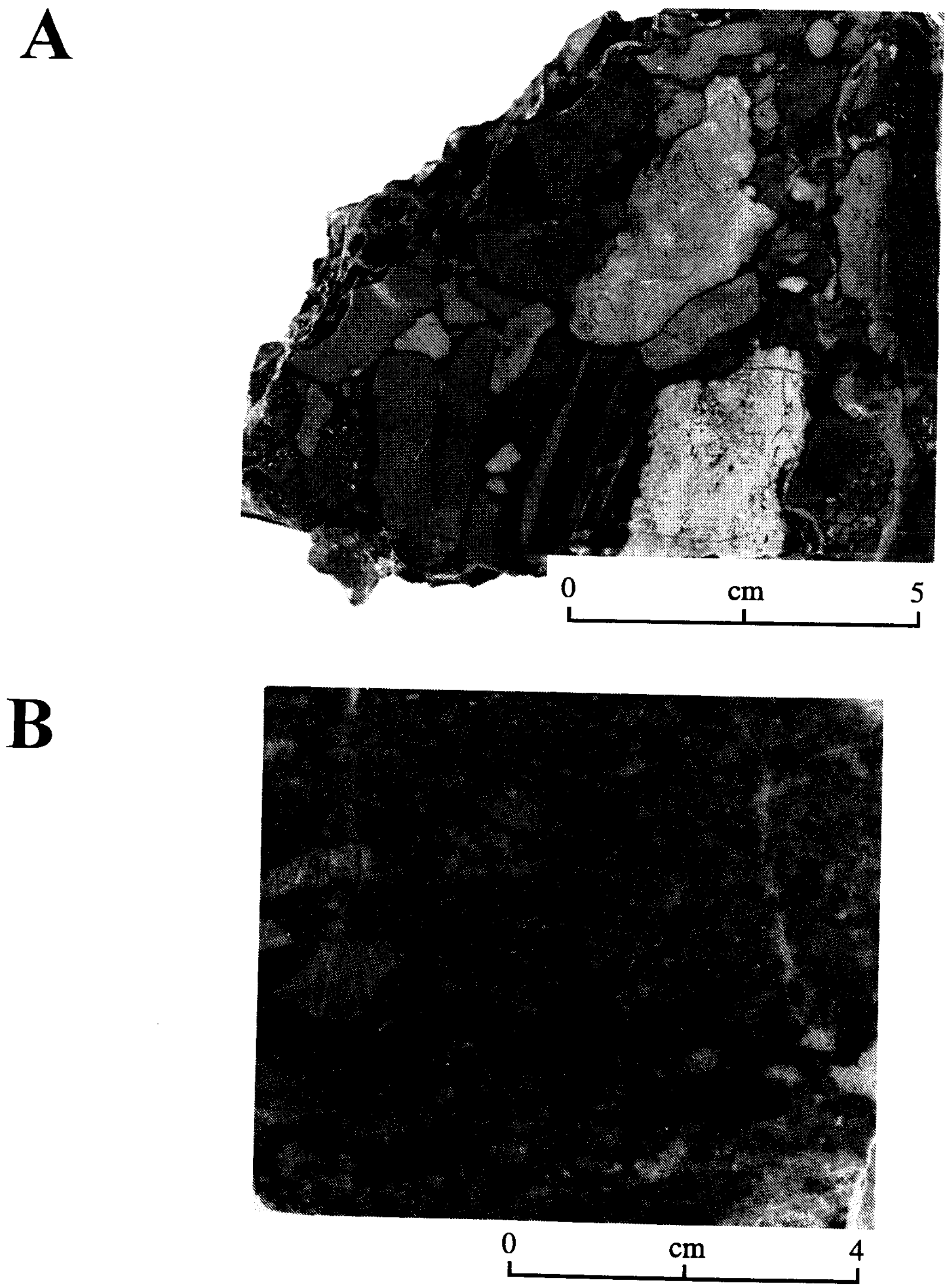



Figure 5.15 Hand specimen photographs of a A) rudstone and B) floatstone as defined by the Embry and Klovan (1971) limestone classification system.

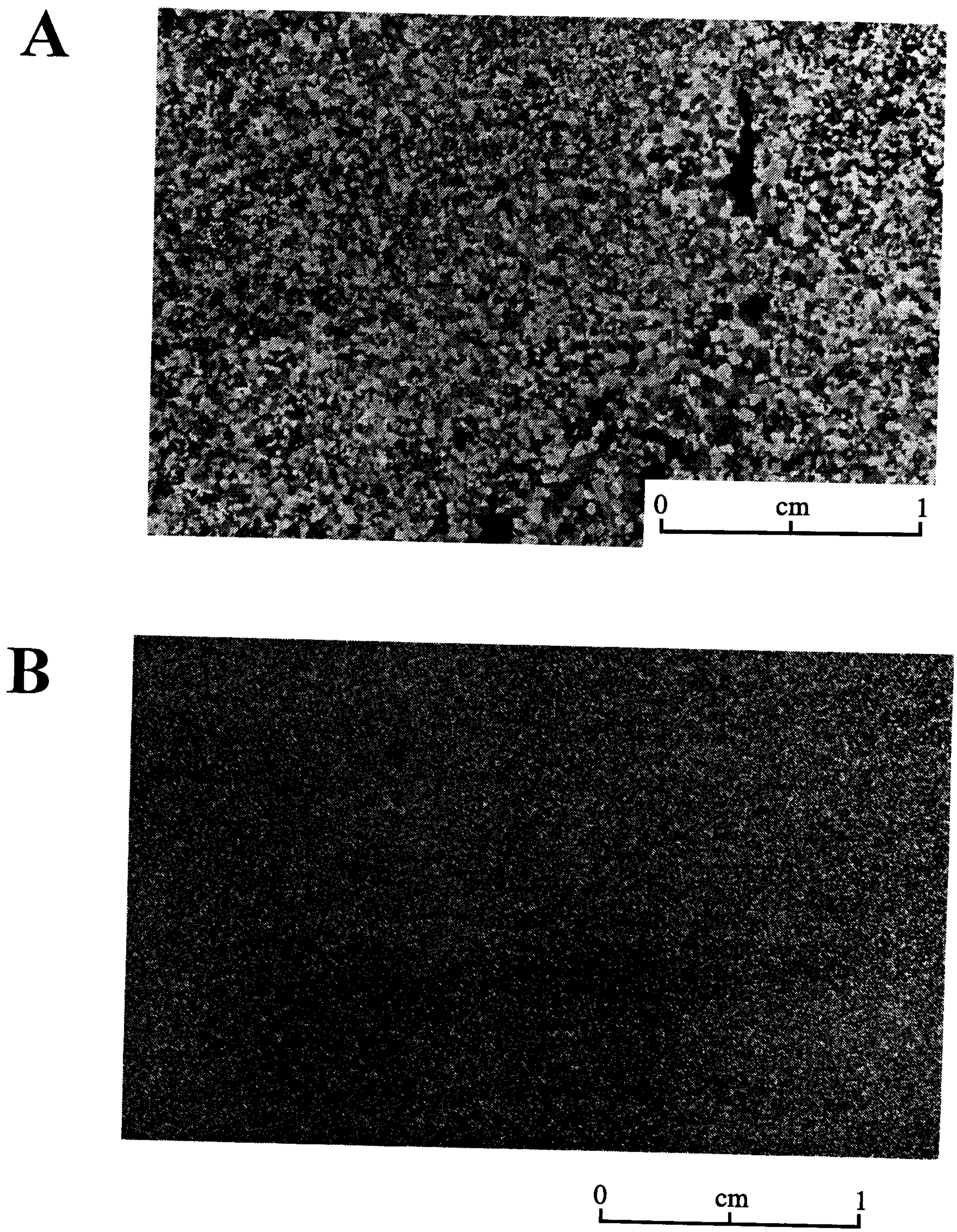



Figure 5.16 Thin section photographs of A) dolomite (note the abundance of rhomb-shaped crystals) and B) calcareous siltstone (very fine-grained rock).

Table 5.21 Karren dimensions across the littoral zone in association with the major carbonate rocks found within the study regions.

| | Zone | | |
|---|---|---|---|
| Karren Measurement | Intertidal | Supratidal Swash | Backshore |
| **Calcareous Siltstone** | | | |
| Avg. Diameter (cm) | 10.73 | 7.95 | 2.56 |
| Avg. Microrelief (cm) | 3.00 | 2.52 | 0.98 |
| Avg. Density (per $m^2$ quadrat) | 9.00 | 7.88 | 12.00 |
| *N* (quadrats) | 2 | 6 | 1 |
| **Dolomite** | | | |
| Avg. Diameter (cm) | 4.50 | 3.20 | 5.37 |
| Avg. Microrelief (cm) | 2.12 | 1.46 | 4.16 |
| Avg. Density (per $m^2$ quadrat) | 20.00 | 56.75 | 13.50 |
| *N* (quadrats) | 1 | 4 | 2 |
| **Mudstone** | | | |
| Avg. Diameter (cm) | 10.08 | 15.68 | 25.25 |
| Avg. Microrelief (cm) | 3.45 | 6.25 | 10.44 |
| Avg. Density (per $m^2$ quadrat) | 31.78 | 12.41 | 8.19 |
| *N* (quadrats) | 27 | 28 | 13 |
| **Wackestone** | | | |
| Avg. Diameter (cm) | 7.71 | 10.64 | 48.00 |
| Avg. Microrelief (cm) | 3.42 | 4.87 | 6.50 |
| Avg. Density (per $m^2$ quadrat) | 29.38 | 15.56 | 5.00 |
| *N* (quadrats) | 10 | 10 | 1 |

Table 5.21 Continued.

| Karren Measurement | Zone: Intertidal | Zone: Supratidal Swash | Zone: Backshore |
|---|---|---|---|
| **Packstone** | | | |
| Avg. Diameter (cm) | 4.18 | 17.68 | 7.89 |
| Avg. Microrelief (cm) | 2.28 | 10.90 | 3.79 |
| Avg. Density (per $m^2$ quadrat) | 50.00 | 10.00 | 7.00 |
| *N* (quadrats) | 1 | 1 | 2 |
| **Grainstone** | | | |
| Avg. Diameter (cm) | 11.01 | 12.72 | 6.00 |
| Avg. Microrelief (cm) | 6.21 | 9.07 | 2.44 |
| Avg. Density (per $m^2$ quadrat) | 40.00 | 19.13 | 10.00 |
| *N* (quadrats) | 2 | 8 | 1 |
| **Floatstone** | | | |
| Avg. Diameter (cm) | ----- | 17.45 | 9.90 |
| Avg. Microrelief (cm) | ----- | 8.47 | 7.51 |
| Avg. Density (per $m^2$ quadrat) | ----- | 8.50 | 12.00 |
| *N* (quadrats) | ----- | 2 | 1 |
| **Rudstone** | | | |
| Avg. Diameter (cm) | 10.03 | 13.10 | 17.18 |
| Avg. Microrelief (cm) | 4.41 | 6.95 | 7.00 |
| Avg. Density (per $m^2$ quadrat) | 14.67 | 12.97 | 10.67 |
| *N* (quadrats) | 4 | 11 | 3 |

however, that karren forming on calcareous siltstones is much more sporadic than on limestone, probably developing in sections of the rock where there is a lower percentage of insoluble silt.

Among the different limestones, there appears to be no visible association between grain size, amount of matrix, and karren development. There are smaller karren depths associated with the matrix-supported rocks (mudstone and wackestone), as compared to karren developing in grainstones and rudstones, in the inter- and supratidal swash zones. This is not what would be expected, as finer-grained limestones are usually the most soluble (Ford and Williams, 1989). Ford and Williams also point out that the finest-grained rocks tend to be the least soluble where the grains are of a very uniform texture. This may be the case for many of the mudstones and wackestones taken from western Newfoundland. Mudstones do display the largest average karren diameters and microrelief in the backshore (not including the one quadrat representing the wackestone). There is a very limited representation of packstone and floatstone rocks, so this may not be an accurate reflection of the potential karren development that can occur with these rock types.

### 5.3.3 Rock Composition and Karren Development

The composition of these rocks, stressing the three principal components of matrix, cement (spar) and allochems, are studied in relation to karren development. The most common limestone matrix is micrite, which is fine-grained carbonate mud less than 5$\mu$m in diameter accumulating during deposition. Spar refers to crystals of calcite greater than 5$\mu$m; they usually occupy pore-spaces in the rock, acting as a form of cement (Adams *et al.*, 1984). Table 5.22 compares karren development with respect to rocks which possess a matrix composed of greater than 95%, and 50 to 95% micrite, with those composed of greater than 95%, and 50 to 95%, spar. Upon viewing Table 5.22, it is clear that there is an uneven representation of quadrats between the different categories, and karren averages associated with low *N* values, especially in the backshore, will be somewhat inflated and may not indicate the true potential for karren development and rock composition.

Table 5.22 Comparison of karren dimensions for rocks composed predominantly of a micritic matrix as compared to those cemented by spar.

| | Zone | | |
|---|---|---|---|
| Karren Measurement | Intertidal | Supratidal Swash | Backshore |
| **> 95% micrite matrix** | | | |
| Diameter (cm) | 8.43 | 11.80 | 14.56 |
| Microrelief (cm) | 2.90 | 5.04 | 5.96 |
| Density (per $m^2$ quadrat) | 14.17 | 8.42 | 6.50 |
| *N* (quadrats) | 4 | 6 | 5 |
| **50 - 95% micrite matrix** | | | |
| Diameter (cm) | 9.68 | 14.36 | 20.29 |
| Microrelief (cm) | 3.81 | 5.17 | 9.34 |
| Density (per $m^2$ quadrat) | 35.76 | 15.04 | 8.77 |
| *N* (quadrats) | 28 | 29 | 10 |
| **> 95% spar cement** | | | |
| Diameter (cm) | 11.97 | 12.01 | 20.19 |
| Microrelief (cm) | 5.61 | 6.28 | 8.29 |
| Density (per $m^2$ quadrat) | 19.60 | 17.26 | 2.50 |
| *N* (quadrats) | 6 | 18 | 3 |
| **50 - 95% spar cement** | | | |
| Diameter (cm) | 11.70 | 11.36 | 22.43 |
| Microrelief (cm) | 6.81 | 6.17 | 6.07 |
| Density (per $m^2$ quadrat) | 33.75 | 13.20 | 4.50 |
| *N* (quadrats) | 6 | 8 | 3 |

When comparing different percentages of the components there are some contrasting patterns evident. With all zones a high percentage of spar (>95%) appears to be related to slightly larger, deeper and lower density karren (except for the swash zone karren). Rocks which have a high percent of micrite (>95%), produce smaller karren dimensions and lower densities, especially in the backshore, than rocks with lower amounts of micrite. The difference in karren development is more dramatic between the two micrite categories, as opposed to those involving spar cement. In general, karren development is noticeably enhanced in association with spar cement rocks, especially in the intertidal zone and when comparing the two high percentage categories (>95% micrite and spar). These results reveal that the existence of spar in a limestone rock would appear to moderately enhance karren development, possibly because the coarser size of its crystals allows for deeper penetration of sea water inside the rock between grains, thereby facilitating erosion better than the compact, fine-grained matrix compostion of micrite-dominated rocks.

Allochems are aggregates of carbonate sediment formed during deposition, producing different type of skeletal and non-skeletal grains depending on the environment of deposition (Adams *et al.*, 1984). The primary allochems found in the western Newfoundland carbonate rocks are, peloids (pellets), limeclasts and aggregate grains.

From Blatt *et al.* (1980) and Tucker and Wright (1991), peloids are the most common of the limestone allochems, usually 100 to 500 $\mu$m in diameter, composed of micrite and are often internally structureless. Pellets refer to peloids which contain organic matter and are faecal in origin. Limeclast is a collective term used to describe both intraclast (local origin of deposition) and lithoclast allochems (allogenic origin), where the distinction between the two cannot be made. It is also used here to acknowledge the presence of skeletal grains or bioclasts. Aggregate grains are composite particles of at least two peloids cemented together by spar or micrite. The peloids are sand-sized (0.10 to 2 mm) and the aggregate lumps range in size from 0.5 to 3 mm.

Table 5.23 compares karren development in relation to the different allochems identified in thin section. Since peloids are present in all limestone samples the three categories are peloids, peloids in combination with at least one limeclast and peloids in combination with aggregate grains.

Table 5.23 Comparison of karren dimensions for rocks composed of different allochems.

| | Zone | | |
|---|---|---|---|
| Karren Measurement | Intertidal | Supratidal Swash | Backshore |
| **Peloids (pellets)** | | | |
| Diameter (cm) | 9.40 | 12.24 | 22.34 |
| Microrelief (cm) | 4.26 | 5.50 | 8.60 |
| Density (per m$^2$ quadrat) | 25.94 | 13.44 | 9.92 |
| *N* (quadrats) | 15 | 27 | 13 |
| **Peloids - Limeclasts** | | | |
| Diameter (cm) | 9.48 | 16.76 | 19.79 |
| Microrelief (cm) | 3.35 | 7.36 | 7.40 |
| Density (per m$^2$ quadrat) | 27.15 | 12.96 | 4.30 |
| *N* (quadrats) | 29 | 27 | 7 |
| **Peloids - Aggregate Grains** | | | |
| Diameter (cm) | 17.84 | 13.02 | 6.00 |
| Microrelief (cm) | 10.13 | 6.96 | 2.44 |
| Density (per m$^2$ quadrat) | 30.00 | 19.67 | 10.00 |
| *N* (quadrats) | 1 | 6 | 1 |

There are only a few quadrats associated with limestones which possess predominantly aggregate grains, mostly at The Bar, Port au Port Peninsula. Thus, the much higher intertidal karren values, and much lower backshore values, may not be a true indication of the degree of karren development associated with this type of allochem. Comparisons between rocks containing only peloids and those containing peloids and limeclasts are generally inconclusive. Karren associated with rocks containing limeclasts are somewhat larger in the supratidal swash zone, and somewhat smaller in the backshore, as compared to karren development on rocks containing only peloids. It is difficult, however, to determine how much of this difference is attributable to the presence/non-presence of limeclasts in the rocks.

Thus, karren is likely to develop better on rocks with the presence of spar filling any void spaces, especially when involving extremely high percentages (> 95%), as opposed to rocks composed of high percentages of micrite, regardless of the combination of allochems existing in those rocks.

### 5.3.4 Principal Lithologic Properties Affecting Karren Development

There are several lithologic properties of carbonate rocks which can exert strong control upon the development of karst features and cave formation. Of importance to this study are rock purity (insoluble residue), grain size and percent dolomite. These properties are relevant at the scale of hand specimen analysis, and have the most influence on the development of small-scale surface features such as karren (Ford and Williams, 1989). Note that porosity is excluded from this study, even though porosity (percentage of rock consisting of void space) is of fundamental importance to karst development. This is because all of the carbonate rocks taken from western Newfoundland possess the same approximate porosity (< 1-2%), so it is not a factor in terms of helping explain intersite karren variation. Because these rocks are very ancient (Sec. 3.2.1), most of them have experienced extensive recrystallization, which probably significantly reduced the primary pore space initially present in the rock (Buck, Pers. Comm., 1994).

### A) Percent Insoluble Residue

It should be expected that the greater the degree of purity of a limestone, the more soluble it will be, thus potentially hosting the most spectacular karren development. Common insoluble impurities, such as clay, terrigenous sediment and fossils, all clog available pore spaces and reduce overall rock solubility. In his multivariate model Ley (1976 and 1979) found insoluble residue to be the most important lithologic factor (66.6 % $r^2$), affecting the mean values of karren throughout the Bristol Channel.

Chips of each rock sample from the field were used to determine the percentage of the rock which is composed of insoluble materials. Details of the procedure involved and individual results of 100 chip samples analyzed are given in Appendix B. Average insoluble residue percentages for each of the major sites, along with karren measurements of diameter, microrelief and density, are provided in Tables 5.24 through 5.26 for the inter-, supratidal swash and backshore zones respectively. Table 5.27 provides a list of sites with insoluble residue percentages where karren development was limited or non-existent.

Regressions were performed for insoluble residue against each of the karren measurements. Data were combined from Table 5.27 with those in each of the previous tables to produce a separate regression for each zone, including karren and non-karren areas of the platform. Lower Cove, Jerrys Nose, New Ferrolle Peninsula and the Cook's Harbour region, in Table 5.27, were sites which had dolomitic rocks, or at least a relatively high percentage of dolomite in the rocks located there (Appendix A). Thus, karren development is minimized at these sites, regardless of the insoluble residue, and were eliminated from the regression analysis here. The presence of karren in Table 5.27 refers only to the inter- and supratidal swash zones, where high density micropitting or sporadic karren did exist. These sites were given diameter and microrelief values of 0.5 cm (average dimensions of a micropit). Sites with no karren development were given a value of zero for all measurements.

The $r^2$ results from the regressions are provided in Table 5.28. The only significant relationships with insoluble residue and karren development are in the supratidal swash zone, where

Table 5.24 Average insoluble residue percentages and intertidal zone karren diameter, microrelief and density for rocks hosting karren.

| Site (*N*)* | Average Insoluble Residue % | Avg. Karren Diameter (cm) | Avg. Karren Microrelief (cm) | Avg. Karren Density (per $m^2$ quadrat) |
|---|---|---|---|---|
| Long Point (3) | 8.94 | 6.21 | 3.00 | 17.20 |
| The Bar (4) | 6.01 | 19.06 | 11.00 | 18.50 |
| Lower Cove (3) | 4.12 | 6.33 | 3.12 | 25.00 |
| Port au Port East Bay (3) | 2.74 | 9.81 | 4.48 | 25.00 |
| Cow Head Peninsula (1) | 12.50 | 18.59 | 8.38 | 4.00 |
| Broom Point (1) | 10.05 | 8.18 | 3.83 | 6.00 |
| Port au Choix Peninsula (5) | 10.25 | 6.08 | 1.90 | 26.71 |
| Pointe Riche Peninsula (4) | 5.96 | 13.87 | 3.79 | 15.63 |
| Ingornachoix Bay (1) | 4.04 | 5.98 | 2.04 | 52.54 |
| Cook's Harbour Region (1) | 6.74 | 3.51 | 1.44 | 100.00 |
| Average | 6.74 | 9.69 | 4.35 | 29.85 |

* number in brackets refers to the number of rock samples tested for insoluble residue, where karren existed in the intertidal zone at that site (see Appendix B for individual sample results)

Table 5.25 Average insoluble residue percentages and supratidal swash zone karren diameter, microrelief and density for rocks hosting karren.

| Site (*N*)* | Average Insoluble Residue % | Avg. Karren Diameter (cm) | Avg. Karren Microrelief (cm) | Avg. Karren Density (per $m^2$ quadrat) |
|---|---|---|---|---|
| Long Point (3) | 9.12 | 9.37 | 4.40 | 12.80 |
| The Bar (5) | 5.40 | 11.58 | 6.40 | 21.00 |
| Lower Cove (3) | 4.11 | 7.53 | 3.11 | 20.67 |
| Ship Cove (1) | 3.74 | 16.93 | 6.67 | 3.00 |
| Port au Port East Bay (4) | 5.21 | 8.45 | 4.56 | 10.67 |
| Cow Head Peninsula (3) | 7.80 | 17.81 | 9.98 | 9.86 |
| Broom Point (1) | 9.71 | 17.21 | 10.24 | 11.00 |
| Stearing Island (1) | 4.93 | 18.46 | 8.58 | 13.00 |
| Daniel's Harbour (1) | 4.76 | 17.68 | 10.90 | 10.00 |
| Port au Choix Peninsula (5) | 7.94 | 11.92 | 3.06 | 12.25 |
| Pointe Riche Peninsula (3) | 5.49 | 15.87 | 4.93 | 9.00 |
| Ingornachoix Bay (1) | 4.04 | 16.87 | 5.83 | 8.72 |
| Cook's Harbour Region (4) | 2.90 | 31.06 | 12.20 | 25.67 |
| Average | 5.36 | 15.00 | 7.205 | 13.15 |

* number in brackets refers to the number of rock samples tested for insoluble residue, where karren existed in the supratidal swash zone at that site (see Appendix B for individual sample results)

Table 5.26 Average insoluble residue percentages and backshore zone karren diameter, microrelief and density for rocks hosting karren.

| Site (*N*)* | Average Insoluble Residue % | Avg. Karren Diameter (cm) | Avg. Karren Microrelief (cm) | Avg. Karren Density (per $m^2$ quadrat) |
|---|---|---|---|---|
| Cow Head Peninsula (2) | 3.41 | 19.58 | 8.33 | 3.00 |
| Broom Point (1) | 9.71 | 11.15 | 4.39 | 7.00 |
| Daniel's Harbour (1) | 4.76 | 9.78 | 5.13 | 4.00 |
| Lower Head (1) | 2.54 | 9.90 | 7.51 | 12.00 |
| Port au Choix Peninsula (3) | 5.48 | 18.96 | 5.37 | 7.00 |
| Pointe Riche Peninsula (4) | 6.03 | 16.60 | 3.66 | 6.60 |
| Ingornachoix Bay (1) | 4.04 | 24.35 | 12.94 | 2.50 |
| New Ferrolle Peninsula (2) | 3.51 | 6.47 | 4.87 | 18.00 |
| Cook's Harbour Region (4) | 3.05 | 22.79 | 14.60 | 15.56 |
| Average | 4.72 | 15.00 | 7.31 | 9.08 |

* number in brackets refers to the number of rock samples tested for insoluble residue, where karren existed in the backshore zone at that site (see Appendix B for individual sample results)

Table 5.27 Insoluble residue percentages for the rock samples which came from areas where karren development was absent or limited to a micropit scale (i.e. < 1cm dimensions).

| Site | Average Insoluble Residue % Intertidal/Swash Zone (*N*)* | Backshore Zone (*N*)* | Presence of Karren |
|---|---|---|---|
| Long Point | 34.18 (3) | ---------- | dense micropits |
| The Bar | 32.96 (3) | 5.27 (3) | none |
| Three Rock Point | 12.72 (1) | 12.72 (1) | micropits and/or concussion marks? |
| Lower Cove | 4.96(3) | 5.03(4) | dense micropits |
| Ship Cove | 10.26 (1) | ---------- | none |
| Jerrys Nose | 6.12 (1) | 6.12 (1) | micropits |
| Port au Port East Bay | 18.22 (1) | 10.70(3) | none |
| Cow Head Peninsula | 57.50(3) | 7.22(5) | none |
| Broom Point (1) | 14.64 (1) | 14.64 (1) | patchy micropits |
| Port au Choix Peninsula | 10.81(4) | 9.52(5) | patchy micropits |
| Pointe Riche Peninsula | 33.73(3) | 5.87(2) | none |
| Ingornachoix Bay | 14.04 (1) | 5.85 (1) | none |
| New Ferrolle Peninsula | 2.67(1) | 7.57(2) | none |
| Cook's Harbour Region | 8.23(3) | 7.57(2) | none |
| Average | 17.95 | 8.32 | |

* number in brackets refers to the number of rock samples tested for insoluble residue, where karren did not exist in the associated zones (see Appendix B for individual sample results)

Table 5.28 Comparison of the coefficients of determination ($r^2$) for each zone in relation to the control of insoluble residue on karren development.

| Karren Measurement | ZONE<br>Intertidal $r^2$ (*N*) | <br>Supratidal Swash $r^2$ (*N*) | <br>Backshore $r^2$ (*N*) |
|---|---|---|---|
| Diameter | 0.00 (20) | **0.55 (23)** | 0.26 (17) |
| Microrelief | 0.24 (20) | **0.48 (23)** | 0.40 (17) |
| Density | 0.03 (20) | **0.50 (23)** | 0.36 (17) |

there is an inverse power relationship with karren diameter (Figure 5.17A) and microrelief (Figure 5.17B), and a negative, logarithmic relationship with karren density (Figure 5.17C). These trends show that a rock must be near 90% pure for any measureable karren to develop on it; karren are significantly restricted on rocks with impurity amounts much below 90%. Generally, when comparing rocks which are between 90 and 100% pure, there is little effect on karren development except for possibly a general decline in karren size, and corresponding increased density, with increasing impurities. The low $r^2$ values for the backshore can be attributed to the lack of karren associated with relatively low insoluble residue percentages (Table 5.27). With these backshore sites, it would appear that karren development is more a function of location away from active coastal erosion, as opposed to the purity of the rock. It is difficult to explain the extremely low $r^2$ values associated with the intertidal zone.

### B) Grain Size

As discussed in Section 5.3.2, grain size is a rock property of fundamental importance to karren formation, as karren are small-scale features strongly affected by texture (Ford and Williams, 1989). The type of karren formed at a particular place, as classified in Ford and Williams (Table

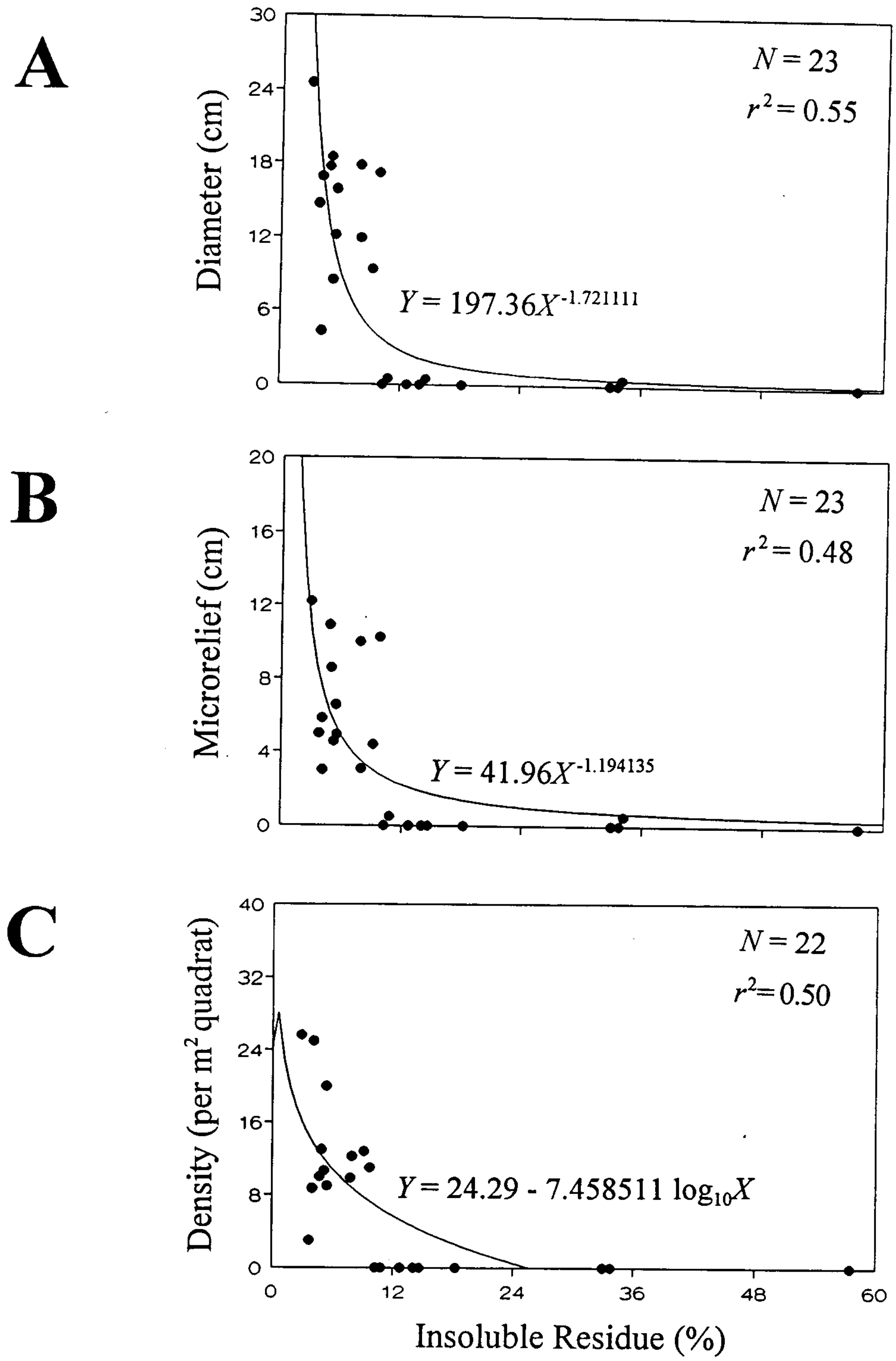



Figure 5.17 Supratidal swash zone relationships with insoluble residue and karren A) diameter, B) microrelief and C) density.

9.1, p. 376-377), can often be linked to grain size and degree of heterogeneity. This section will attempt to quantify any relationship which may exist between grain size and karren development in the coastal zone. Individual measurements of average and maximum grain size for the allochems visible in the hand specimens and/or thin sections are provided in Appendix A. It is the average grain size of each rock sample, representing as best as possible the primary deposition, which is used in the analysis here. Separate values are provided for any lithoclasts, or bioclasts, which do not appear to be representative of the overall grain size of the rock, indicating that they were probably externally introduced to the environment of deposition.

Average grain size for the rocks, in each of the three littoral zones and where there was limited karren development, are provided in Table 5.29. There are missing data where there were no karren, or if an accurate grain size measurement of the rock could not be determined (i.e. for several mudstone hand specimens). These data are then used in a regression analysis using the same karren data presented in the previous section, eliminating the same sites where dolomitic rock was present. Daniel's Harbour swash and backshore data, Cook's Harbour swash data, and the Cow Head Peninsula value for the intertidal zone and limited karren in the backshore (9.50 mm for both), were all eliminated from the analysis, as they proved to be obvious outliers in the data set. The $r^2$ results from the regressions are given in Table 5.30.

Significant grain size regressions are provided in Figure 5.18 for intertidal zone karren density (Figure 5.18A), and supratidal swash zone diameter (Figure 5.18B) and microrelief (Figure 5.18C). It is strange that the density is dramatically more significant than diameter and microrelief in the intertidal zone (Table 5.30), once again showing that sample size, especially for measureable karren, is a problem in this zone. All three trends in Figure 5.18 reveal that an increase in average grain size appears to increase karren diameter, microrelief and density in these zones. This pattern does not conform to the theory discussed in Ford and Williams (1989), but there could also be an increased heterogeneity of grain size as well, which will create more soluble rock conditions (e.g. many grain-supported rocks in this study). It may be that there are other factors existing in the areas where there are finer-grained rocks, which may be suppressing karren development more than

Table 5.29 Average grain size of the study site rocks in relation to position in the littoral zone and karren development.

| Site | Average Grain Size (mm) Intertidal (N)* | Supratidal Swash (N) | Backshore (N) | Limited Karren (N)** |
|---|---|---|---|---|
| Long Point | 0.30 (3) | 0.63 (3) | ------ | 0.20 (3 - it/sw) |
| The Bar | 0.50 (2) | 0.96 (5) | ------ | 0.53 (5-entire) |
| Lower Cove | 1.33 (3) | 2.01 (3) | ------ | 2.00 (3 - back) |
| Ship Cove | ------ | 1.60 (1) | ------ | 0.12 (1-entire) |
| Three Rock Point | ------ | ------ | ------ | 0.40 (1-entire) |
| Jerrys Nose | ------ | ------ | ------ | 0.15 (1-entire) |
| Port au Port East Bay | ------ | 6.25 (2) | ------ | ------ |
| Cow Head Peninsula | 9.50 (1) | 10.85 (2) | 14.20 (1) | 9.50 (2 - back)<br>0.30 (1 - it/sw) |
| Broom Point | 0.40 (1) | 10.50 (1) | 10.50 (1) | ------ |
| Stearing Island | ------ | 8.00 (1) | ------ | ------ |
| Daniel's Harbour | ------ | 0.40 (1) | 0.40 (1) | ------ |
| Lower Head | ------ | ------ | 4.30 (1) | ----- |
| Port au Choix Peninsula | 0.85 (2) | 0.70 (2) | 0.40 (1) | 0.20 (1 - it/sw)<br>1.00 (1 - back) |
| Pointe Riche Peninsula | 0.40 (1) | 0.35 (2) | 0.30 (1) | ------ |
| Ingornachoix Bay | ------ | ------ | ------ | 0.30 (1-entire) |
| New Ferrolle Peninsula | ------ | ------ | 0.50 (1) | 0.20 (1 - sw) |
| Cook's Harbour Region | ------ | 0.10 (1) | ------ | 0.30 (1 - sw)<br>0.40 (1-entire) |
| Average | 1.90 | 3.53 | 4.37 | 1.11 |

* number in brackets refers to the number of rock samples taken from that site, which were measured for average grain size

** refers to the number of rock samples measured for grain size where there was minimal karren development for separate zones, or the entire platform

Table 5.30 Comparison of the coefficients of determination ($r^2$) for each zone in relation to the control of average grain size on karren development.

| Karren Measurement | ZONE | | |
|---|---|---|---|
| | Intertidal $r^2$ ($N$) | Supratidal Swash $r^2$ ($N$) | Backshore $r^2$ ($N$) |
| Diameter | 0.04 (16) | 0.57 (18) | 0.26 (14) |
| Microrelief | 0.09 (16) | **0.70 (18)** | 0.40 (14) |
| Density | **0.60 (16)** | 0.34 (18) | 0.16 (14) |

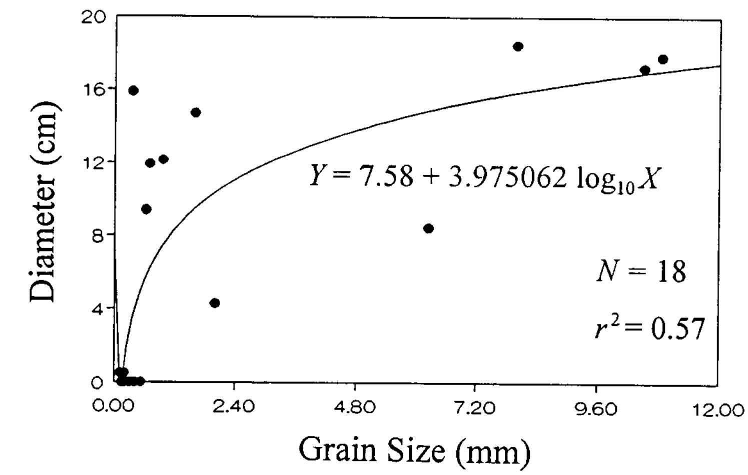
expected for these rocks. As with insoluble residue, karren variation in the backshore appears to be more related to proximity to active coastal erosion, than it is to the average grain size of the rocks.

Table 5.31 gives a listing of average grain size for each site, and each zone, associated with karren and non-karren locations. For each region (except Cook's Harbour) the occurrence of karren in the inter-and supratidal swash zones are much more prevalent with coarser-grained rocks. This helps to confirm the regression trends provided in Figure 5.18. This is especially true of the Cow Head Peninsula region, where the very large clasts associated with the conglomerates of the Cow Head Group are closely associated with karren sections of the shore. For the backshore, however, the rocks in areas of limited karren development possess average grain sizes which are the same as, or larger, than the average grain size of rocks hosting karren.

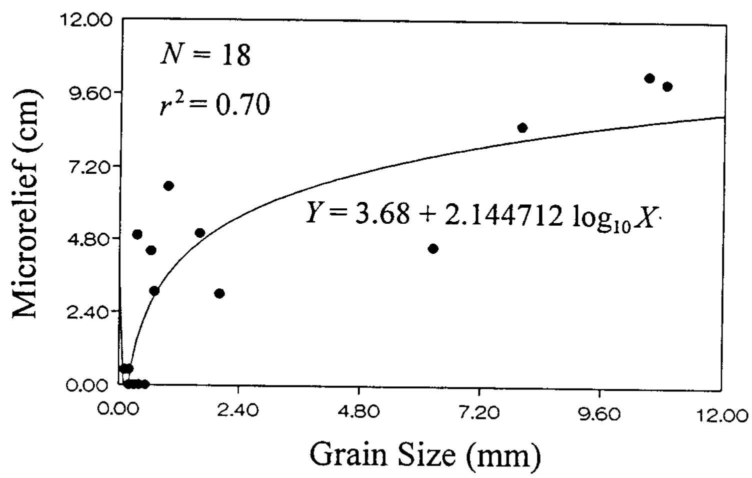
## C) Percent Dolomite

Dolomite exists in virtually all limestones and is an important constituent, because its chemical composition greatly reduces the solubility of the rock (Sec. 2.2.2). High percentages of dolomite in the rock will supress karren development, even if the percent insoluble residue is

A




B




C

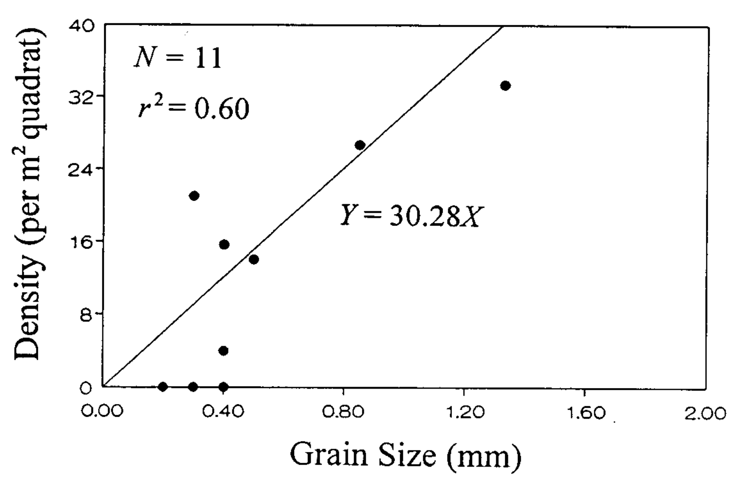



Figure 5.18 Supratidal swash zone relationships with grain size and karren A) diameter, B) microrelief and C) density.

Table 5.31 Comparison of average grain size between rocks in the study regions which host karren and those that do not.

| Region | Zone: Intertidal | Zone: Supratidal Swash | Zone: Backshore |
|---|---|---|---|
| **Port au Port Peninsula** | | | |
| avg. grain size - karren (mm) | 0.71 | 2.29 | 0.64 |
| avg. grain size - limited karren (mm) | 0.28 | 0.28 | 0.64 |
| **Cow Head Peninsula Region** | | | |
| avg. grain size - karren (mm) | 4.95 | 7.44 | 7.35 |
| avg. grain size - limited karren (mm) | 0.30 | 0.30 | 9.50 |
| **Port au Choix Peninsula Region** | | | |
| avg. grain size - karren (mm) | 0.63 | 0.53 | 0.40 |
| avg. grain size - limited karren (mm) | 0.20 | 0.23 | 0.65 |
| **Cook's Harbour Region** | | | |
| avg. grain size - karren (mm) | ------ | 0.10 | ------ |
| avg. grain size - limited karren (mm) | ------ | 0.35 | 0.40 |

extremely low (e.g. New Ferrolle Peninsula in the swash zone). Thus, the percent dolomite was determined for all thin sections and hand specimens (where possible), with individual results provided in Appendix A. The exact percentage of dolomite is not necessary for the purposes of this study, so an approximate range was determined.

The rock samples from western Newfoundland were put into dolomitic categories, as defined in Figure 5.10, based on the percentage of carbonates in the rock that are dolomite. Karren development associated with the defined categories are given in Table 5.32. There were no calcareous dolomites and only a few dolomite rocks in the study area. The expected trend in the data is evident, for as the percentage of dolomite increases in the rock, karren development is minimized, although very high density micropits are common on pure dolomite, or very high percentage dolomitic limestones, especially for very exposed sites (e.g. Cook's Harbour region; Sec. 5.2.2). The great reduction in the number of quadrats associated with dolomitic limestones and dolomite rocks also provides evidence of a reduced occurrence of karren. The disparity in karren development is most evident when comparing limestones with dolomitic limestones in the inter- and supratidal swash zones, especially the swash zone, where the average diameter and microrelief of limestones are more than double that of dolomitic limestones.

It is possible that the intersite karren variation in relation to the percent dolomite is more significant in the intertidal and backshore zones, as opposed to the supratidal swash zone, thereby partially explaining the low $r^2$ values associated with variations in insoluble residue for these zones. However, the data for percent dolomite do not render themselves conducive to a regression analysis.

### 5.3.5 Structural Controls on Karren Development

Section 2.2.4 mentions the potential significance of structural controls on rates of karst erosion at a given locality. Slope gradient and orientation, in particular, can be of the utmost importance in affecting the erosion processes. Ley (1976; 1979) found that 27.5% of intersite karren variation (mean values) could be explained by the varying dip of the strata, which was the second most important independent variable in his multivariate model. Thus, this section will focus on the

Table 5.32 Comparision of karren development with dolomitic composition of the carbonate rocks found in the study regions.

| Karren Measurement | Zone: Intertidal | Zone: Supratidal Swash | Zone: Backshore |
|---|---|---|---|
| **Limestone (<10% dolomite)*** | | | |
| Avg. Diameter (cm) | 11.23 | 14.67 | 25.41 |
| Avg. Microrelief (cm) | 4.87 | 6.65 | 10.66 |
| Avg. Density (per $m^2$ quadrat) | 26.58 | 12.76 | 7.98 |
| *N* (quadrats) | 20 | 50 | 12 |
| **Dolomitic Limestone (10-50% dolomite)** | | | |
| Avg. Diameter (cm) | 6.62 | 6.80 | 25.83 |
| Avg. Microrelief (cm) | 2.73 | 3.21 | 6.14 |
| Avg. Density (per $m^2$ quadrat) | 30.37 | 15.33 | 6.00 |
| *N* (quadrats) | 9 | 7 | 6 |
| **Dolomite (>90% dolomite)** | | | |
| Avg. Diameter (cm) | 4.50 | 3.20 | 5.37 |
| Avg. Microrelief (cm) | 2.12 | 1.46 | 4.16 |
| Avg. Density (per $m^2$ quadrat) | 20.00 | 56.75 | 13.50 |
| *N* (quadrats) | 1 | 4 | 2 |

* rock type categories are determined by the dolomitic percentage of the carbonate rocks, as defined by Ford and Williams (1989, p.10)

possible influence that the amount, as well as direction, of dip may have on karren development at western Newfoundland.

### A) Amount of Dip

Individual dip angles and slope directions, for all transects and quadrats used in the study regions, are provided in Appendix C for each littoral zone and associated karren measurements. If a transect was taken across several scarp slopes, then an average dip angle was determined for that transect. Regressions were performed for each littoral zone, with dip angle regressed against the karren measurements. The resultant $r^2$ values are provided in Table 5.33.

The only significant relationships with dip angle and karren development occur in the intertidal zone (Figure 5.19). Karren diameter and microrelief both increase exponentially with an increase in the gradient of the rock upon which the karren are formed. This does support the notion that increased slope angle will enhance surface roughness and erosion of that rock (Sec. 2.2.4). It should be noted, however, that Broom Point and transect T5 from the Pointe Riche Peninsula (Appendix C), were eliminated from the regression, as they proved to be extreme outliers to the general trend of data. The dip at Broom Point is very high (55°), and may be too steep for adequate karren development to occur. The south side of the Pointe Riche Peninsula (T5) is at a very exposed site (Sec. 3.5.1), which may have an influence on the much larger intertidal karren than expected for that dip (27.97 cm). When combined with the results from the previous section, it would appear that dip of the rock, and not lithologic properties, is a stronger control on karren development in the intertidal zone.

These results reveal that rock dip of the shore platforms appears to affect the rates of erosion and karren development in the intertidal zone, more so than geologic properties. It is possible that karren is enhanced with increasing dip, since steeper slopes produce a more pronounced surface roughness and localized relief (Sec. 2.2.4), as the elevated rock surface concentrates wave energy at lithologically weak beds of the platform. This focused energy can then enlarge the karren pits to a greater degree than if the strata were horizontal.

Table 5.33 Comparison of the coefficients of determination ($r^2$) for each zone in relation to the control of platform structure, and degree of dip, on karren development.

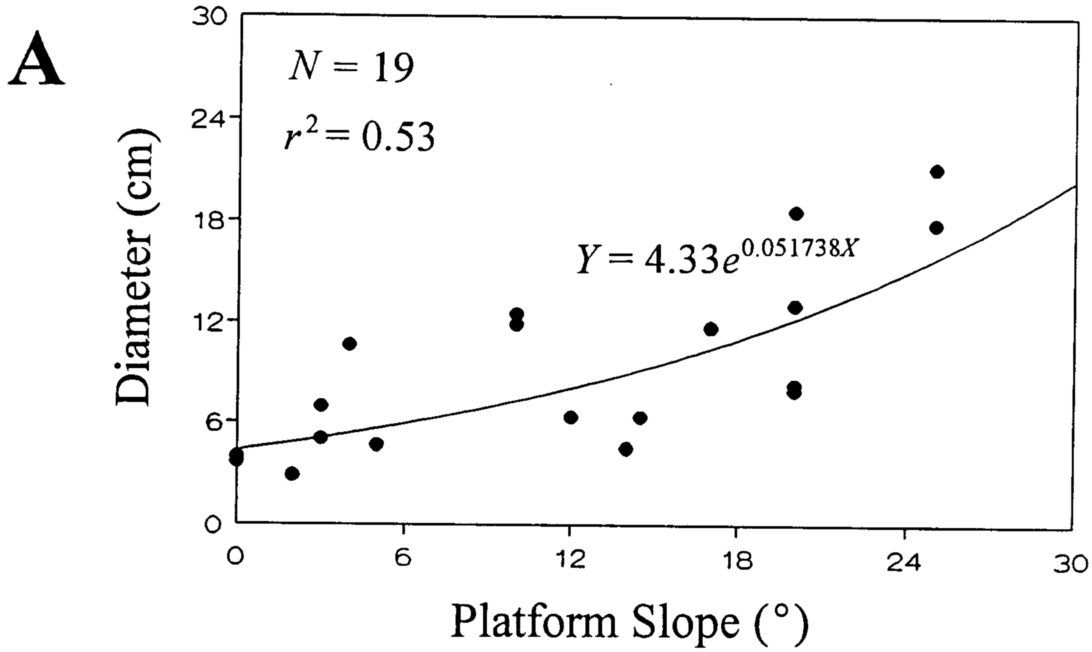
| Karren Measurement | ZONE | | |
|---|---|---|---|
| | Intertidal $r^2$ ($N$) | Supratidal Swash $r^2$ ($N$) | Backshore $r^2$ ($N$) |
| Diameter | **0.53 (19)** | 0.28 (32) | 0.06 (14) |
| Microrelief | **0.70 (19)** | 0.17 (32) | 0.04 (14) |
| Density | 0.32 (19) | 0.00 (32) | 0.04 (14) |

Conversely, there is no clear relationship with dip angle and karren development in the supratidal swash and backshore zones. The lithologic controls on karren are much stronger in these two zones, and it would appear that karren can develop to the same degree, regardless of the slope of the rock upon which it forms. It could also be that these lithologic properties may be masking any relationship which would otherwise exist. Percent insoluble residue, for example, may be higher in association with some of the steeper sloping rock strata in these zones, which would minimize karren development more than expected for those slope angles.

## B) Direction of Dip

Something Ley does not address is the possible influence of slope direction on karren. All platform measurements were categorized into dip and scarp slopes, and horizontal strata (<5°), to see if there is slope direction has any influence on karren development. Since the number of groups and observations are quite small, the Mann-Whitney and Kruskal-Wallis non-parametric tests, described in Section 5.2.3, are used with this data.

Table 5.34 provides the data involved in comparing dip and scarp slopes on karren klklkllkdevelopment in a form prepared for the Mann-Whitney test. Only dip and scarp slopes with a minimum 10° angle are considered, in order to create some separation from the horizontal strata.



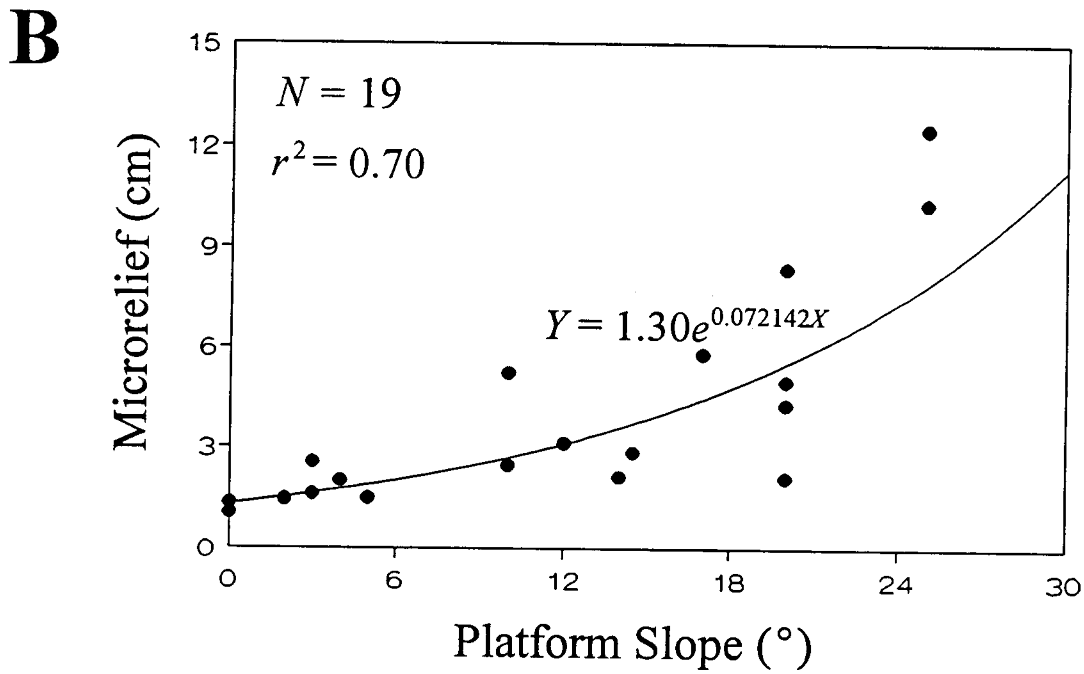




Figure 5.19 Significant exponential relationships between platform dip angle and karren development in the intertidal zone. A) karren diameter and B) karren microrelief.

Table 5.34 Mann-Whitney testing of variations in karren development between dip and scarp slopes (min. 10° angle) for the inter-, supratidal swash and backshore zones.

| Slope | Average Diameter (cm) | Avg. Rank | Average Microrelief (cm) | Avg. Rank | Average Density (per $m^2$ quadrat) | Avg. Rank |
|---|---|---|---|---|---|---|
| **Intertidal** | | | | | | |
| Dip (7 - 22°)* | 11.77 | 6.86 | 4.52 | 6.86 | 16.29 | 7.29 |
| Scarp (7 - 17°) | 13.25 | 8.14 | 6.24 | 8.14 | 16.21 | 7.71 |
| *U* Statistic | 20 | | 20 | | 23 | |
| Probability of *U* (0.05)** | 0.310 | | 0.310 | | 0.451 | |
| **Supratidal Swash** | | | | | | |
| Dip (13 - 17.8°) | 12.37 | 13.15 | 5.73 | 12.83 | 13.82 | 11.77 |
| Scarp (12 - 17.8°) | 10.81 | 12.83 | 5.05 | 13.15 | 16.42 | 14.33 |
| *U* Statistic | 76 | | 76 | | 62 | |
| Critical *U* (0.05) + | 47 | | 47 | | 47 | |
| **Backshore** | | | | | | |
| Dip (4 - 17.3°) | 16.09 | 4.75 | 10.84 | 4.50 | 9.95 | 5.38 |
| Scarp (4 - 19.7°) | 13.10 | 4.25 | 9.28 | 4.50 | 9.07 | 3.63 |
| *U* Statistic | 7 | | 8 | | 4.5 | |
| Probability of *U* (0.05)++ | 0.243 | | 0.543 | | 0.207 | |

* number in brackets refers to the number of platform measurements and average slope angle for each group

** probabilities for the Mann-Whitney test statistic *U* are from Appendix Vb, p. 343 in Shaw and Wheeler (1985)

+ Critical values for the Mann-Whitney test statistic *U* are from Appendix Vd, p. 345 in Shaw and Wheeler (1985)

++ probabilities for the Mann-Whitney test statistic *U* are from Appendix Va, p. 342 in Shaw and Wheeler (1985)

From the results in Table 5.34 it is clear that there is minimal difference in karren development between the two contrasting slope directions. For the intertidal and backshore zones, the probability of $U$ is significantly larger than the 0.05 level of significance used here, and in the supratidal swash zone the $U$ test statistic is much larger than the critical $U$ defined for the 0.05 level of significance. The degree of dip for both types of slopes are relatively the same, thus essentially discounting any bias which may be created by slope angle.

Table 5.35 presents the data in the form necessary for a Kruskal-Wallis test, with the inclusion of horizontal strata in the data set. The $H$ test statistic is larger than the critical $H$ for each karren measurement in the intertidal zone, indicating a statistically significant difference between the three groups. This is what one would expect, as it has been established that an in increase in slope helps to produce larger karren in this zone. The supratidal swash and backshore zones reveal no statistical significant difference between the three different groups, although average karren dimensions are larger with horizontal strata, especially in the supratidal swash zone, as opposed to steeper slopes. Note that critical $H$ values for the backshore had to be extrapolated, due to the occurrence of one group having more than five observations in its sample size, thereby providing a combination of sample sizes not directly applicable to any table produced for significance testing of the $H$ statistic (see Kruskal and Wallis, 1952 for details).

It can be concluded that it appears that the largest karren in the intertidal zone are associated with steeper sloping strata, regardless of orientation, whereas in the supratidal swash and backshore zones, where the erosion processes function at a higher magnitude, it is the more horizontal strata which host the larger karren. Increasing the dip in these zones does not appear to increase the size of the karren, nor is the direction of dip a factor in influencing karren development.

## 5.4 Exposure to the Marine Environment and Karren Development

### 5.4.1 Onshore Energy Losses (available wave energy)

Section 3.5.1 discussed the degree of exposure of the study regions and correlated onshore

Table 5.35 Kruskal-Wallis testing of variations in karren development between dip and scarp slopes (min. 10° angle), as well as gentle-sloping to horizontal strata (5° or less), for the inter-, supratidal swash and backshore zones.

| Slope | Average Diameter (cm) | Avg. Rank | Average Microrelief (cm) | Avg. Rank | Average Density (per $m^2$ quadrat) | Avg. Rank |
|---|---|---|---|---|---|---|
| **Intertidal** | | | | | | |
| Dip (7 - 22°)* | 11.77 | 13.14 | 4.52 | 13.71 | 16.29 | 8.14 |
| Scarp (7 - 17°) | 13.25 | 14.29 | 6.24 | 14.86 | 16.21 | 8.71 |
| Horizontal (7 - 2.5°) | 5.49 | 5.57 | 1.74 | 4.43 | 47.53 | 16.14 |
| *H* Statistic | 8.15 | | 11.90 | | 7.26 | |
| Critical *H* (0.05)** | 5.99 | | 5.99 | | 5.99 | |
| **Supratidal Swash** | | | | | | |
| Dip (13 - 17.8°) | 12.37 | 15.15 | 5.73 | 15.77 | 13.82 | 16.08 |
| Scarp (12 - 17.8°) | 10.81 | 14.75 | 5.05 | 15.96 | 16.42 | 19.50 |
| Horizontal (7 - 1.2°) | 21.53 | 22.00 | 11.54 | 18.79 | 16.09 | 12.14 |
| *H* Statistic | 3.09 | | 0.54 | | 2.76 | |
| Critical *H* (0.05)** | 5.99 | | 5.99 | | 5.99 | |
| **Backshore** | | | | | | |
| Dip (4 - 17.3°) | 16.09 | 7.50 | 10.84 | 6.00 | 9.95 | 8.38 |
| Scarp (4 - 19.7°) | 13.10 | 6.75 | 9.28 | 6.50 | 9.07 | 6.38 |
| Horizontal (6 - 2.2°) | 18.60 | 8.00 | 11.80 | 9.17 | 12.22 | 7.67 |
| *H* Statistic | 0.21 | | 1.70 | | 0.79 | |
| Critical *H* (0.05)+ | approx. 5.70 | | approx. 5.70 | | approx. 5.70 | |

* number in brackets refers to the number of platform measurements and average slope angle for each group

** critical values of the Kruskal-Wallis test statistic *H* are from Appendix III (chi-square), p. 340 in Shaw and Wheeler (1985).

+ critical values of the Kruskal-Wallis test statistic *H* are extrapolated from sample sizes presented in Appendix VIII, p. 351 in Shaw and Wheeler (1985).

energy losses with fetch. As maximum fetch distance increases, there is a corresponding exponential increase in onshore energy (work - $\Delta E$ ), used to transport shingle across the littoral zone to the backshore (Figure 3.11). With this relationship established, the derived $\Delta E$ values provided in Table 3.2 are regressed against the karren measurements for the inter- (Table 5.36), supratidal swash and backshore zones (Table 5.37). One would expect that increasing $\Delta E$, and therefore, the fetch, would produce an increase in karren development, although Ley (1976) excluded fetch from his final multivariate model, as it was highly correlated to other 'environmental' variables and, when it was included in a series of regression equations, significantly lowered the explained intersite karren variation.

The $r^2$ results of the regression analysis are provided in Table 5.38. It is clear that, for western Newfoundland, there is also no established relationship between fetch ($\Delta E$ ) and karren development in any zone. Diameter is the only karren measurement which displays *any* level of variation explained in relation to $\Delta E$, with the supratidal swash zone producing a marginally statistically significant, linear relationship between the two variables (Figure 5.20). In this zone it can be fairly well predicted that an increase in available $\Delta E$, at a given site, will produce larger karren diameters. Maximum wave energy, on a daily basis, occurs in the supratidal swash zone more than the other zones (Sec. 5.2.2). Thus, it can be expected that any defined variables relating to this available energy, will produce the strongest relationship with karren development here.

These low $r^2$ values signify the importance of geologic variables in controlling karren development at a given site. A site may be very exposed and have a very high $\Delta E$, but the corresponding karren dimensions are significantly smaller than expected for the available wave energy (e.g. Ingornachoix Bay, intertidal zone). Lithologic and/or structural factors may be limiting karren at these sites, regardless of the available wave energy, and strength of the erosion processes, acting upon that rock surface. There is also the problem of sample availability, where there are a limited number of quadrats for a particular site (e.g. Cook's Harbour region, intertidal zone), and the data presented here may not be a true representation of the karren development which may potentially occur at that site (Sec. 5.5.2). It is unclear, though, why the $r^2$ values for microrelief are

Table 5.36 Comparison of potential available onshore work at selected sites with karren development for the intertidal zone.

| Site ($N$)* | $\Delta E$ ($Nm^{-1}$) | Karren Measurement Diameter (cm) | Microrelief (cm) | Density (per $m^2$ quadrat) |
|---|---|---|---|---|
| Cook's Harbour Region (1) | 2711 | 3.51 | 1.44 | 100.00 |
| Ingornachoix Bay (15) | 3747 | 5.02 | 2.55 | 52.54 |
| Ingornachoix Bay (cove - 2) | 238 | 6.95 | 1.60 | 46.67 |
| Pointe Riche Peninsula WNW+ (3) | 144 | 7.92 | 1.90 | 29.25 |
| Pointe Riche Peninsula SW (2) | 7910 | 27.92 | 7.50 | 6.50 |
| Port au Choix Peninsula N (2) | 709 | 10.65 | 2.00 | 8.50 |
| Port au Choix Peninsula W (1) | 638 | 4.50 | 2.12 | 20.00 |
| Port au Choix Peninsula ENE (2) | 96 | 4.64 | 1.48 | 20.00 |
| Cow Head Peninsula WSW (1) | 1731 | 18.59 | 8.38 | 4.00 |
| Cow Head Peninsula N (0) | 100 | ------ | ------ | ------ |
| Cow Head Peninsula S (0) | 28 | ------ | ------ | ------ |
| Port au Port Peninsula (1) | 2790 | 21.14 | 12.50 | 30.00 |
| Port au Port Peninsula (1) | 935 | 17.84 | 10.13 | 7.00 |

* refers to the total number of quadrats used for karren measurements within the intertidal zone

\+ refers to the direction of maximum fetch for that shoreline used to obtain $\Delta E$ values for each site as described in Sec. 3.5.1

Table 5.37 Comparison of potential available onshore work at selected sites with karren development for the supratidal swash and backshore zones.

| Site ($N$)* | $\Delta E$ ($Nm^{-1}$) | Karren Measurement: Diameter (cm) | Microrelief (cm) | Density (per $m^2$ quadrat) |
|---|---|---|---|---|
| **Supratidal Swash Zone** | | | | |
| Cook's Harbour Region (8) | 2711 | 24.56 | 12.20 | 25.67 |
| Ingornachoix Bay (14) | 3747 | 15.64 | 5.54 | 9.30 |
| Ingornachoix Bay (cove - 1) | 238 | 13.25 | 3.25 | 4.00 |
| Pointe Riche Peninsula WNW+ (3) | 144 | 10.53 | 4.32 | 7.67 |
| Pointe Riche Peninsula SW (1) | 7910 | 25.63 | 5.50 | 6.00 |
| Port au Choix Peninsula N (3) | 709 | 12.09 | 3.04 | 9.50 |
| Cow Head Peninsula WSW (2) | 1731 | 13.97 | 6.82 | 16.50 |
| Cow Head Peninsula N (1) | 100 | 14.12 | 6.10 | 10.00 |
| Cow Head Peninsula S (1) | 28 | 11.77 | 8.57 | 7.00 |
| Port au Port Peninsula (1) | 2790 | 16.15 | 6.94 | 7.00 |
| Port au Port Peninsula (3) | 935 | 5.76 | 3.64 | 22.00 |
| **Backshore Zone** | | | | |
| Cook's Harbour Region (6) | 2711 | 22.79 | 14.60 | 15.56 |
| Ingornachoix Bay (2) | 3747 | 24.35 | 12.94 | 2.50 |
| Pointe Riche Peninsula WNW (4) | 144 | 16.27 | 4.51 | 7.00 |
| Pointe Riche Peninsula SW (1) | 7910 | 24.10 | 2.20 | 5.00 |
| Port au Choix Peninsula N (1) | 709 | 2.56 | 1.00 | 12.00 |
| Port au Choix Peninsula W (1) | 638 | 17.46 | 8.67 | 6.00 |
| Port au Choix Peninsula ENE (1) | 96 | 7.25 | 3.00 | 2.00 |

* refers to the total number of quadrats used for karren measurements within the intertidal zone

\+ refers to the direction of maximum fetch for that shoreline used to obtain $\Delta E$ values for each site as described in Sec. 3.5.1

Table 5.38 Comparison of the coefficients of determination ($r^2$) for each zone in relation to the control of potential available onshore energy losses ($\Delta E$) on karren development.

| | ZONE | | |
|---|---|---|---|
| Karren Measurement | Intertidal $r^2$ ($N$) | Supratidal Swash $r^2$ ($N$) | Backshore $r^2$ ($N$) |
| Diameter | **0.29 (11)** | **0.54 (11)** | **0.36 (7)** |
| Microrelief | 0.03 (11) | 0.00 (11) | 0.00 (7) |
| Density | 0.00 (11) | 0.00 (11) | 0.00 (7) |

so much lower than those for diameter as these two karren measurements are usually at similar levels of significance.

### 5.4.2 Overall Fetch and the Exposure Index

The previous section deals only with sites which possessed shingle in the backshore, or at least at some location in the littoral zone, so that an estimate of available wave energy could be determined and correlated with karren development. This section deals strictly with fetch and eliminates any subjectivity involved in producing the $\Delta E$ values, as well as involving all the sites in the study regions.

A) Derivation

Overall fetch is a term used to describe the combined influence of regional and local fetch affecting a particular shoreline, so that the shoreline configuration, with respect to the line of maximum fetch, is taken into account. The derivation of overall fetch for each site is based on calculations performed by Ley (1976) and is described in detail in Appendix D.

The concept of the exposure index ($EI$) goes one step further than the work of Ley, and

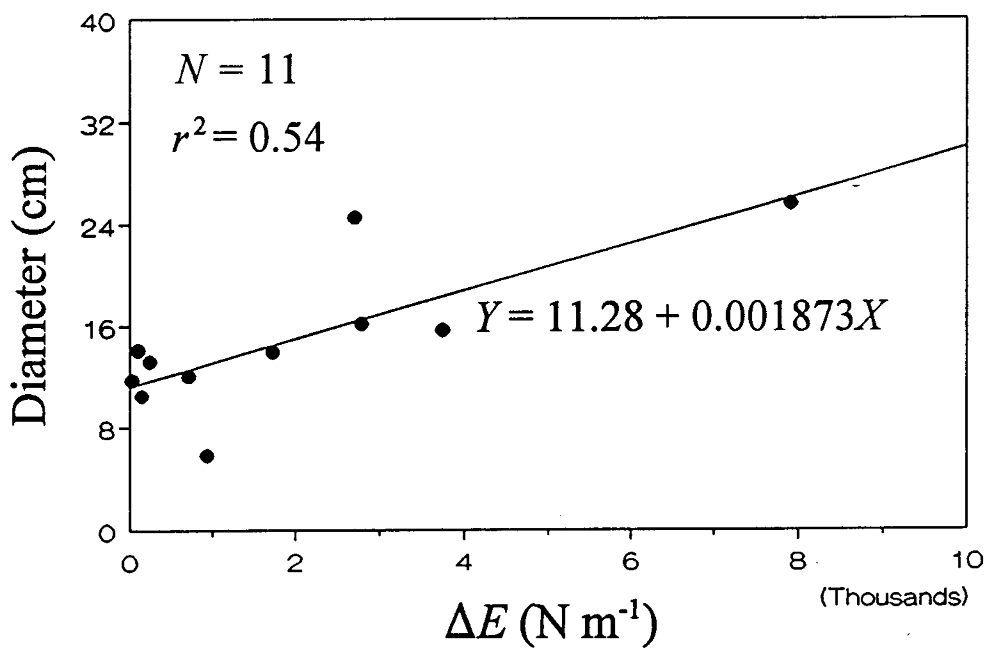



Figure 5.20 Linear relationship with karren diameter and $\Delta E$ in the supratidal swash zone.

incorporates the potential influence that wind may have on karren development, using the data presented in Section 3.4.3. Thus, *EI* values can help to determine the relative significance of the overall fetch affecting each site, since the size of wind-generated waves are a function of fetch, wind duration and velocity (Davies Jr., 1987). *EI* is calculated by

$$EI \text{ (km}^2\text{/hr)} = \text{fetch x wind duration x wind velocity} \quad (5.11)$$

where

| | | |
|---|---|---|
| fetch | = | overall fetch in km |
| wind duration | = | frequency percent |
| wind velocity | = | km/hr |

and takes into account shoreline configuration and wind, both of which were not included in the previous section.

### B) Inter-regional Analysis

*EI* values produced for the major sites, for the inter- (Table 5.39), supratidal swash (Table 5.40) and backshore zones (Table 5.41), are provided along with the karren measurements for each zone. For some sites there are separate *EI* values produced for different shorelines, so the karren data will not always be the same values as those used in the previous section. Sites are included if there is platform rock existing in that zone, even if there was a minimal occurrence of karren. These sites were given a karren value of 0.5 cm for diameter and microrelief, to represent the reduced development of karren, similar to what was done in the previous section. Separate regressions were performed for both *EI* and overall fetch (Appendix D) with the karren measurements for each zone.

The $r^2$ values produced for overall fetch and *EI* are provided in Table 5.42. There is no relationship at all in the intertidal zone, with any of the karren measurements, for both overall fetch and *EI*, and the only statistically significant relationship is in the backshore in relation to overall fetch (Figure 5.21). There is a crude linear relationship between karren development and overall fetch, for as overall fetch distance increases so does karren diameter. These results would appear to verify that exposure to the open marine environment is not as important as some of the lithologic and structural variables discussed in the previous section. It should be noted that most geologic variables had extremely low $r^2$ values, especially in the intertidal zone, and this may be more of a problem of lack of an adequate representation of quadrats, and/or the inability to study the intersite effects of one variable when others are not kept constant. Also, overall fetch, at least in the backshore, is much more important than *EI* in its influence on karren development. In other words, this would indicate that fetch distance, and not wind, is the most important exposure variable controlling the potential wave energy, and strength of the erosion processes acting upon the shoreline.

### C) Intra-regional Analysis

Regressions were then performed for the sites within each of the four major study regions,

Table 5.39 Karren development in the intertidal zone at the major sites in relation to the corresponding exposure index (*EI*).

| Site (*N*)* | Exposure Index ($km^2/hr$)** | Avg. Karren Diameter (cm) | Avg. Karren Microrelief (cm) | Avg. Karren Density (per $m^2$ quadrat) |
|---|---|---|---|---|
| **Port au Port Peninsula** | | | | |
| Port au Port E. Bay | | | | |
| E Shore (1) | 16.50 | 11.69 | 5.80 | 10.00 |
| Aguathuna (1) | 213.85 | 7.93 | 4.98 | 40.00 |
| The Bar (4) | 2.87 | 19.06 | 11.0 | 18.50 |
| Long Point SE (5) | 3.33 | 6.85 | 3.00 | 17.20 |
| Lower Cove (3) | 129.13 | 6.33 | 3.12 | 25.00 |
| Ship Cove (0) | 129.13 | ------ | ------ | ------ |
| **Cow Head Peninsula Region** | | | | |
| Cow Head Peninsula | | | | |
| WNW Shore (1) | 606.36 | 18.59 | 8.38 | 4.00 |
| SW Shore (0) | 3164.62 | ------ | ------ | ------ |
| Stearing Island (0) | 3164.62 | ------ | ------ | ------ |
| Belldowns Island (0) | 1.49 | ------ | ------ | ------ |
| Broom Point N (0) | 168.16 | ------ | ------ | ------ |
| Broom Point S (1) | 2208.95 | 8.18 | 3.84 | 6.00 |

* refers to the number of quadrats used to measure intertidal karren for that site (shoreline)

** calculation of the exposure index is discussed in the text

Table 5.39 Continued.

| Site ($N$)* | Exposure Index ($km^2/hr$)** | Avg. Karren Diameter (cm) | Avg. Karren Microrelief (cm) | Avg. Karren Density (per $m^2$ quadrat) |
|---|---|---|---|---|
| **Port au Choix Peninsula Region** | | | | |
| Port au Choix Peninsula | | | | |
| E Shore (2) | 2.03 | 4.64 | 1.48 | 20.00 |
| N Shore (2) | 74.74 | 10.65 | 2.00 | 8.50 |
| NW Shore (2) | 79.95 | 3.69 | 1.04 | 55.00 |
| W Shore (1) | 656.00 | 4.50 | 2.12 | 20.00 |
| Pointe Riche Peninsula | | | | |
| WNW Shore (3) | 532.39 | 8.67 | 1.94 | 22.33 |
| W Shore (3) | 3052.44 | 9.13 | 4.08 | 15.00 |
| S Shore (2) | 2908.77 | 27.97 | 7.50 | 6.50 |
| Ingornachoix Bay (15) | 3786.72 | 5.02 | 2.55 | 52.54 |
| Gargamelle Cove (2) | 0.22 | 6.95 | 1.60 | 46.67 |
| **Cook's Harbour Region** | | | | |
| W. Cape Norman (1) | 1497.06 | 3.51 | 1.44 | 100.00 |

* refers to the number of quadrats used to measure intertidal karren for that site (shoreline)

** calculation of the exposure index is discussed in the text

Table 5.40 Karren development in the supratidal swash zone at the major sites in relation to the corresponding exposure index (*EI*).

| Site (*N*)* | Exposure Index ($km^2/hr$)** | Avg. Karren Diameter (cm) | Avg. Karren Microrelief (cm) | Avg. Karren Density (per $m^2$ quadrat) |
|---|---|---|---|---|
| **Port au Port Peninsula** | | | | |
| Port au Port E. Bay | | | | |
| E Shore (2) | 16.50 | 11.26 | 3.79 | 6.67 |
| Aguathuna (1) | 213.85 | 3.06 | 1.37 | 15.00 |
| The Bar (10) | 2.87 | 11.58 | 6.40 | 21.00 |
| Long Point NW (3) | 292.28 | 5.85 | 1.90 | 6.25 |
| Long Point SE (4) | 3.33 | 10.48 | 6.61 | 17.75 |
| Lower Cove (3) | 129.13 | 7.53 | 3.11 | 20.67 |
| Ship Cove (1) | 129.13 | 16.93 | 6.67 | 3.00 |
| Three Rock Point (0) | 1245.80 | ------ | ------ | ------ |
| **Cow Head Peninsula Region** | | | | |
| Cow Head Peninsula | | | | |
| N Shore (1) | 158.81 | 14.12 | 6.10 | 10.00 |
| WNW Shore (3) | 606.36 | 13.91 | 6.82 | 16.50 |
| SW Shore (2) | 3164.62 | 29.92 | 15.25 | 4.50 |
| SSE Shore (1) | 1727.90 | 11.77 | 10.00 | 7.00 |
| Stearing Island (1) | 3164.62 | 18.46 | 8.58 | 13.00 |
| Belldowns Island (1) | 1.49 | 5.52 | 3.03 | 40.00 |
| Broom Point N (1) | 168.16 | 3.45 | 1.97 | 18.00 |

* refers to the number of quadrats used to measure supratidal swash karren for that site (shoreline)

** calculation of the exposure index is discussed in the text

Table 5.40 Continued.

| Site ($N$)* | Exposure Index ($km^2$/hr)** | Avg. Karren Diameter (cm) | Avg. Karren Microrelief (cm) | Avg. Karren Density (per $m^2$ quadrat) |
|---|---|---|---|---|
| Broom Point S (2) | 2208.95 | 17.21 | 10.24 | 11.00 |
| Daniel's Harbour (1) | 3381.00 | 17.68 | 10.90 | 10.00 |
| **Port au Choix Peninsula Region** | | | | |
| Port au Choix Peninsula | | | | |
| E Shore (0) | 2.03 | ------ | ------ | ------ |
| N Shore (3) | 74.74 | 12.09 | 3.03 | 9.50 |
| NW Shore (1) | 79.95 | 5.42 | 2.83 | 23.00 |
| W Shore (1) | 656.00 | 4.95 | 3.00 | 6.00 |
| Pointe Riche Peninsula | | | | |
| WNW Shore (3) | 532.39 | 10.53 | 4.32 | 7.67 |
| W Shore (2) | 3052.44 | 24.33 | 6.43 | 3.00 |
| S Shore (1) | 2908.77 | 25.63 | 5.50 | 6.00 |
| Ingornachoix Bay (13) | 3786.72 | 15.64 | 5.54 | 9.30 |
| Gargamelle Cove (1) | 0.22 | 13.25 | 3.25 | 4.00 |
| New Ferrolle Peninsula (0) | 193.95 | ------ | ------ | ------ |
| **Cook's Harbour Region** | | | | |
| Cape Norman (3) | 1769.02 | 12.16 | 2.38 | 68.00 |
| E. Cape Norman (2) | 2030.45 | 27.21 | 20.25 | 3.00 |
| W. Cape Norman (3) | 1497.02 | 36.42 | 28.06 | 6.00 |

* refers to the number of quadrats used to measure supratidal swash karren for that site (shoreline)
** calculation of the exposure index is discussed in the text

Table 5.41 Karren development in the backshore zone at the major sites in relation to the corresponding exposure index (*EI*).

| Site (*N*)* | Exposure Index (km$^2$/hr)** | Avg. Karren Diameter (cm) | Avg. Karren Microrelief (cm) | Avg. Karren Density (per m$^2$ quadrat) |
|---|---|---|---|---|
| **Cow Head Peninsula Region** | | | | |
| Cow Head Peninsula | | | | |
| WNW Shore (0) | 606.36 | ------ | ------ | ------ |
| SW Shore (1) | 3164.62 | 19.58 | 8.33 | 3.00 |
| SSE Shore (0) | 1727.90 | ------ | ------ | ------ |
| Stearing Island (0) | 3164.62 | ------ | ------ | ------ |
| Belldowns Island (0) | 1.49 | ------ | ------ | ------ |
| Lower Head (1) | 2657.07 | 9.90 | 7.51 | 17.00 |
| Broom Point N (0) | 168.16 | ------ | ------ | ------ |
| Broom Point S (1) | 2208.95 | 11.15 | 4.39 | 7.00 |
| Daniel's Harbour (1) | 3381.00 | 9.78 | 5.13 | 4.00 |
| **Port au Choix Peninsula Region** | | | | |
| Port au Choix Peninsula | | | | |
| E Shore (0) | 2.03 | ------ | ------ | ------ |
| N Shore (2) | 74.74 | 4.91 | 2.00 | 7.00 |
| NW Shore (1) | 79.95 | 18.00 | 6.50 | 3.00 |
| W Shore (2) | 656.00 | 11.73 | 5.56 | 8.00 |

* refers to the number of quadrats used to measure backshore karren for that site (shoreline)

** calculation of the exposure index is discussed in the text

Table 5.41 Continued.

| Site ($N$)* | Exposure Index ($km^2$/hr)** | Avg. Karren Diameter (cm) | Avg. Karren Microrelief (cm) | Avg. Karren Density (per $m^2$ quadrat) |
|---|---|---|---|---|
| Pointe Riche Peninsula | | | | |
| WNW Shore (4) | 532.39 | 12.41 | 3.51 | 9.88 |
| S Shore (1) | 2908.77 | 24.10 | 2.20 | 5.00 |
| Ingornachoix Bay (2) | 3786.72 | 24.35 | 12.94 | 2.50 |
| Gargamelle Cove (0) | 0.22 | ------ | ------ | ------ |
| New Ferrolle Peninsula (2) | 193.95 | 6.47 | 4.87 | 18.00 |
| **Cook's Harbour Region** | | | | |
| Cape Norman (1) | 1769.02 | 8.54 | 3.41 | 34.06 |
| E. Cape Norman (3) | 2030.45 | 47.54 | 37.88 | 9.72 |
| W. Cape Norman (2) | 1497.02 | 16.00 | 6.36 | 2.33 |

* refers to the number of quadrats used to measure backshore karren for that site (shoreline)

** calculation of the exposure index is discussed in the text

Table 5.42 Comparison of the coefficients of determination ($r^2$) for western Newfoundland in relation to the potential effects of overall fetch distances and the exposure index (*EI*) with karren development.

| Karren Measurement | ZONE<br>Intertidal $r^2$ (*N*) | <br>Supratidal Swash $r^2$ (*N*) | <br>Backshore $r^2$ (*N*) |
|---|---|---|---|
| **Overall Fetch (km)** | | | |
| Diameter | 0.00 (22) | 0.31 (30) | **0.41(21)** |
| Microrelief | 0.00 (22) | 0.26 (30) | 0.37 (21) |
| Density | 0.03 (22) | 0.00 (30) | 0.04 (21) |
| **Exposure Index ($km^2$ hr)** | | | |
| Diameter | 0.00 (22) | 0.35 (30) | 0.14 (21) |
| Microrelief | 0.00 (22) | 0.17 (30) | 0.05 (21) |
| Density | 0.03 (22) | 0.00 (30) | 0.01 (21) |

using the data presented in Tables 5.39 to 5.41. The sample size is obviously very small, due to the nature of the observations involved, but at least it might be determined if overall fetch and/or *EI* have more significance in affecting karren variation between sites within one region. This may also possibly reduce some of the intersite variation of some of the other variables involved in this study, to better illustrate the effects of fetch and *EI* on karren development.

The $r^2$ values for each region, and littoral zone, are provided in Table 5.43 for both overall fetch and *EI*, with $r^2$ values highlighted if there is a significant difference between overall fetch and *EI* for that karren measurement. Statistically significant relationships between overall fetch and karren development are presented in Figures 5.22 through 5.25. Figures 5.26 and 5.27 display statistically significant relationships between *EI* and karren development, only if the $r^2$ value associated with *EI* is significantly higher than that for overall fetch.

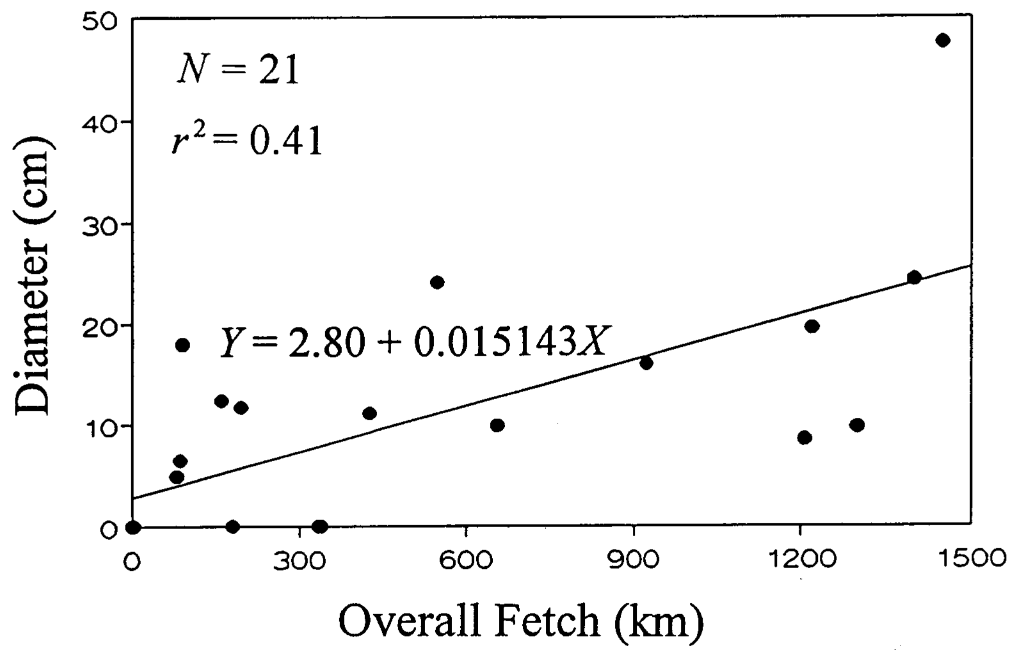



Figure 5.21 Scattergraphs of overall fetch and backshore karren diameter illustrating the marginal relationship which does exist between the two variables.

There are several trends evident in the data presented in Table 5.43. First, almost no relationship exists, again, between either overall fetch or *EI*, and karren development in the intertidal zone, except for *EI* and microrelief in the Port au Choix Peninsula region (Figure 5.27A). There is also a poor correlation with overall fetch and *EI* in association with karren density at all regions (except for the Cow Head Peninsula region, Figure 5.23C). The strongest relationships for both exposure variables and karren development exists in the Cow Head Peninsula region (Figures 5.23 and 5.24), for all karren measurements except backshore density. This would lead one to believe that exposure to the marine environment is a more important influence on intersite karren variation in this region than in the others. It could also be that the geologic variables are more uniform in this region, in association with the Cow Head Group conglomerates, than with rocks existing in other regions. It is also apparent that most of the other regions, except Cook's Harbour (very small *N*), possess a strong relationship with at least one of the exposure variables and karren diameter

Table 5.43 Comparison of the coefficients of determination ($r^2$) for each region in relation to the potential effects of overall fetch distances and the exposure index ($EI$) with karren development.

| Region | Intertidal $r^2$ ($N$) (fetch/exp.index) | Supratidal Swash $r^2$ ($N$) (fetch/exp.index) | Backshore $r^2$ ($N$) (fetch/exp.index) |
|---|---|---|---|
| | ZONE | | |
| **Port au Port Peninsula** | | | |
| Diameter | 0.00/0.11 (6) | **0.66/0.43 (8)** | ------ |
| Microrelief | 0.00/0.00 (6) | **0.78/0.91 (8)** | ------ |
| Density | 0.00/0.00 (6) | 0.08/0.27 (8) | ------ |
| **Cow Head Peninsula Region** | | | |
| Diameter | ------ | 0.54/0.55 (9) | **0.61/0.34 (9)** |
| Microrelief | ------ | **0.48/0.67 (9)** | **0.59/0.36 (9)** |
| Density | ------ | 0.81/0.80 (9) | 0.00/0.05 (9) |
| **Port au Choix Peninsula Region** | | | |
| Diameter | 0.00/0.04 (9) | **0.24/0.51 (10)** | **0.50/0.62 (9)** |
| Microrelief | **0.15/0.52 (9)** | 0.10/0.16 (10) | **0.58/0.30 (9)** |
| Density | 0.08/0.00 (9) | 0.00/0.00 (10) | 0.00/0.00 (9) |
| **Cook's Harbour Region** | | | |
| Diameter | ------ | 0.00/0.00 (3) | 0.14/0.14 (3) |
| Microrelief | ------ | 0.00/0.00 (3) | 0.34/0.34 (3) |
| Density | ------ | 0.00/0.00 (3) | 0.00/0.00 (3) |

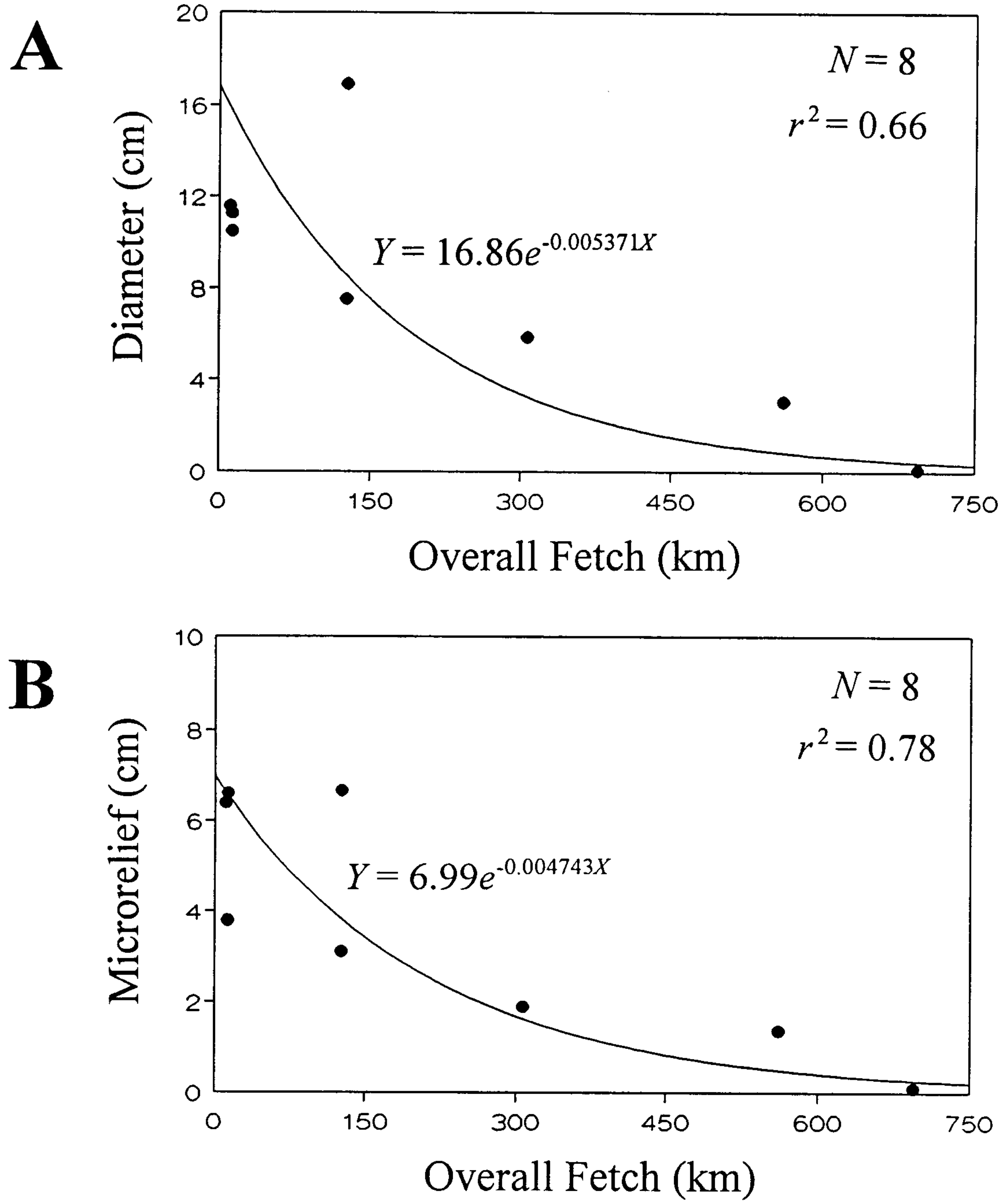



Figure 5.22 Exponential relationships between overall fetch and karren A) diameter and B) microrelief for the supratidal swash zone of the Port au Port Peninsula.

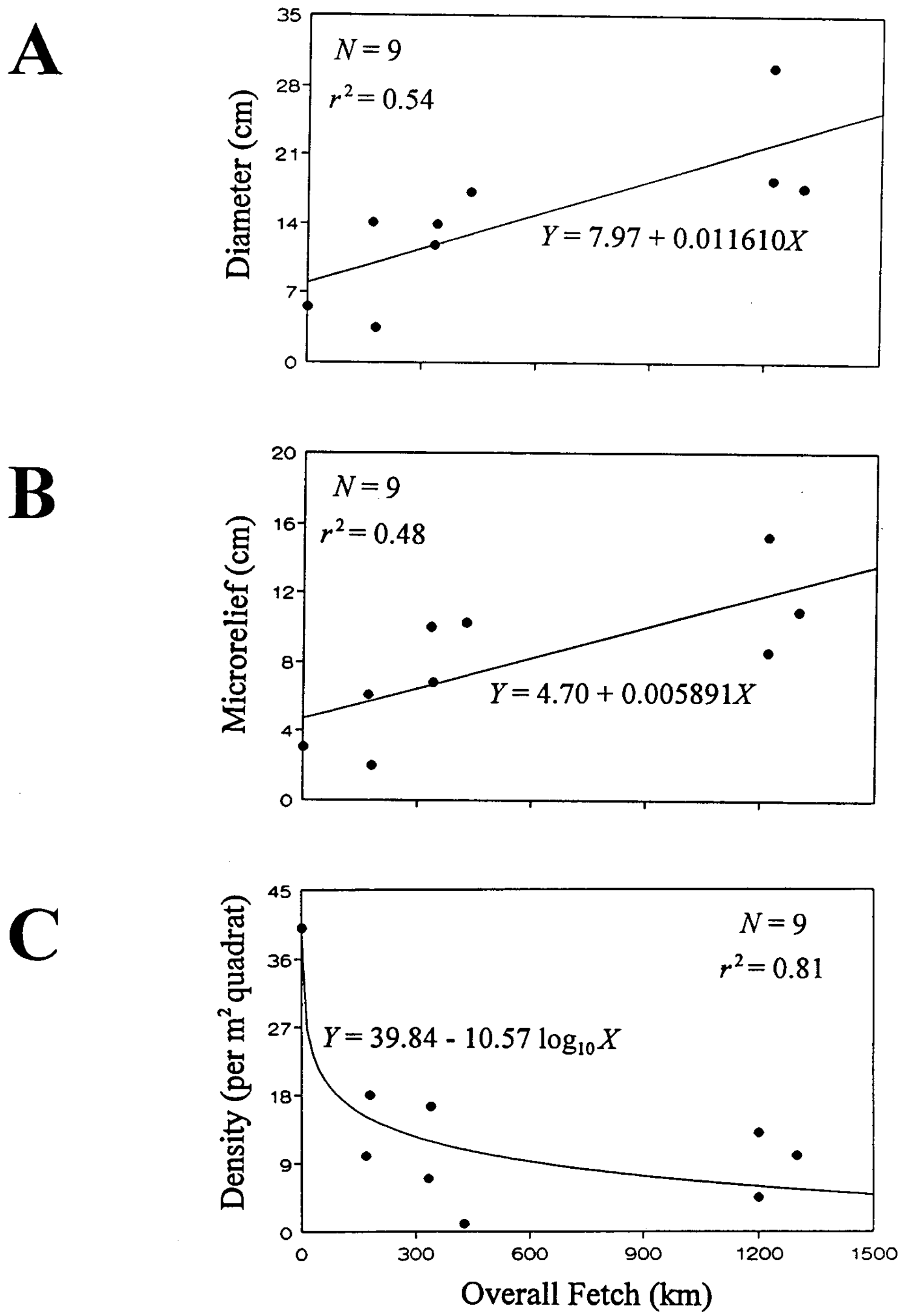
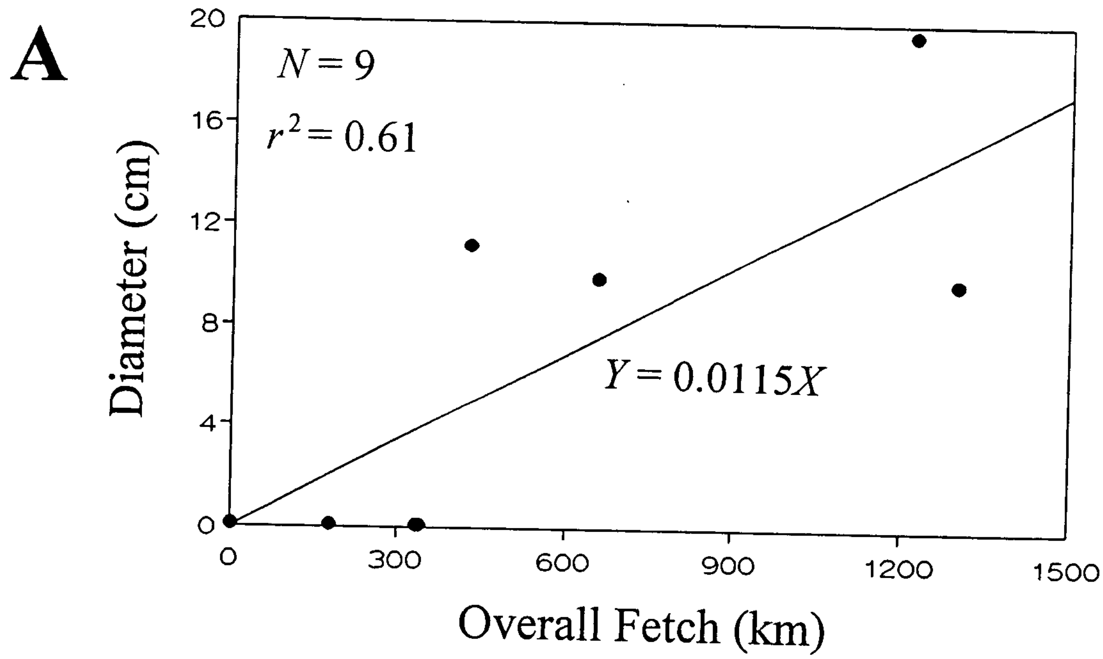



Figure 5.23 Relationships between overall fetch and karren A) diameter, B) microrelief and C) density for the supratidal swash zone of the Cow Head Peninsula region.



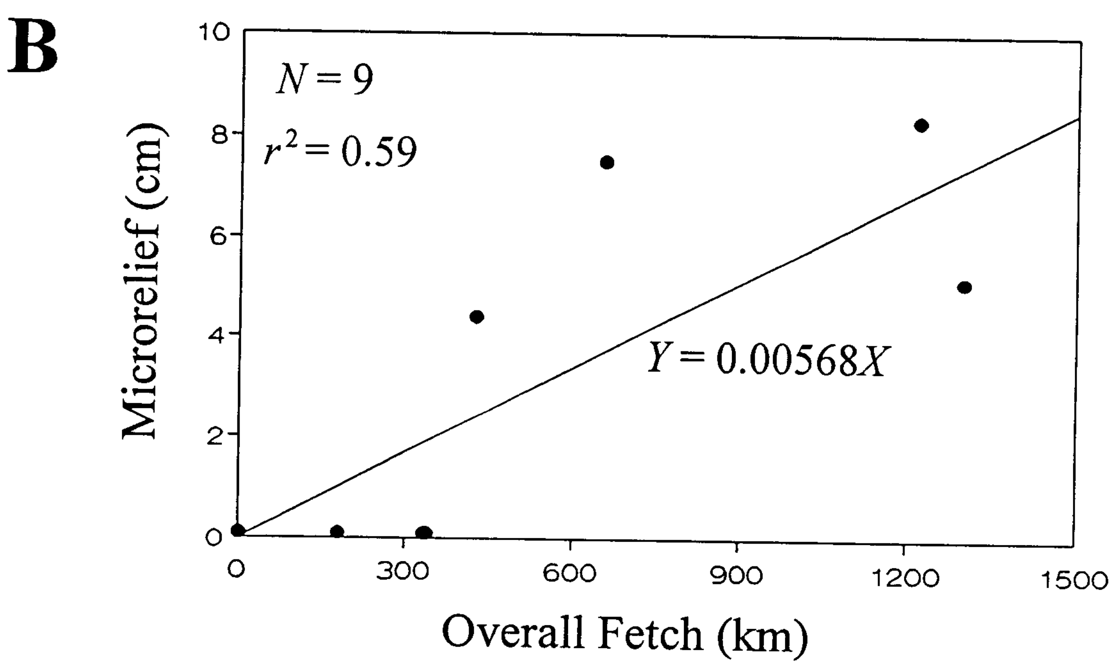




Figure 5.24 Linear relationships between overall fetch and karren A) diameter and B) microrelief for the backshore zone of the Cow Head Peninsula region.

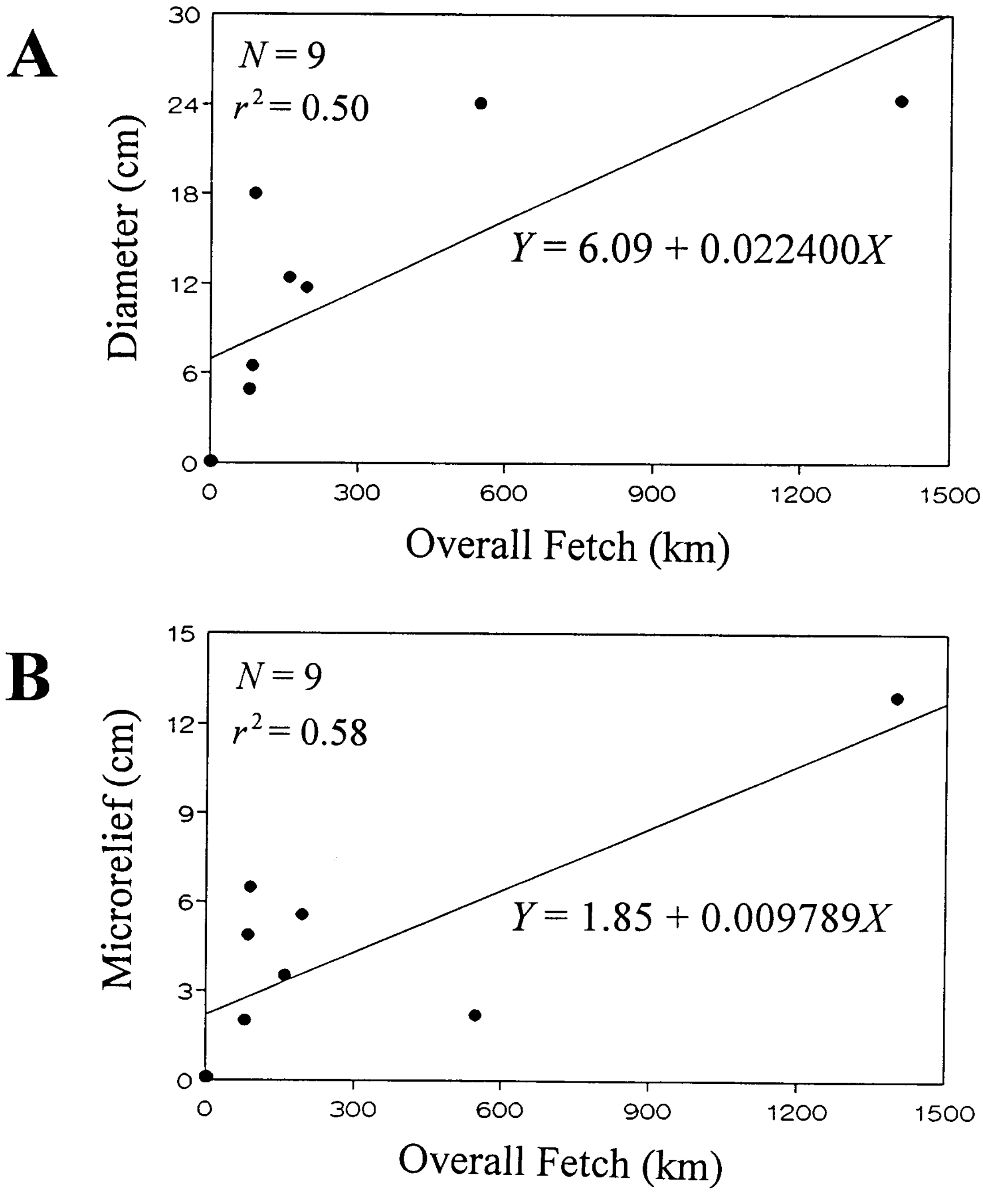
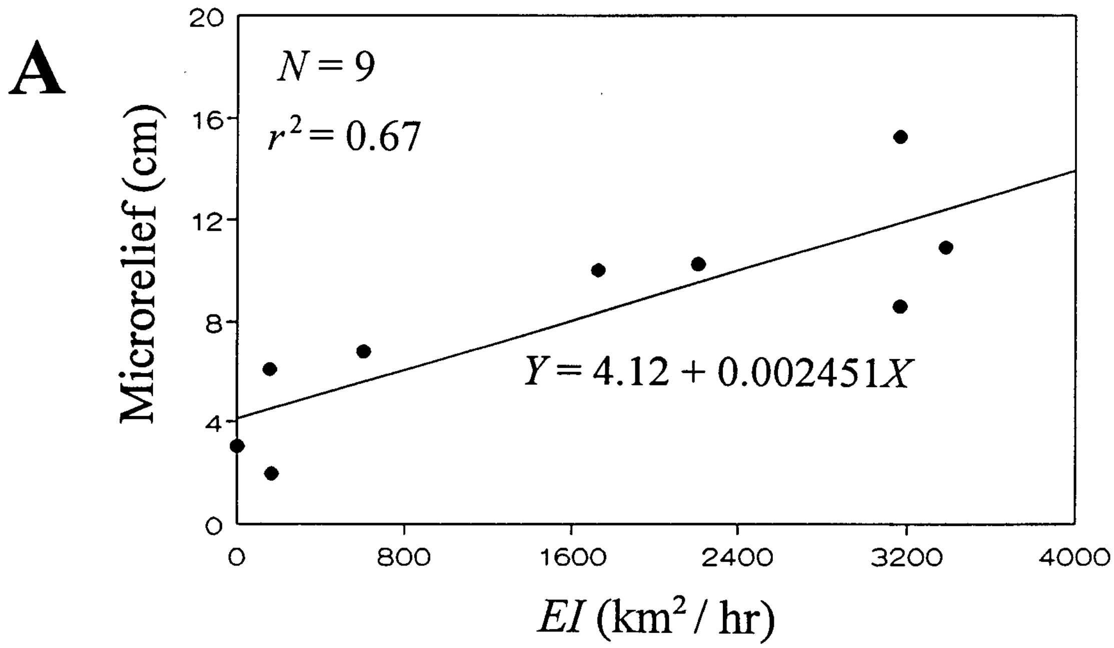



Figure 5.25 Linear relationships between overall fetch and karren A) diameter and B) microrelief for the backshore zone of the Port au Choix Peninsula region.



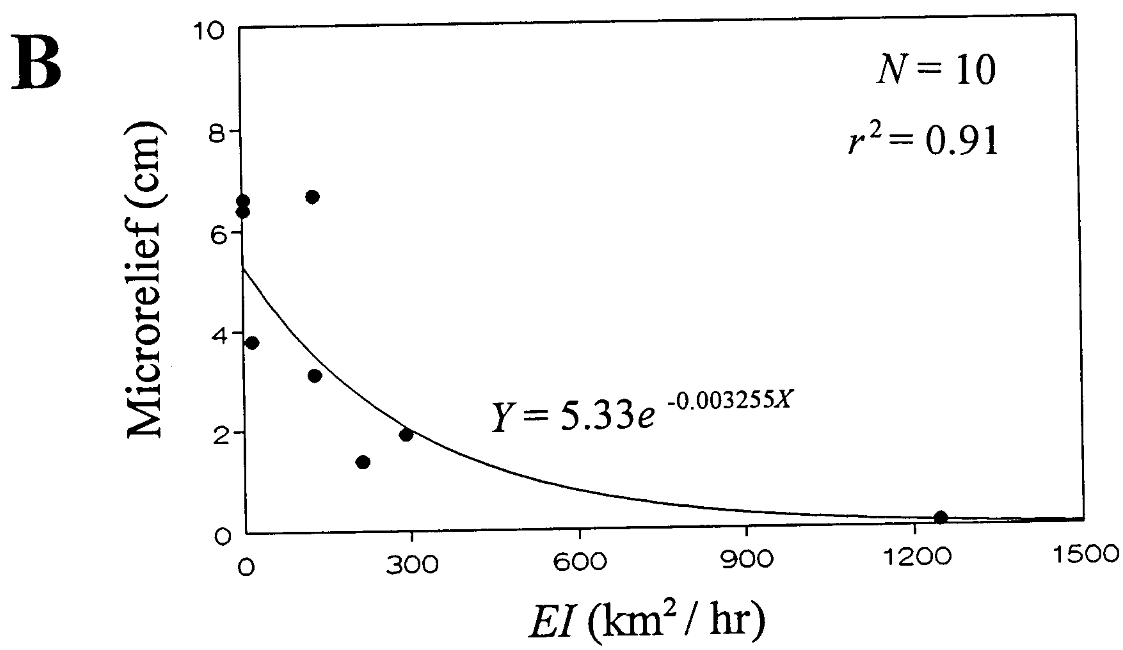




Figure 5.26 Relationships between *EI* and karren microrelief for the supratidal swash zone of A) the Cow Head Peninsula region and B) the Port au Port Peninsula.

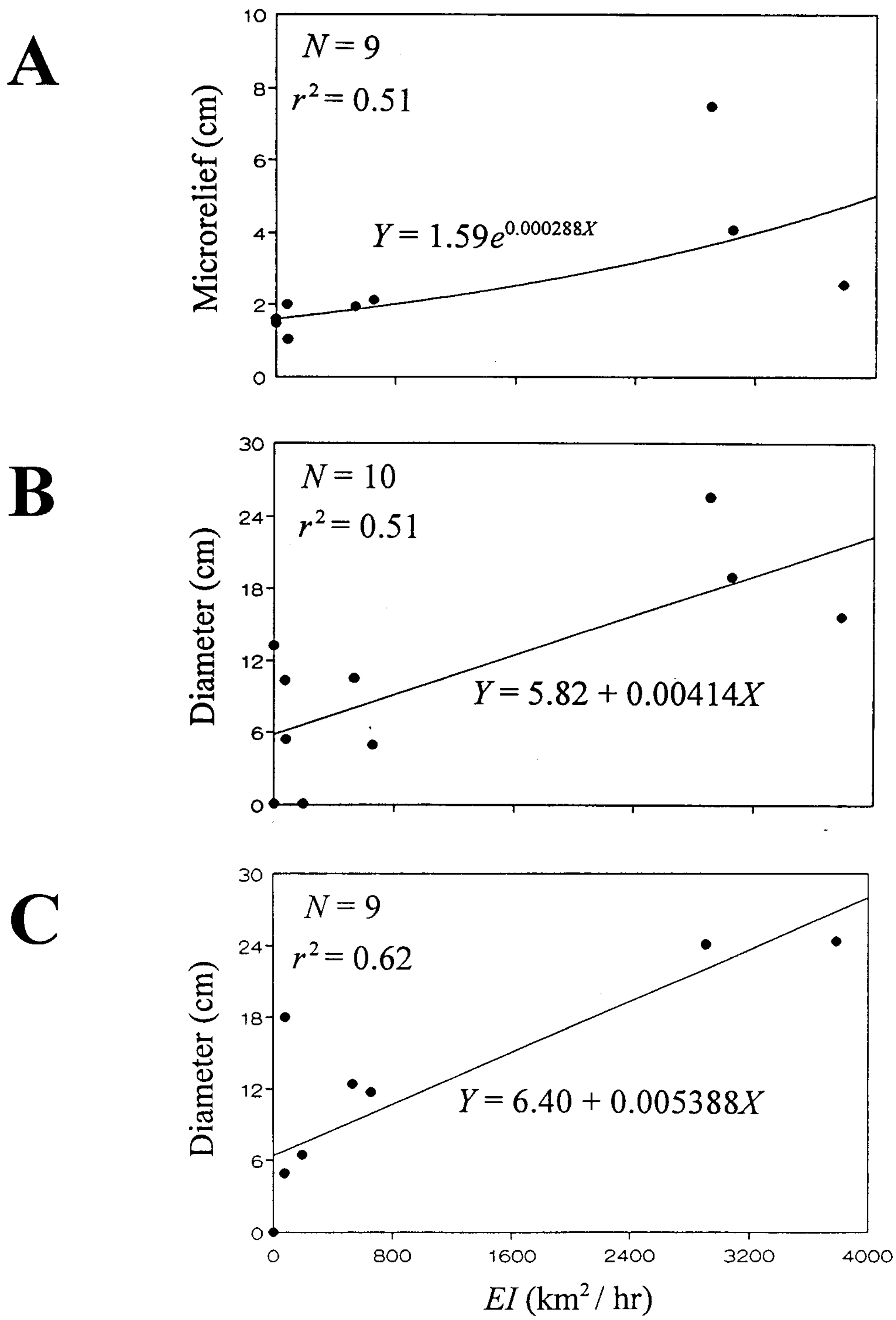



Figure 5.27 Relationships between *EI* and karren development at the Port au Choix Peninsula region for, A) intertidal zone microrelief, B) supratidal swash zone diameter and C) backshore zone diameter.

and microrelief. Finally, most of the statistical relationships between overall fetch/*EI* and karren diameter/microrelief are positive, which means that increased exposure to the marine environment produces larger karren in the supratidal swash and backshore zones. The exception is the Port au Port Peninsula region (Figure 5.23 and 5.28A), where karren diameter and microrelief increase with produces larger karren in the supratidal swash and backshore zones. The exception is the Port au Port Peninsula region (Figures 5.23 and 5.28A), where karren diameter and microrelief increase with decreasing overall fetch and *EI* values (i.e. an inverse relationship), thus indicating that karren becomes larger with increased shelter from the open marine environment.

There are some interesting trends apparent when comparing the effects of the two independent exposure variables on karren development. Karren diameter variations are almost always explained equally by both variables or, there is significantly higher association with overall fetch (Figures 5.22A and 5.24A), except for the supratidal swash zone of the Port au Choix Peninsula region (Figure 5.27B). Microrelief variations, however, are better explained by variations in *EI* values within each region (Figures 5.26 and 5.27), except for the backshore zones of the Cow Head Peninsula and Port au Choix Peninsula regions (Figures 5.24B and 5.25B). It can be supposed that fetch is more important in affecting the diameter of karren in the swash and backshore zones, while wind duration and velocity have an additional influence on karren microrelief in these zones. Certainly more research would be needed to verify if such trends actually exist.

### 5.4.3 Offshore and Onshore Gradients and Karren Development

The amount of wave energy expended along the shore is also a function of the offshore gradient at a site, and onshore gradient will affect the distribution of this wave energy across the littoral zone (Sec. 2.2.1). A shoreline may be very exposed, in relation to fetch distance and wind velocities, yet still receive a reduced level of wave energy at the shoreline if the offshore, littoral slope minimizes wave energy before it reaches the shore (i.e. gentle gradient). This may provide part of an explanation for the low $r^2$ values associated with overall fetch and *EI*, thus, an intersite analysis of offshore and onshore gradients was performed.

A) Derivation

The onshore gradients calculated in Section 3.5.1 are used here. Offshore gradients are calculated from the bathymetric maps of Chapter 3 (Figures 3.13 to 3.16). Where possible, the offshore gradient was calculated from an ocean depth of 20 m, extending across the geological definition of the littoral zone (Sec. 2.1). Both gradient measurements ($\beta$) for the individual sites are provided in Table 5.44. Missing offshore gradients occurred when bathymetric contours did not exist adjacent to that site, due to the scale of maps available. Missing onshore gradients occurred with sites which had no shore-normal profiles constructed there, as it is these profiles that allowed an approximate angle of slope to be determined across the onshore littoral zone (Sec. 3.5.1).

B) Inter-regional Analysis

The two gradients were regressed against the karren data used in the preceding section, in an attempt to determine the potential significance of gradient on karren development. The $r^2$ results, for both offshore and onshore gradients, are presented in Table 5.45. There are no strong statistical relationships in any of the zones especially when considering offshore gradients. Onshore gradients produce some marginally significant relationships with diameter and microrelief in the supratidal swash and backshore zones. In these zones, to a certain extent, an increase in the onshore gradient of the littoral bedrock, will produce a corresponding increase in the size of the karren. There are no relationships in the intertidal zone, or with karren density in any zone. It should be remembered that calculations of complex, scarp slopes have been idealized to represent a uniform slope (Sec. 3.5.1), and it is not known how much error this has created in the gradient values provided in Table 5.44.

When comparing the results in Table 5.45 with those in Table 5.42 (fetch and *EI*), it is evident that there are no strong relationships between any of these exposure variables and intersite karren variation. Clearly, offshore gradient has no direct influence on intersite karren variation at western Newfoundland, but it still exerts some control on the available wave energy at a given site. Onshore gradient is most important in the supratidal swash zone, where it would appear that the

Table 5.44 Approximate offshore and onshore gradients for the study sites.

| Site | Offshore Gradient ($\beta$ )* | Onshore Gradient ($\beta$ )* |
|---|---|---|
| **Port au Port Peninsula Region** | | |
| Port au Port East Bay ; | | |
| E. Shore / Aguathuna | 1.31 / 1.64 | 2.27 / 1.95 |
| Long Point SE / Long Point NW | 0.65 / 0.19 | 7.02 / 3.18 |
| Lower Cove / Ship Cove | 0.65 / 0.82 | 1.41 / ------ |
| Three Rock Point / The Bar | 1.64 / 1.64 | ------ / 5.48 |
| **Cow Head Peninsula Region** | | |
| Cow Head Peninsula ; | | |
| WNW Shore / N Shore | 7.67 / 0.46 | 3.43 / 3.45 |
| SW Shore / SSE Shore | 1.04 / ------ | 2.00 / 5.74 |
| Stearing Island / Belldowns Island | 1.27 / ------ | ------ / ------ |
| Broom Point N / Broom Point S | 0.64 / 0.60 | 3.58 / 2.81 |
| Lower Head / Daniel's Harbour | 0.48 / ----- | ------ / ------ |
| **Port au Choix Peninsula Region** | | |
| Port au Choix Peninsula ; | | |
| E Shore / N Shore | ------ / 1.15 | 6.65 / 4.57 |
| NW Shore / W Shore | 3.06 / 1.83 | 2.70 / 2.58 |
| Pointe Riche Peninsula ; | | |
| WNW Shore / W Shore | ------ / 1.53 | 0.69 / 2.64 |
| S Shore | 1.03 | 2.29 |
| Ingornachoix Bay / Gargamelle Cove | 0.52 / 0.46 | 3.05 / 5.45 |
| New Ferrolle Peninsula | ------ | 11.54 |
| **Cook's Harbour Region** | | |
| Cape Norman | 4.20 | 8.95 |
| E Cape Norman / W Cape Norman | 1.40 / 3.61 | 0.74 / 2.43 |

* for calculation of gradients refer to equation 3.4, p.58

Table 5.45 Comparison of the coefficients of determination ($r^2$) for western Newfoundland in relation to the potential effects of offshore and onshore gradients with karren development.

| | ZONE | | |
|---|---|---|---|
| Karren Measurement | Intertidal $r^2$ ($N$) | Supratidal Swash $r^2$ ($N$) | Backshore $r^2$ ($N$) |
| **Offshore Gradient ($\beta$)** | | | |
| Diameter | 0.02 (19) | 0.00 (24) | 0.00 (15) |
| Microrelief | 0.07 (19) | 0.00 (24) | 0.00 (15) |
| Density | 0.00 (19) | 0.11 (24) | 0.00 (15) |
| **Onshore Gradient ($\beta$)** | | | |
| Diameter | 0.00 (19) | 0.31 (24) | 0.36 (17) |
| Microrelief | 0.00 (19) | 0.35 (24) | 0.08 (17) |
| Density | 0.00 (19) | 0.05 (24) | 0.16 (17) |

overall slope of the platform rock, to some extent, affects karren development. In the backshore overall fetch distance has the most influence on karren, as this zone is usually only affected by storm waves, and varying the fetch probably has the most pronounced influence on the level of wave energy, and degree of karren development, in this zone. Overall, when comparing the regression results from both the geologic and marine environment variables, it is evident that geologic variations are more important in controlling the erosion processes and karren development in western Newfoundland.

Table 5.46 Comparison of the coefficients of determination ($r^2$) for each region in relation to the potential effects of offshore and onshore gradients with karren development.

| | ZONE | | |
|---|---|---|---|
| Region | Intertidal $r^2$ ($N$) (offshore/onshore) | Supratidal Swash $r^2$ ($N$) (offshore/onshore) | Backshore $r^2$ ($N$) (offshore/onshore) |
| **Port au Port Peninsula** | | | |
| Diameter | 0.32(6)/0.00(5) | 0.00(8)/0.13(6) | ------ |
| Microrelief | **0.47(6)**/0.00(5) | 0.00(8)/**0.64(6)** | ------ |
| Density | 0.00(6)/0.00(5) | 0.00(8)/0.00(6) | ------ |
| **Cow Head Peninsula Region** | | | |
| Diameter | ------ | 0.00/0.39(6) | 0.28(6)/**0.63(5)** |
| Microrelief | ------ | 0.00/0.00(6) | 0.29(6)/**0.63(5)** |
| Density | ------ | 0.00/0.00(6) | 0.00(6)/0.30(5) |
| **Port au Choix Peninsula Region** | | | |
| Diameter | 0.00(7)/0.00(5) | 0.34(7)/**0.60(10)** | 0.00(6)/0.21(9) |
| Microrelief | 0.00(7)/0.00(5) | 0.03(7)/**0.68(10)** | 0.00(6)/0.00(9) |
| Density | 0.00(7)/0.00(5) | **0.61(7)**/0.24(10) | 0.21(6)/0.09(9) |
| **Cook's Harbour Region** | | | |
| Diameter | ------ | 0.01/**0.61(3)** | **0.99/0.94(3)** |
| Microrelief | ------ | 0.00/**0.80(3)** | **0.99/0.82(3)** |
| Density | ------ | 0.30/**0.99(3)** | 0.00/**0.68(3)** |

### C) Intra-regional Analysis

Regressions were also performed to establish if gradient had any influence in explaining intersite karren variation within each of the regions. The $r^2$ results are provided in Table 5.46. There are very few statistically significant relationships between offshore gradient and karren variation. Only intertidal microrelief at Port au Port Peninsula (Figure 5.28A), and supratidal swash density in the Port au Choix Peninsula region (Figure 5.28B), provide marginally significant positive, linear relationships. This excludes the Cook's Harbour region where there are only three observations in the data set. Increasing offshore gradient at Port au Port Peninsula is associated with an increase in karren microrelief in the intertidal zone. This can be expected, as the increased offshore gradient allows waves to break closer to the shore, exerting more force upon the rock necessary for facilitating karren development (Sec. 2.2.1). One would then expect karren density to decline with an increase in offshore gradient, but this is not the case for the Port au Choix Peninsula region, where density increases with increasing offshore gradient in the swash zone. This would lead one to believe that other factors (i.e. geologic) are probably more involved in affecting these trends in the data.

The only statistically significant relationships with karren and onshore gradients are in the supratidal swash zone of the Port au Port Peninsula (Figure 5.29A) and the Port au Choix Peninsula region (Figure 5.29B and C). This excludes the Cook's Harbour region, as well as the Cow Head Peninsula region where there are only two actual measured observations. There is a positive, linear relationship between onshore gradient and karren microrelief at the Port au Port Peninsula, as increasing the slope of the onshore rocks here enhances karren in the swash zone. At the Port au Choix Peninsula region, however, there is an exponential decrease in karren diameter and microrelief in the swash zone, with increasing onshore gradient. The latter relationships may be a more accurate reflection of what one can expect, as increasing onshore gradient will reduce the lateral distribution of the tidal range and wave energy across the platform, so that swash zone erosion is minimized.

When comparing Table 5.46 with Table 5.43, it is evident that, in general, overall fetch and *EI* are still more important than gradient in explaining intersite karren variations within a region.

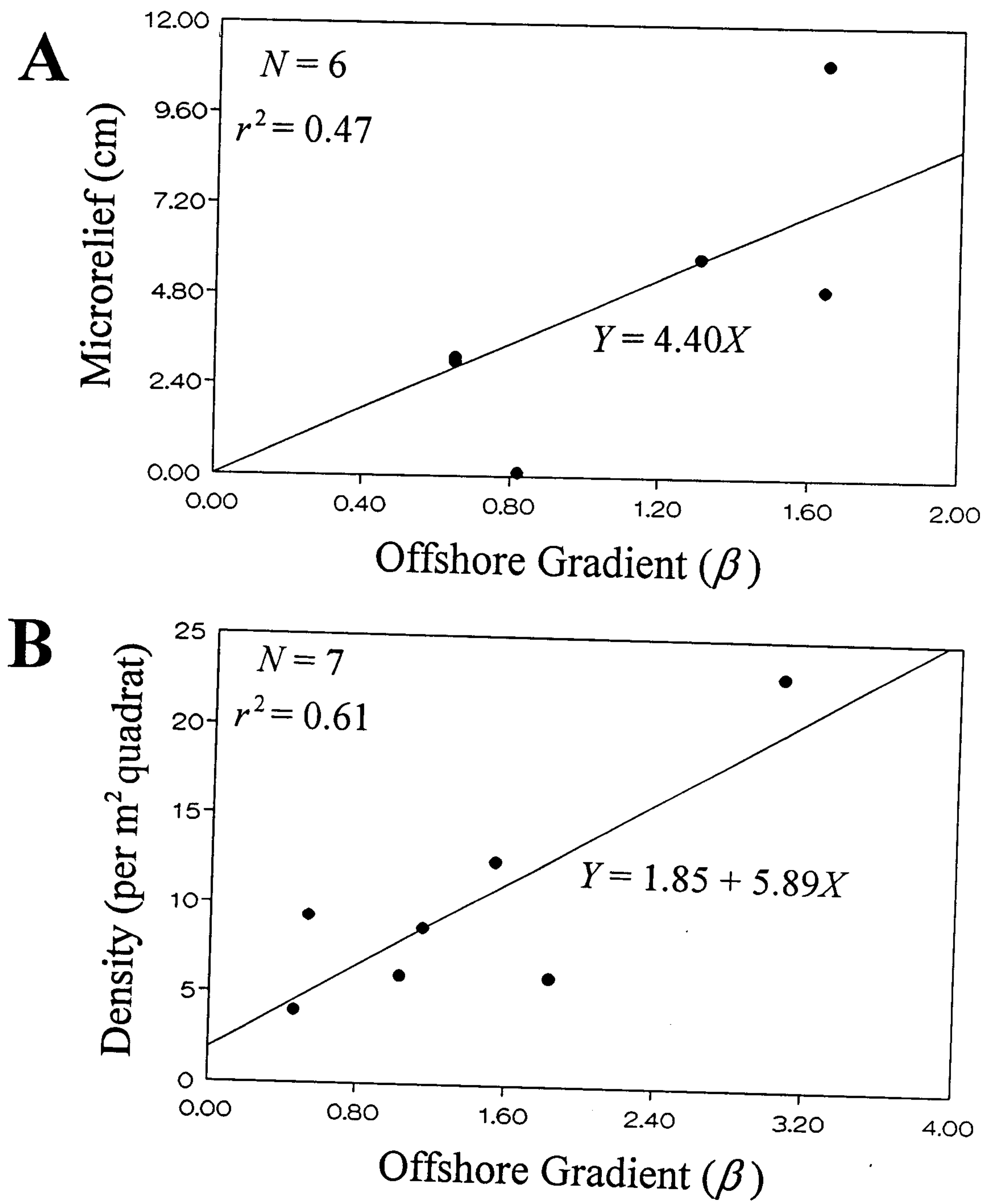



Figure 5.28 Linear relationships with offshore gradient and karren A) microrelief at the intertidal zone of the Port au Port Peninsula, and B) density at the supratidal swash zone of the Port au Choix Peninsula region.

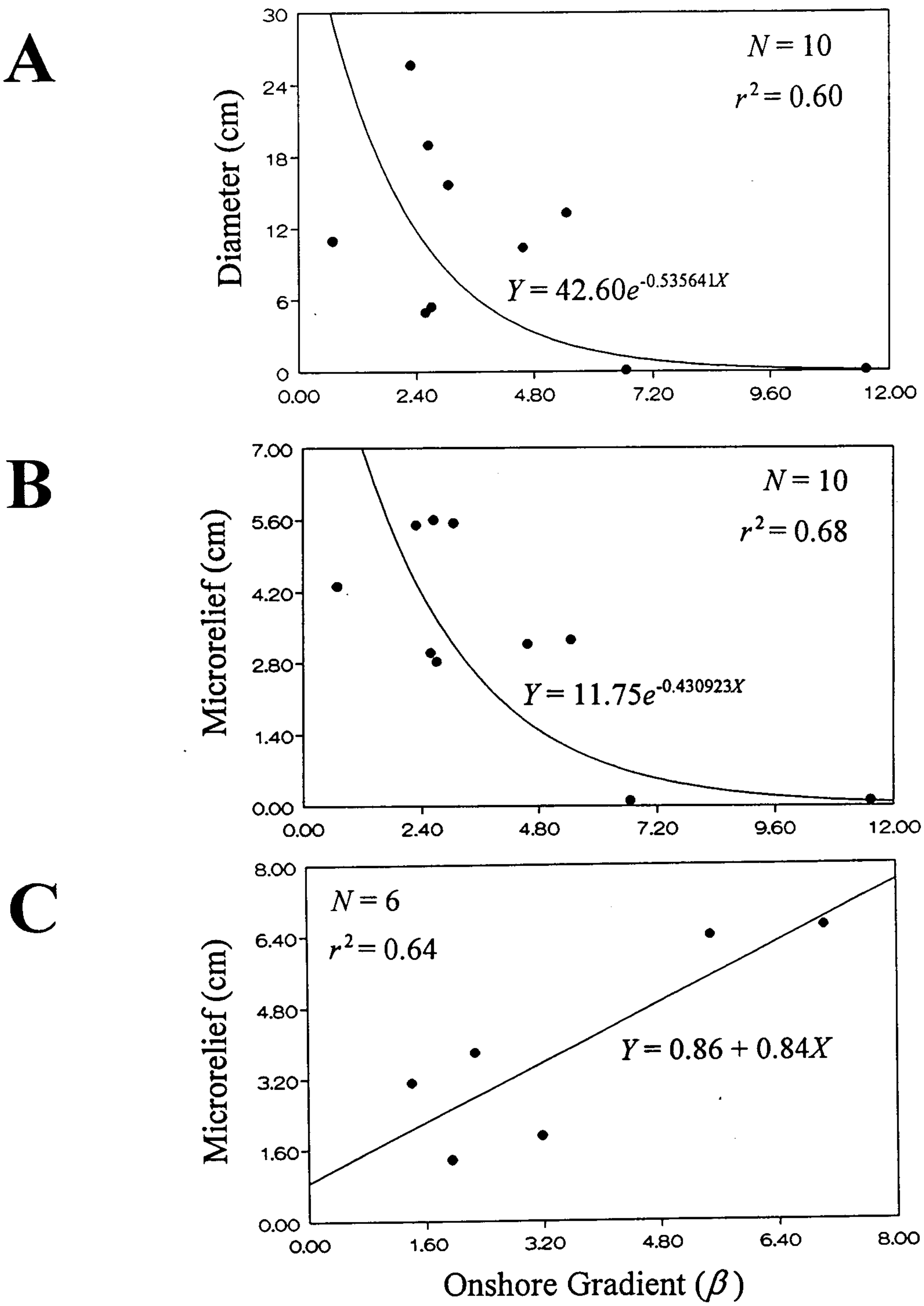



Figure 5.29 Relationships between onshore gradient and supratidal swash zone karren development for, A) diameter and B) microrelief at the Port au Choix Peninsula region and C) microrelief at the Port au Port Peninsula.

Again, excluding the Cow Head Peninsula and Cook's Harbour regions due to a lack of observations, only the Port au Port Peninsula intertidal zone (offshore, microrelief), and the supratidal swash zone of the Port au Choix Peninsula region (offshore, density; onshore, diameter and microrelief), possess $r^2$ values for gradient which are statistically significant, and higher, than those for fetch and *EI*. This reinforces the conclusions of the previous section, where offshore gradients possess little direct influence on karren development; onshore gradients primarily appear to have the strongest affect on karren in the supratidal swash zone and karren in the backshore are most affected by the overall fetch.

### 5.4.4 The Effect of Shingle on Karren

Section 2.2.1 discusses the relative importance of clastic materials for potentially enhancing erosion of carbonate coastal rocks. Ley (1976 and 1979) showed that the presence of a sand supply along the Bristol Channel improved the development of karren if there was not an overabundance. He found that the availability of sand accounted for 25.7% of the intersite karren variation (using karren standard deviation as the dependent variable). Sites which had a supply of sand experienced enhanced abrasion erosion upon the rock, producing variable effects on karren development, depending on the amount of sand present and the wave energy of the swash zone.

In western Newfoundland there appears to be some association between abrasion erosion and karren development, although this was not quantitatively measured. The majority of the coastline in the study area is composed of rocky platforms, and there are few areas which would provide a sand supply big enough to generate abrasion. There is the presence of shingle (pebble to boulder-size) at several of the sites (e.g. Sec. 3.5.1), which may have a similar effect. At more exposed coastlines the swash energy is strong enough to promote the development (or enlargement) of karren pits by the process of potholing (Sec. 2.2.1). If there is an abundant shingle being dragged and rolled across the platform, then the rock surface becomes smooth and polished, thereby minimizing any significant karren formations in that area. At the same time there are a number of sites in the study area (50% of the sites listed in Table 4.1) which are not at all influenced by the presence of shingle, but it doesn't appear that the karren at these sites are significantly different than the karren at shingle-dominated coastlines (when otherwise equal environments and/or lithologies are compared).

## 5.5 Water Chemistry Analysis

There has yet to be any detailed process study involving littoral karren development in relation to the seawater properties of conductivity (SpC), salinity and pH. Ley (1976) did not include any water properties in his multivariate model of karren development, and Lundberg (1974) obtained inconclusive results, and so focused on biological zonation instead. This section investigates properties existing in the littoral rock pools of western Newfoundland, and their correlation (if any) with karren development. The more detailed study undertaken at the Pointe Riche Peninsula (Sec. 4.5) is emphasized.

### 5.5.1 Basic Seawater Properties of the Rock Pools

Individual measurements for the rock pools are provided in Appendix E (Table E1), with detailed discussion on the calibration procedures necessary for the measurements of salinity and SpC. Averages for temperature, salinity and SpC, for each littoral zone and study site, are provided in Tables 5.47 and 5.48. Missing values indicate the lack of any rock pools in that zone, or in the case of pH, there were some erroneous recordings due to problems experienced with pH meters in the field.

SpC and salinity both measure ion concentration in solution. SpC ($\mu$mhos cm$^{-1}$ at 25°C) measures the electrical conductance of an aqueous solution and provides a measure of its ionic strength (White, 1988), while salinity (‰, parts per thousand) directly measures the average concentration of total dissolved solids in solution (Open University Course Team, 1989a). SpC readings are usually somewhat higher than those for salinity in the same littoral zone. Both water properties are highest in the intertidal zone, where the rock pools experience daily subaqueous exposure, then slightly decline in the supratidal swash zone where the pools are predominantly

Table 5.47 Tidal pool properties of conductivity (SpC), salinity and pH across the littoral zone for the Port au Port Peninsula, Cow Head Peninsula and Broom Point.

| Site | SpC (25°C) | Salinity (‰) | pH |
|---|---|---|---|
| **Port au Port Peninsula** | | | |
| **Long Point/The Bar** | | | |
| Intertidal Zone Averages | 42,925 | 27.51 | 8.84 |
| Supratidal Zone Averages | 41,851 | 26.74 | 9.06 |
| Backshore Zone Averages | 27,181 | 17.08 | 8.16 |
| **South Coast Sites** | | | |
| Intertidal Zone Averages | ---------- | -------- | -------- |
| Supratidal Zone Averages | 45,536 | 29.55 | 8.61 |
| Backshore Zone Averages | 4,582 | 2.95 | 9.66 |
| **Port au Port East Bay** | | | |
| Intertidal Zone Averages | 40,532 | 26.12 | 8.35 |
| Supratidal Zone Averages | 38,749 | 24.34 | 8.69 |
| Backshore Zone Averages | 754 | 0.39 | 8.10 |
| **Cow Head Peninsula** | | | |
| Intertidal Zone Averages | 42,229 | 27.20 | 8.13 |
| Supratidal Zone Averages | 45,509 | 29.19 | 9.47 |
| Backshore Zone Averages | 5,336 | 3.58 | 10.00 |
| **Broom Point** | | | |
| Intertidal Zone Averages | ---------- | -------- | -------- |
| Supratidal Zone Averages | 35,672 | 23.00 | -------- |
| Backshore Zone Averages | 44,165 | 28.85 | -------- |

Table 5.48 Tidal pool properties of conductivity (SpC), salinity and pH across the littoral zone for the Port au Choix Peninsula and Cook's Harbour regions.

| Site | SpC (25℃) | Salinity (‰) | pH |
|---|---|---|---|
| **Port au Choix Peninsula** | | | |
| Intertidal Zone Averages | 42,881 | 27.30 | -------- |
| Supratidal Zone Averages | 43,016 | 27.50 | 9.54 |
| Backshore Zone Averages | 14,041 | 13.05 | 10.88 |
| **Pointe Riche Peninsula** | | | |
| Intertidal Zone Averages | 43,333 | 28.10 | -------- |
| Supratidal Zone Averages | 39,080 | 25.91 | 11.15 |
| Backshore Zone Averages | 22,572 | 15.43 | 11.41 |
| **Ingornachoix Bay** | | | |
| Intertidal Zone Averages | 40,191 | 27.00 | -------- |
| Supratidal Zone Averages | 40,128 | 26.29 | -------- |
| Backshore Zone Averages | 23,258 | 14.90 | -------- |
| **New Ferrolle Peninsula** | | | |
| Intertidal Zone Averages | 43,793 | 28.47 | -------- |
| Supratidal Zone Averages | 13,717 | 8.92 | -------- |
| Backshore Zone Averages | 5,651 | 3.34 | -------- |
| **Cook's Harbour Region** | | | |
| Intertidal Zone Averages | 43,766 | 28.00 | 8.24 |
| Supratidal Zone Averages | 37,725 | 24.47 | 8.99 |
| Backshore Zone Averages | 14,092 | 9.76 | 9.38 |

subjected to subaerial exposure and a decline in oceanic ionic species. The backshore experiences the least submergence in sea water and, at the same time, is affected the most by dilution from rainfall. Therefore, there is usually a much lower recording of SpC and salinity in this zone. Variations in this trend will occur with differing weather conditions. If recordings were taken during warm, sunny days, when there was increased evaporation from subaerially exposed rock pools, especially the smaller ones, then there was a higher ionic concentration than expected for that zone. If recordings were taken during overcast, cool conditions, then the measurement of SpC and salinity was lower than the expected average for that zone.

pH is a difficult field measurement of any water sample involved in karst research, even if the procedure outlined in Section 4.5 is carefully followed (see White, 1988 for more detail). pH meters involve a glass electrode and reference electrode in measuring the concentration of the $H^+$ ion in solution, thereby determining the acidity level of the water. The average pH of seawater is slightly alkaline, often ranging from 8.0 to 8.3, depending on the level of $CO_2$ in the water (Open University Course Team, 1989a). This is reflected in the average pH measurements taken in the intertidal zone for the study sites, where the rock pool water is somewhat more alkaline than the open ocean, due to the addition of dissolved $HCO_3^-$ (bicarbonate) from the platform rock, as well as the presence of other alkaline ions not taken into account. For most sites there is an increase in alkalinity towards the backshore, where there were occasionally values as high as 12. The increased alkalinity in the backshore may be reflective of some precipitation of $CaCO_3$ in the rock pool water at the time pH was recorded, especially since many of the more alkaline recordings were taken in the later afternoon on warmer, sunny days.

### 5.5.2 Rock Pool Properties and Karren Development

SpC and pH were regressed against the karren measurements to determine if any relationships exist between these properties. Salinity was excluded from the analysis, as its range of values are quite similar to that for SpC, and salinity is more important for affecting biological species colonization throughout the littoral zone (Sec. 4.6). The results of the regressions are given in Table 5.49. Average values for the karren measurements differ from those in Tables 5.2 and 5.3, because this data only includes sites where there were recordings of SpC and pH.

Table 5.49 reveals that there is no established relationship between SpC or pH and karren development. Because large quantities of foreign ions boost carbonate dissolution (Ford and Williams, 1989), one would expect that the more saline rock pools would boost chemical dissolution and facilitate erosion at that location. Since the largest karren often occur in the backshore, where there are usually much fewer dissolved species in the rock pools, the influence of ionic strength may be masked by geologic and marine exposure factors in the controlling karren development. At the same time, some of the largest SpC values (i.e. > 50,000 $\mu$mhos $cm^{-1}$ ), were measured in many of the supratidal swash rock pools, and it is in this zone where the greatest frequency of spectacular karren occurred. Weather conditions preceding/during the time SpC was measured will also create some error in the expected ionic strength of that particular rock pool.

Although there is a low statistical correlation with pH and karren development, there are trends evident in the littoral zone. The increase in alkalinity towards the backshore coincides with the increased karren diameter and microrelief. This would confirm that the more aggressive rock pools are located in the swash and backshore zones, enhancing carbonate dissolution and isolated karren erosion. Geologic and marine exposure factors, once again, are probably more important in controlling karren development, and therefore, obscure any direct association between karren and pH which may exist.

### 5.5.3 Diurnal Chemical Study at the Pointe Riche Peninsula

Section 4.5 described a site at the western shore of the Pointe Riche Peninsula, where an excellent range of saline conditions was detected in the rock pools, across the littoral zone along the dip slope platform there (Figure 4.30). Thus, this site was chosen for a more detailed, process-oriented water chemical analysis. Recordings of temperature, SpC, pH, and field titrations of $Ca^{2+}$, $Mg^{2+}$ and $HCO_3^-$ (bicarbonate) were undertaken for both the early morning and the evening, so that the recordings and measurements were taken 12 hours apart (Table 5.50).

Table 5.49 Average values of SpC and pH across the littoral zone and the coefficients of determination ($r^2$) for each water property in relation to the karren measurements.

| | ZONE | | | |
|---|---|---|---|---|
| | Intertidal | Supratidal Swash | Backshore | $r^2$ (SpC/pH) |
| **Water Property** | | | | |
| SpC (25°C) | 42,015 | 40,359 | 15,922 | ------ |
| pH | 8.44 | 9.77 | 10.56 | ------ |
| **Karren Measurement** | | | | |
| Avg. Diameter (cm) | 11.00 | 14.69 | 20.08 | 0.11 / 0.21 |
| Avg. Microrelief (cm) | 4.48 | 6.43 | 9.34 | 0.12 / 0.00 |
| Avg. Density (per $m^2$ quadrat) | 27.02 | 10.25 | 8.94 | 0.16 / 0.23 |

It is evident from Table 5.50 that there are two distinct groups of water samples; an oceanic group comprising the shallow ocean and the upper inter- and supratidal swash rock pools (pools 1-3), and a group consisting of backshore rock pools (pools 4-7) and an inland sample of bog water at the top of the platform. With both groups there are several diurnal trends evident in the water chemistry data.

With the oceanic waters there is evidence for increased limestone dissolution, especially during the day, as compared to the backshore and bog water. The pH increases during the day in all cases by about the same amount except for pool 1, which is somewhat smaller than the others and, thus, should be more affected by warming and evaporation than the others. However, cooler temperatures (14°C) and scattered showers prevailed that day, so the rise in pH may be more related to increased biochemical activity during the day and this was not measured (Ford, Pers. Comm, 1997). With all three rock pools there is a corresponding increase in the concentration of

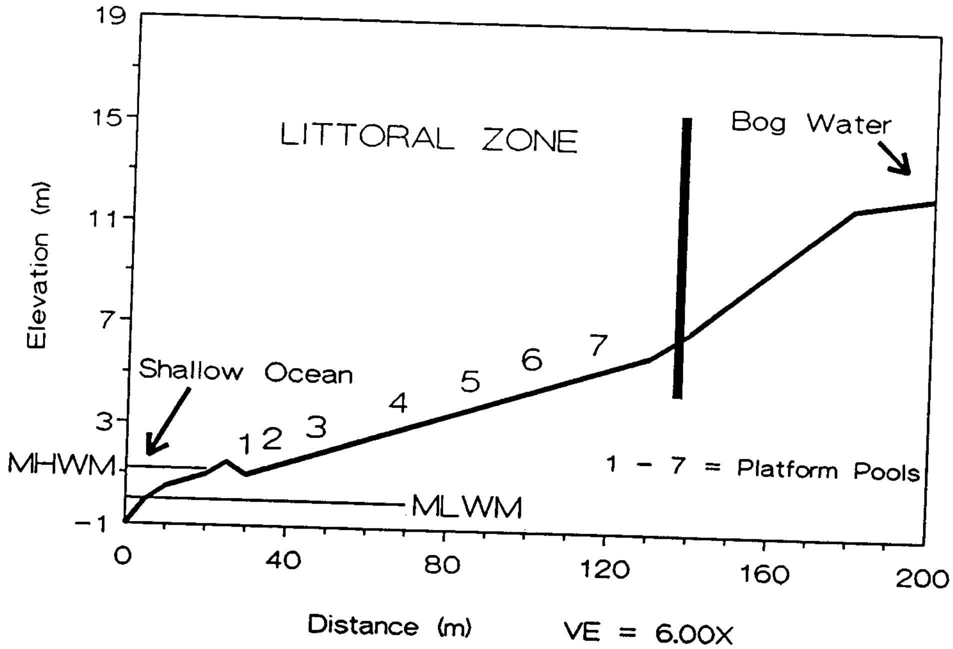



Figure 4.30 Profile across the western dip slope of the Pointe Riche Peninsula, illustrating the location of platform pools, shallow ocean and bog water, which were used for detailed water chemistry sampling and measurements.

$Ca^{2+}$ and $HCO_3^-$ during the day (except pool 1 and $HCO_3^-$), and this can be correlated with pH to a certain degree (Figure 5.30). $Mg^{2+}$ does not change significantly during the day. The increase in $HCO_3^-$ in the rock pools also provides evidence of biochemical activity taking place. These results favour increased limestone dissolution during the day for the oceanic water samples, however, this could not be verified. Due to the complex nature of seawater chemistry, calculation of actual saturation index values for the rock pools here (a modified version of eqn. 2.8) were inconclusive, due to extreme ion balance errors far outside the acceptable range of error allowed for meaningful results (< 5%).

The cooler, rainy weather explains the general drop in SpC during the day, but both sets of readings are significantly higher than those from the backshore and top of the platform. This indicates that the effects of ionic strength are much stronger with the oceanic group of water samples, which also favour increased limestone dissolution.

The *m*Ca/*m*Mg atomic ratio is derived by determining the concentration (molality) of these

Table 5.50 Diurnal comparison of specific conductance (SpC), pH and concentrations of calcium

Table 5.50 Diurnal comparison of specific conductance (SpC), pH and concentrations of calcium ($Ca^{2+}$), magnesium ($Mg^{2+}$) and bicarbonate ($HCO_3^-$) for littoral zone water pools across the western shore of the Pointe Riche Peninsula.

| Sample | SpC (25°C) | pH | $Ca^{2+}$ (ppm) | $Mg^{2+}$ (ppm) | *m*Ca/*m*Mg | $HCO_3^-$ (ppm) | Ca/$HCO_3^-$ |
|---|---|---|---|---|---|---|---|
| **Shallow Ocean** | | | | | | | |
| 5:00 am | 42,335 | 8.02 | 340 | 1057 | 0.19 | 145 | 2.34 |
| 5:00 pm | 38,117 | 8.78 | 332 | 1006 | 0.19 | 116 | 2.86 |
| **Pool 1** | | | | | | | |
| 5:10 am | 28,632 | 7.22 | 356 | 1130 | 0.19 | 88 | 4.05 |
| 5:10 pm | 25,930 | 11.58 | 404 | 1040 | 0.21 | 44 | 9.18 |
| **Pool 2** | | | | | | | |
| 5:20 am | 39,161 | 9.43 | 284 | 1010 | 0.17 | 49 | 5.80 |
| 5:20 pm | 42,116 | 10.71 | 300 | 1040 | 0.16 | 88 | 3.41 |
| **Pool 3** | | | | | | | |
| 5:35 am | 40,715 | 10.40 | 292 | 1100 | 0.16 | 49 | 5.96 |
| 5:35 pm | 37,392 | 11.44 | 320 | 1164 | 0.17 | 65 | 4.92 |
| **Pool 4** | | | | | | | |
| 5:45 am | 890 | 8.95 | 84 | 120 | 0.42 | 71 | 1.18 |
| 5:45 pm | 1,320 | 11.44 | 64 | 90 | 0.42 | 90 | 0.71 |
| **Pool 5** | | | | | | | |
| 6:00 am | 552 | 8.54 | 60 | 43 | 0.83 | 79 | 0.76 |
| 6:00 pm | 1,170 | 11.30 | 54 | 30 | 1.08 | 101 | 0.54 |
| **Pool 6** | | | | | | | |
| 6:10 am | 693 | 7.98 | 64 | 49 | 0.72 | 106 | 0.60 |
| 6:10 pm | 327 | 11.30 | 53 | 22 | 1.32 | 122 | 0.43 |
| **Pool 7** | | | | | | | |
| 6:20 am | 693 | 8.33 | 72 | 40 | 1.13 | 73 | 0.98 |
| 6:20 pm | 320 | 11.70 | 49 | 21 | 1.40 | 154 | 0.32 |
| **Bog Water** | | | | | | | |
| 6:35 am | 170 | 7.10 | 9 | 8 | 0.67 | 9 | 1.00 |
| 6:35 pm | 249 | 9.00 | 5 | 4 | 0.75 | 15 | 0.33 |

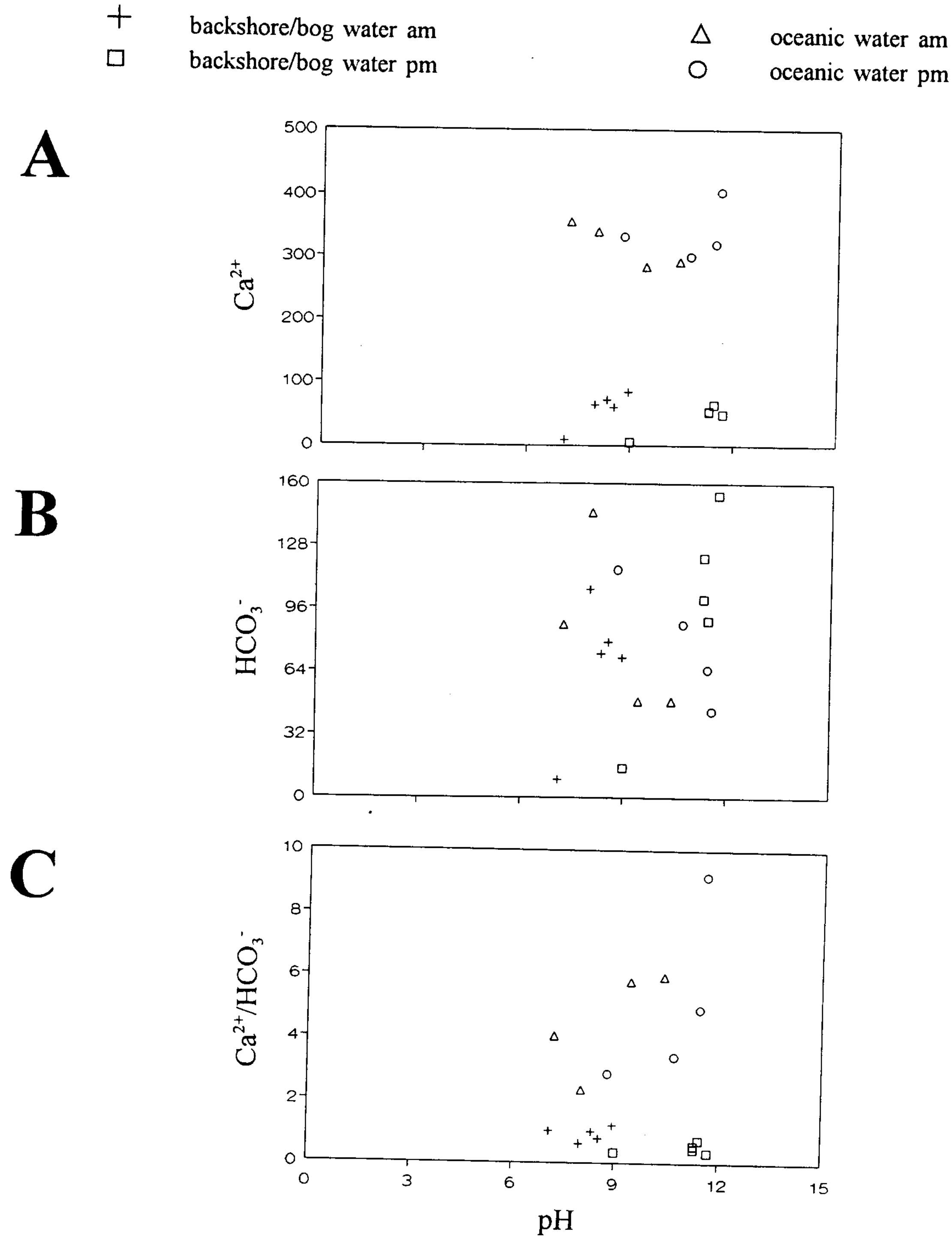



Figure 5.30 Illustration of the effects of pH on A) $Ca^{2+}$, B) $HCO_3^-$ and C) $Ca/HCO_3^-$ from the water samples collected along the western shore of the Pointe Riche Peninsula.

cations in solution,

$$Molality\ (m) = \frac{\text{mgl}^{-1}}{1000 \text{ x atomic weight}} \tag{5.12}$$

and, for fresh water karst studies, can be used to determine the rock surface that water sample is in contact with (White, 1988). The rock for this area of the Pointe Riche Peninsula is limestone, but the *m*Ca/*m*Mg ratio here reveals how much the rock pools vary from the standard ocean value of 0.20 (Blatt *et al.*, 1980). The *m*Ca/*m*Mg ratios for the oceanic waters are relatively constant throughout the day and are close to the oceanic mean value of 0.20.

With the backshore and bog water samples there are many unclear patterns in the data. pH increases during the day in all cases, as with the oceanic waters, but $Ca^{2+}$ and $Mg^{2+}$ decline and, at the same time, $HCO_3^-$ and the *m*Ca/*m*Mg ratio increase. The drop in both $Ca^{2+}$and $Mg^{2+}$indicate precipitation is accompanying any evaporation which is occurring during the day, but more $Ca^{2+}$ is being produced by dissolution than is being precipitated, as it does not drop as much as $Mg^{2+}$. There is a more distinct linear trend in the data with concentrations of $Ca^{2+}$ and $HCO_3^-$ in relation to pH (Figure 5.30A and C), but further research is required to clear up these oddities with the data here.

SpC varies much more within this group of samples than with the oceanic waters. Ionic strength is drastically reduced with these pools, which may help to explain why more spectacular karren is formed in the supratidal swash zone as opposed to the backshore. Pools 6 and 7 are somewhat larger than pools 4 and 5, which helps to explain the lower SpC values for both sets of readings. These pools have a reduced SpC during the day, as opposed to the other backshore pools, as they are not affected by sea spray/mist as much as pools 4 and 5. There may also be more freshwater runoff into pools 6 and 7 from the top of the platform.

## 5.6 Sea Ice and Karren Development

As discussed in Section 2.2.1, Newfoundland is in a cold region environment and, unlike

Galway Bay and the Bristol Channel, is subject to the effects of frost weathering and pack ice. It was originally feared that there would be minimal karren development along any of the coast, due to the destructive nature of freeze and thaw action upon the carbonate rocks. It became evident from field observations, however, that there are few signs of frost weathering, and the littoral karren of western Newfoundland are essentially preserved by the floating pack ice during the winter. Pack ice exists for most of the winter months for the entire study area, except for St. George's Bay which occasionally remains ice free year round (Dept. of Fisheries and Oceans, 1986). It appears that this pack ice does act as an important buffer in protecting the karren on the platforms from frost erosion, as well as supporting Trenhaile's (1987) notion that sea ice has minimal erosion effects upon rocky coasts (Sec. 2.2.1).

# CHAPTER 6

# MULTIVARIATE ANALYSIS OF INTERSITE KARREN VARIATION

## 6.1 Introduction

This chapter will attempt to extend the bivariate analyses presented in Chapter 5 by incorporating some of the independent variables into a multivariate analysis of intersite karren variation; specifically the geology and marine environment variables which are conducive to regression analysis. It was decided separate multiple regression equations would be constructed for two groups of variables. The geologic multiple regression equation incorporates bedrock insoluble residue percent and average grain size, and platform dip; the marine environment variables are *EI*, offshore and onshore gradient (Table 6.1). The initial plan was to perform an aggregate regression analysis by combining data from all three littoral zones. However, data for the marine environment variables are the same for all three zones and, thus, would skew the results and not provide a proper comparison with geology. It is for this reason that the analysis is focused upon the supratidal swash zone, as it is this zone where the greatest number of observations occur, and where the separate bivariate analyses, for the most part, produced the largest explained variance in karren development (Table 6.1). Even though both overall fetch and *EI* explain about the same proportion of karren variation at the bivariate statistical level (Table 5.42), overall fetch was not incorporated into the marine environment multivariate model here, as it is highly correlated with *EI* (i.e. $r = 0.70$) and *EI* is the more significant variable, because it takes into account wind frequency and velocity in addition to fetch.

These multivariate models may better explain some of the intersite karren variation which does exist, as they allow for the study of separate, bivariate relationships between each independent variable and karren development, as well as assessing the relative importance of the interaction

Table 6.1 Geologic and marine environment variables used in the multivariate analysis and their $r^2$ values, for the supratidal swash zone, from the separate bivariate analyses performed in Chapter 5.

| Geologic Variable | $r^2$ | Marine Environment Variable | $r^2$ |
|---|---|---|---|
| **Insoluble Residue %** | | **Exposure Index** | |
| Diameter | 0.55 | Diameter | 0.35 |
| Microrelief | 0.48 | Microrelief | 0.17 |
| Density | 0.50 | Density | 0.00 |
| **Average Grain Size** | | **Offshore Gradient** | |
| Diameter | 0.57 | Diameter | 0.00 |
| Microrelief | 0.70 | Microrelief | 0.00 |
| Density | 0.34 | Density | 0.11 |
| **Platform Dip** | | **Onshore Gradient** | |
| Diameter | 0.28 | Diameter | 0.31 |
| Microrelief | 0.17 | Microrelief | 0.35 |
| Density | 0.00 | Density | 0.05 |

involved when combining these variables together into one model. At the same time the results may provide a clue as to the relative importance of geology and the marine environment in controlling karren development. Interpretation of the statistical output is based on multivariate theory discussed by Johnston (1980), Shaw and Wheeler (1985) and SPSS Base System User's Guide (1992).

## 6.2 Proposed Multivariate Equations of Karren Development

### 6.2.1 Geologic Analysis

The geologic variables selected for the multivariate model here are data which are on an interval/ratio scale and can be utilized in a regression analysis. Thus, rock type and percent dolomite are excluded from the analysis, leaving insoluble residue percent, average grain size and platform dip as the three independent variables used to explain karren development. The same data presented in Tables 5.25, 5.27, 5.29 and Appendix C2 are used here, but this time the data are combined together into one multivariate equation. Since the scale of observations for platform dip is different from that of insoluble residue and grain size, average supratidal swash zone dips for the karren sites were determined (e.g. one dip value for the Cow Head Peninsula), so that the data set is consistent. Only swash zone data for non-karren insoluble residue and grain size sites are used, with residue percent values below 10% excluded from the analysis, so as to reduce the effects of dolomitic rocks (Sec. 5.3.4C). Daniel's Harbour and the Cook's Harbour region are included in the data set here, despite proving to be outliers in the bivariate grain size analysis, as they were not outliers for the other independent variables. There were no dip measurements taken where karren didn't exist, as with insoluble residue and grain size, for the dip was usually similar in karren and non-karren areas. Thus, an average dip from all observations (14.0°) were used in conjunction with the non-karren data for insoluble residue and grain size, to eliminate any bias in the statistical output which may be caused from such a high number of missing observations.

The most serious problem with multivariate models involves that of multicollinearity. Multicollinearity refers to the existence of a high correlation between two independent variables

(Shaw and Wheeler, 1985), meaning that these two variables are essentially explaining the same amount of variation in the dependent variable. This will create a reduced precision in the overall multivariate equation and a large amount of ambiguity when attempting to differentiate the effects of individual independent variables on the dependent one. Thus, a zero-order correlation matrix was computed (Table 6.2) to determine the degree of multicollinearity existing in the multivariate geology model. The correlations between the three independent variables are quite small, with the highest being 0.28 between grain size and dip. This bodes well for the independent variables selected here, as they are essentially uncorrelated to one another, implying a statistically valid multivariate equation. It should be noted that it is almost impossible to fully eliminate the problem of collinearity, but if the correlations between the independent variables are less than 0.40, then the proposed statistical model is valid (Kuz, Pers. Comm., 1997).

Regressions were run for karren diameter, microrelief and density using the values in Table 5.25, and the statistical output for each is provided in Table 6.3. All three equations are statistically significant at the 0.05 level of significance ($F$ statistic), and at the 0.01 level of significance for diameter and microrelief. The adjusted $R^2$ values take into account the smaller sample size, as with the bivariate analysis of Chapter 5, although it is stressed that there should be about 20 observations for each independent variable in the equation (Kuz, Pers. Comm., 1997), so the $N$ level is far from ideal in this analysis. However, the results do provide a basis on the importance of geology in affecting intersite karren variation for western Newfoundland.

The multivariate equation for the karren measurements takes the form,

$$Y = a + b_1X_1 + b_2X_2 + b_3X_3 \pm e \tag{6.1}$$

where $a$ = intercept value (constant)
$b_1$ = partial regression coefficients
e = error term

The intercept value for karren diameter is 22.45, the value for diameter when $X_1 = X_2 = X_3 = 0$. The partial

Table 6.2 Zero-order correlations of the independent geologic variables involved in the multivariate analysis.

| | Insoluble Residue | Grain Size | Dip |
|---|---|---|---|
| Insoluble Residue | 1.00 | -0.25 | 0.07 |
| Grain Size | -0.25 | 1.00 | 0.28 |
| Dip | 0.07 | 0.28 | 1.00 |

regression coefficients are slope coefficients, which indicate the absolute difference in diameter with a unit change in each independent variable while keeping the others constant. The problem with partial regression coefficients is that they are based on different units used to measure each of the independent variables and, thus, cannot be directly compared to one another. Beta ($B$) coefficients are calculated to provide a standardized measure for the partial regression coefficients (Table 6.3), using the following equation

$$B_i = b_i \frac{S_{xi}}{S_y} \tag{6.2}$$

where $b_i$ = unstandardized $b$ partial regression coefficient
$s_{xi}$ = standard deviation of the independent variable involved
$s_y$ = standard deviation of the dependent variable

Now we have an indication of the relative change in karren diameter with respect to each of the independent variables while the other ones are controlled. Insoluble residue percent has the highest $B$ value (-0.4916), which means that it has the most influence on changes in karren diameter, with an increase in insoluble residue percent producing a decrease in karren diameter. Note that there is also an inverse relationship with platform dip and karren diameter, and a positive relationship with

Table 6.3 Statistical output from the multiple regression of geologic variables with karren diameter, microrelief and density.

| Variable | Beta ($B$) | $Sr^2$ | $t$ |
|---|---|---|---|
| **Diameter ($N$ = 23)** | | | |
| Insoluble Residue | -0.4916 | 0.22 | 3.28 |
| Dip | -0.4278 | 0.16 | 2.84 |
| Grain Size | 0.3880 | 0.12 | 2.49 |
| Constant = 22.45<br>$e$ = 5.99 | Multiple $R^2$ = 0.61<br>Adjusted $R^2$ = 0.55 | $F$ = 9.85<br>*$F$ critical (0.05) = 3.13<br>(0.01) = 5.01 | ** $t$ critical<br>(0.05) = 2.09<br>(0.01) = 2.86 |
| **Microrelief ($N$ = 23)** | | | |
| Grain Size | 0.4406 | 0.17 | 2.62 |
| Insoluble Residue | -0.4226 | 0.16 | 2.61 |
| Dip | -0.3838 | 0.13 | 2.35 |
| Constant =10.42<br>$e$ = 3.42 | Multiple $R^2$ = 0.54<br>Adjusted $R^2$ = 0.47 | $F$ = 7.53<br>*$F$ critical (0.05) = 3.13<br>(0.01) = 5.01 | ** $t$ critical<br>(0.05) = 2.09<br>(0.01) = 2.86 |
| **Density ($N$ = 23)** | | | |
| Insoluble Residue | -0.5186 | 0.25 | 2.72 |
| Grain Size | 0.1781 | 0.03 | 0.90 |
| Dip | -0.1576 | 0.02 | 0.82 |
| Constant = 14.29<br>$e$ = 6.79 | Multiple $R^2$ = 0.37<br>Adjusted $R^2$ = 0.27 | $F$ = 3.64<br>*$F$ critical (0.05) = 3.13<br>(0.01) = 5.01 | ** $t$ critical<br>(0.05) = 2.09<br>(0.01) = 2.86 |

* For critical $F$ values refer to Shaw and Wheeler (1985, p. 349 and 350). Degrees of freedom are calculated by using the total number of independent variables ($v_1$ = 3), and $N$ (23) subtracted by the total number of variables (4) = $v_2$ = 19.

** For critical $t$ values refer to Shaw and Wheeler (1985, p. 339). Degrees of freedom are calculated by subtracting the total number of variables (4) from $N$ (23) = $v$ =19.

grain size. This means that the largest karren diameters are associated with the most pure rocks which have the largest average grain size, forming on gentle sloping platforms.

The multiple $R^2$ (0.60) in multivariate analysis refers to the coefficient of multiple determination, and the adjusted $R^2$ indicates the proportion of the variance in the dependent variable accounted for by the multivariate model, taking into account the small sample size. For karren diameter the adjusted $R^2$ is 0.55, or 55% of the variance in diameter is explained by the interaction of the three geologic variables. This leaves 45% variance unexplained by the regression model, as not all geologic factors involved in karren development are taken into account. A proportion of the unexplained variance would also be explained by the interaction of marine environment variables. It should be mentioned that log-transformation of the data did not improve upon the $R^2$ values. The original data are used even if conditions of normality are not met on a bivariate level, as departures from normality are not as important at the multivariate statistical level (Shaw and Wheeler, 1985). Transforming the data for multiple regression equations can also make statistical interpretations very difficult (Johnston, 1980). This $R^2$ value is higher than that for both karren microrelief and density, revealing that the proposed regression model is better suited for explaining variations in karren diameter than it is for microrelief and density.

The amount of individual variance explained by each of the independent variables is provided by the square of the part correlation ($Sr^2$). Part correlation values are similar to the $B$ coefficients in relation to their association with karren diameter, with the exception that part correlation measures the proportion of variance explained in karren diameter by the unique variance of each independent geologic variable. Insoluble residue has the highest $Sr^2$ (0.22) meaning that 22% of the variance in karren diameter is explained solely by the variance in insoluble residue percent, again revealing its importance in this regression model. In addition, the amount of common variance in the equation can be determined from the $Sr^2$ values. The sum of $Sr^2$ values in Table 6.3 is 0.50 and when subtracted from the multiple $R^2$ of 0.61, produces a value of 0.11, or 11% of the total variance in the model is explained by the combined interaction of insoluble residue, grain size and dip.

The $t$ values are used for significance testing of each of the independent variables, similar to the $F$ statistic which measures the significance of the overall regression equation. With reference to karren diameter, all three geologic variables are statistically significant at the 0.05 level of significance, and insoluble residue is significant at the 0.01 level of significance. This means that all variables in the model are pertinent in explaining intersite karren variation at western Newfoundland, with insoluble residue being the most significant of the three.

When looking at the parameters involved with karren microrelief and density, there are slight differences with the importance of the geologic variables. The $Sr^2$ values reveal that grain size is the most important geologic variable in explaining variations in karren microrelief, although all three are of similar importance and are significant at the 0.05 level of significance. Insoluble residue explains most of the variation in karren density and both grain size and dip are not anywhere near significant even at the 0.10 level of significance and, thus, at this point would be removed from the regression model. This leaves only one independent variable left in the equation (insoluble residue), illustrating that the proposed regression model is insignificant in relation to karren density.

The problem with the geology data set is that it isn't directly comparable to that for the marine environment. The marine environment analysis in Chapter 5 involves using data for each shoreline from the different sites, and there is no distinction between karren and non-karren areas. The same *EI* value for The Bar, for example, would represent both the karren and non-karren data (i.e. micropits or limited karren) used in the previous analysis. The multivariate geologic analysis just discussed also aggregates the data for each site into one value regardless of the number of different shoreline orientations. Thus, a data set has been constructed for the independent geologic variables, so that it is directly comparable to that for the marine environment in the swash zone (Table 6.4), with data for non-occurrences of karren excluded from this analysis. An average insoluble residue and grain size value were determined for those shorelines which had missing data, using an average value for that rock type. Shorelines which had missing platform dips were given an average dip for that peninsula or region, except for Daniel's Harbour where an average dip would not be representative of the platform morphology at that site (Figure 4.18). This allows the

Table 6.4 List of study sites and values for the independent geologic variables, in the supratidal swash zone, using the same scale of observations as that for the marine environment multivariate analysis.

| | Independent Variable | | |
|---|---|---|---|
| Site | Avg. Insoluble Residue (%) | Avg. Grain Size (mm) | Dip Angle (°) |
| **Port au Port Peninsula** | | | |
| Long Point SE | 9.12 | 0.63 | 24.5 |
| Long Point NW | 10.51 | 0.15 | 25 |
| The Bar | 5.40 | 0.96 | 18.5 |
| Port au Port East Bay | | | |
| E Shore | 5.60 | 0.30 | 23.5 |
| Aguathuna | 2.52 | 0.17* | 20 |
| Ship Cove | 3.74 | 1.60 | 12 |
| Lower Cove | 4.11 | 2.01 | 12.5 |
| **Cow Head Peninsula Region** | | | |
| Cow Head Peninsula | | | |
| N Shore | 7.80* | 10.40* | 10 |
| WNW Shore | 12.50 | 9.50 | 12 |
| SW | 3.00 | 14.20 | 18 |
| SSE | 7.89 | 7.50 | 20 |
| Broom Point North | 10.05 | 0.40 | 36 |
| Broom Point South | 9.71 | 10.50 | 36 |

* refers to an average insoluble residue and grain size value associated with that rock type

** refers to an average slope in the swash zone for the Port au Choix Peninsula

Table 6.4 Continued.

| Site | Independent Variable: Avg. Insoluble Residue (%) | Avg. Grain Size (mm) | Dip Angle (°) |
|---|---|---|---|
| Stearing Island | 4.93 | 8.00 | 12 |
| Belldowns Island | 12.18* | 0.17* | 30 |
| Daniel's Harbour | 4.76 | 0.40 | 17.5* |
| **Port au Choix Peninsula Region** | | | |
| Port au Choix Peninsula | | | |
| N Shore | 8.96 | 0.60 | 15 |
| NW Shore | 5.27 | 0.10 | 0 |
| W Shore | 12.71 | 0.40 | 7.5** |
| Pointe Riche Peninsula | | | |
| WNW Shore | 5.74 | 0.40* | 20 |
| W Shore | 7.63 | 0.40 | 17 |
| S Shore | 8.29 | 0.30 | 3 |
| Ingornachoix Bay | 4.04 | 0.17 | 10 |
| Gargamelle Cove | 6.54* | 0.17* | 2 |
| **Cook's Harbour Region** | | | |
| Cape Norman | 2.74 | 0.10 | 3 |
| E Cape Norman | 4.32 | 0.17* | 0 |
| W Cape Norman | 1.98 | 0.17* | 0 |

* refers to an average insoluble residue and grain size value associated with that rock type

new data set to be used for a multivariate analysis without any missing observations, and also increases the total number of observations to 27.

The zero-order correlation matrix is provided in Table 6.5 and the statistical output for karren diameter in Table 6.6. Again, multicollinearity between the independent geologic variables is not a factor. Karren diameter is the only karren measurement presented here, as it is the only equation statistically significant at the 0.05 level of significance ($F$ = 4.38; microrelief $F$ = 2.35; density $F$ = 0.18). However, the adjusted $R^2$ is 10% lower than that for karren diameter with the previous data set. The $B$ and $Sr^2$ values reveal that all three geologic variables are roughly of equal importance in explaining variations in karren diameter, yet none of them are statistically significant at the 0.05 level of significance ($t$ value).

These results indicate that the newly defined geology data set is not much of a factor in explaining intersite karren variation. This shows that geologic factors, such as insoluble residue, grain size and dip, are not as important when it comes to explaining intersite karren variation, when values for non-karren areas are not included in the analysis. It is also possible that the increased number of observations produced more variation with the values of the independent variables, both within each one individually and when comparing trends between them. For example, there is remarkable variation in insoluble residue values for the Cow Head Peninsula, despite consistently high values in the karren measurements (Table 5.40 and 6.4). This will minimize the strength of the relationship between insoluble residue and karren development, even though it has been established that the insoluble residue percent strongly affects the degree of karren development that will occur (Sec. 2.2.4 and 5.3.4A). As discussed in Section 5.3.2, the amount of impurities a rock may have can be quite variable. It is possible that the chip samples used for analysis had a higher percent of impurities than that for the general area where the karren have been forming, despite the close proximity of the chips to the karren pits.

### 6.2.2 Marine Environment Analysis

For the analysis of the marine environment, the dependent karren data from Table 5.40 is

Table 6.5 Zero-order correlations of the independent geologic variables involved in the multivariate analysis, using a scale of observations directly comparable to that used for the marine environment variables.

| | Insoluble Residue | Grain Size | Dip |
|---|---|---|---|
| Insoluble Residue | 1.00 | 0.11 | 0.28 |
| Grain Size | 0.11 | 1.00 | -0.08 |
| Dip | 0.28 | -0.08 | 1.00 |

used with *EI*, onshore and offshore gradient. Any missing offshore and onshore values were substituted with an average value for that peninsula or region. No average offshore gradient values were provided for shorelines adjacent to very shallow water (e.g. Belldowns Island and Cow Head Peninsula, SSE shoreline; Figure 4.2), where virtually no gradient exists, and no average onshore gradient value was provided for Daniel's Harbour, for reasons already discussed. This is not a problem for a small amount of missing data did not affect the statistical output. The zero-order correlation matrix in Table 6.7 reveals no significant problems of multicollinearity.

The statistical output for the marine environment multivariate regressions, involving karren diameter and density are provided in Table 6.8. Microrelief was not statistically significant at the 0.05 level of significance ($F$ = 1.63). The intercept value (constant) for karren diameter is 10.31, meaning that when the independent variables are equal to zero, karren diameter is 10.31 cm. The $B$ coefficients and $Sr^2$ values reveal that *EI* has the strongest influence on karren diameter, explaining 87% of the total variance explained by the model (multiple $R^2$ = 0.46). There exists only 3% common variance between the three variables, and offshore and onshore gradient are not anywhere near significant at the 0.05 level of significance ($t$ statistic). Thus, although the overall equation is significant at both the 0.05 and 0.01 levels of significance ($F$ = 5.72), most of this is a function of *EI*, with increasing *EI* producing a corresponding increase in karren diameter.

Table 6.6 Statistical output from the multiple regression of geologic variables with karren diameter, using data directly comparable to that used for the marine environment.

| Variable | Beta ($B$) | $Sr^2$ | $t$ |
|---|---|---|---|
| **Diameter ($N$ = 27)** | | | |
| Insoluble Residue | -0.3501 | 0.11 | 2.00 |
| Dip | -0.3252 | 0.10 | 1.86 |
| Grain Size | 0.2775 | 0.07 | 1.65 |
| Constant = 22.93<br>$e$ = 7.13 | Multiple $R^2$ = 0.36<br>Adjusted $R^2$ = 0.28 | $F$ = 4.38<br>*$F$ critical (0.05) = 3.03<br>(0.01) = 4.76 | ** $t$ critical<br>(0.05) = 2.07<br>(0.01) = 2.81 |

* For critical $F$ values refer to Shaw and Wheeler (1985, p. 349 and 350). Degrees of freedom are calculated by using the total number of independent variables ($v_1$ = 3), and $N$ (27) subtracted by the total number of variables (4) = $v_2$ = 23.

** For critical $t$ values refer to Shaw and Wheeler (1985, p. 339). Degrees of freedom are calculated by subtracting the total number of variables (4) from $N$ (23) = $v$ =23.

The $R^2$ is almost 10% higher for karren density compared with diameter but again most of the variation in density is explained by only one variable (onshore gradient, $Sr^2$ = 0.37), although at least offshore gradient is statistically significant at the 0.10 level of significance ($t$ critical = 1.71). Onshore gradient explains almost 70% of the total variance (multiple $R^2$ = 0.53), with an increase in the onshore gradient producing a corresponding increase in karren density. This makes sense as the overall onshore gradient of a platform is somewhat similar to dip, where increasing the slope of the onshore littoral zone will decrease karren diameter, at least in the swash zone, thereby increasing the density of the pits. It is interesting, though, that there is a fairly strong relationship between $EI$ and karren diameter, but no relationship at all with density, when one would expect somewhat of an inverse relationship between the two. Increasing $EI$ should produce a decrease in karren density yet this is not the case. It may be that many exposed sites have higher densities due

Table 6.7 Zero-order correlations of the independent marine environment variables involved in the multivariate analysis.

| | Exposure Index | Offshore Gradient | Onshore Gradient |
|---|---|---|---|
| Exposure Index | 1.00 | -0.04 | -0.17 |
| Offshore Gradient | -0.04 | 1.00 | 0.16 |
| Onshore Gradient | -0.17 | 0.16 | 1.00 |

to the onshore gradient and/or geology. It should be noted that the constant for karren density is a negative number (-6.07). This number is not directly interpretable and, thus, the constant can be forced through the origin (0), similar to that for bivariate regressions.

Thus, although the adjusted $R^2$ values from these equations are reasonably high for both karren diameter and density, most of the variance in karren development can be explained by variations in *EI* and onshore gradient. Even when working in conjunction with other marine environment variables, there are almost no direct effects of offshore gradient with karren development. It is clear, however, that there are some very exposed sites which would receive a higher intensity of wave energy if the offshore gradient was steeper and allowed the waves to break directly onto the onshore littoral platform.

## 6.3 Discussion on the Importance of Geology and the Marine Environment on Karren Development

It is apparent from the previous section that the marine environment is significantly more important than geology in explaining intersite karren diameter and density variations in the supratidal swash zone. The adjusted $R^2$ values for karren diameter and density are much higher for the marine environment, especially with density where the $R^2$ is 46% higher than that for geology (0.46 to 0.00). It should be noted that the adjusted $R^2$ values for karren microrelief are very low for both groups of variables, with an $R^2 = 0.14$ for geology and an $R^2 = 0.08$ for the marine environment

Table 6.8 Statistical output from the multiple regression of marine environment variables with karren diameter and density.

| Variable | Beta ($B$) | $Sr^2$ | $t$ |
|---|---|---|---|
| **Diameter ($N$ = 27)** | | | |
| Exposure Index | 0.6440 | 0.40 | 3.86 |
| Offshore Gradient | 0.1421 | 0.02 | 0.86 |
| Onshore Gradient | -0.1168 | 0.01 | 0.69 |
| Constant = 10.31<br>$e$ =6.84 | Multiple $R^2$ = 0.46<br>Adjusted $R^2$ = 0.38 | $F$ = 5.72<br>*$F$ critical (0.05) = 3.03<br>(0.01) = 4.76 | ** $t$ critical<br>(0.05) = 2.07<br>(0.01) = 2.81 |
| **Density ($N$ = 27)** | | | |
| Onshore Gradient | 0.6222 | 0.37 | 3.96 |
| Offshore Gradient | 0.3053 | 0.09 | 1.97 |
| Exposure Index | 0.0391 | 0.00 | 0.25 |
| Constant = -6.07<br>$e$ = 9.76 | Multiple $R^2$ = 0.53<br>Adjusted $R^2$ = 0.46 | $F$ =7.56<br>*$F$ critical (0.05) = 3.03<br>(0.01) = 4.76 | ** $t$ critical<br>(0.05) = 2.07<br>(0.01) = 2.81 |

* For critical $F$ values refer to Shaw and Wheeler (1985, p. 349 and 350). Degrees of freedom are calculated by using the total number of independent variables ($v_1$ = 3), and $N$ (27) subtracted by the total number of variables (4) = $v_2$ = 23.

** For critical $t$ values refer to Shaw and Wheeler (1985, p. 339). Degrees of freedom are calculated by subtracting the total number of variables (4) from $N$ (23) = $v$ =23.

It is interesting that most of the explained intersite karren variation, with respect to geology, is roughly explained equally by all three variables, albeit at an overall low level of explanation. This is in contrast to that for the marine environment group of variables, where most of the explained karren variation is almost solely explained by one variable; *EI* for karren diameter and onshore gradient for density.

In order to better assess the importance of these two groups of variables on karren development, all six independent variables were combined into one multivariate equation. The interaction of all variables together may also provide a stronger explanation of intersite karren variation. A zero-order correlation matrix (Table 6.9) reveals no significant problems with multicollinearity, except for insoluble residue and *EI* (-0.47), although the correlation is only slightly above the 0.40 acceptable limit and these are two completely different variable measurements.

The statistical output for karren diameter and microrelief (Table 6.10), as well as density (Table 6.11), provide the results of the combined multivariate regression model. *EI* (diameter; $Sr^2 = 0.11$) and onshore gradient (density; $Sr^2 = 0.36$) explain most of the variation in these karren measurements, and only onshore gradient, with respect to density, is significant at the 0.05 level of significance ($t = 3.90$). Since none of the other variables are statistically significant at the 0.05 level, the focus here is on the $Sr^2$ values produced from the regressions, in order to assess the relative importance of each variable in affecting karren development.

The individual $Sr^2$ values for each of the independent variables, from the three multiple regression equations, are added together to produce a total $Sr^2$ value for karren development (Table 6.12). This table gives an indication of the importance of each variable in explaining intersite karren variation in the supratidal swash zone of western Newfoundland. It is clear that all of the marine environment variables are more important than geology ($Sr^2 = 0.65$ vs 0.28 for geology) in explaining variations in karren development, with onshore gradient being the most important from its high value for density. Thus, the marine environment appears to be more important than geology in determining the degree of karren development at a given site. When directly comparing sites with similar marine environments (e.g. SW shore of Cow Head Peninsula and W shore of Pointe Riche

Table 6.9 Zero-order correlations of the independent geologic and marine environment variables involved in an overall multivariate analysis of karren development.

| | Insoluble Residue | Grain Size | Dip | Exposure Index | Offshore Gradient | Onshore Gradient |
|---|---|---|---|---|---|---|
| Insoluble Residue | 1.00 | 0.13 | 0.19 | -0.47 | 0.11 | 0.05 |
| Grain Size | 0.13 | 1.00 | -0.08 | 0.07 | 0.10 | -0.11 |
| Dip | 0.19 | -0.08 | 1.00 | -0.33 | -0.26 | 0.03 |
| Exposure Index | -0.47 | 0.07 | -0.33 | 1.00 | 0.16 | -0.12 |
| Offshore Gradient | 0.11 | 0.10 | -0.26 | 0.16 | 1.00 | 0.16 |
| Onshore Gradient | 0.05 | -0.11 | 0.03 | -0.12 | 0.16 | 1.00 |

Peninsula; Table 5.40 and 5.44), however, karren development is not identical, so geology may be more important at certain sites depending on the rock types involved. As mentioned, insoluble residue may have been more significant were it not due to some data inconsistencies at this level of study. The original total $Sr^2$ for insoluble residue is 0.63, when the insoluble residue values are averaged for many of the study sites (Table 6.3), and is almost twice as important as the other two geologic variables in that data set. This is opposed to a total $Sr^2$ of only 0.20 for insoluble residue, when the data set was expanded to represent different shorelines. It also reveals the importance of insoluble residue when comparing karren and non-karren sites.

Thus, despite the small number of observations and the exclusion of some important geologic factors (e.g. percent dolomite), there are two preliminary, yet firm, conclusions which can be drawn from the results presented in this chapter. First, geology, especially insoluble residue, is the most important factor in determining whether karren will develop beyond the scale of micropits at a given shoreline, regardless of how exposed that shoreline is to the open marine environment. This was evident with the bivariate insoluble residue regressions presented in Section 5.3.4A (Figure 5.18). Second, when strictly comparing sites where karren do exist at a measurable scale, it seems that the marine environment might

Table 6.10 Statistical output from the multiple regression of geologic and marine environment variables with karren diameter and microrelief.

| Variable | Beta ($B$) | $Sr^2$ | $t$ |
|---|---|---|---|
| **Diameter ($N$ = 27)** | | | |
| Exposure Index | 0.3993 | 0.11 | 1.87 |
| Grain Size | 0.2460 | 0.06 | 1.36 |
| Dip | -0.2401 | 0.05 | 1.26 |
| Insoluble Residue | -0.1529 | 0.03 | 0.74 |
| Onshore Gradient | -0.1135 | 0.01 | 0.63 |
| Offshore Gradient | -0.0213 | 0.00 | 0.11 |
| Constant =17.54<br>$e$ = 7.32 | Multiple $R^2$ = 0.48<br>Adjusted $R^2$ = 0.29 | $F$ =2.58<br>*$F$ critical (0.05) = 3.10<br>(0.01) = 4.94 | ** $t$ critical<br>(0.05) = 2.09<br>(0.01) = 2.86 |
| **Microrelief ($N$ = 27)** | | | |
| Insoluble Residue | -0.2512 | 0.04 | 1.07 |
| Onshore Gradient | -0.1759 | 0.03 | 0.86 |
| Dip | -0.1831 | 0.03 | 0.85 |
| Grain Size | 0.1678 | 0.03 | 0.82 |
| Offshore Gradient | 0.1717 | 0.03 | 0.80 |
| Exposure Index | 0.1862 | 0.02 | 0.77 |
| Constant =11.57<br>$e$ = 6.96 | Multiple $R^2$ = 0.34<br>Adjusted $R^2$ = 0.10 | $F$ =1.43<br>*$F$ critical (0.05) = 3.10<br>(0.01) = 4.94 | ** $t$ critical<br>(0.05) = 2.09<br>(0.01) = 2.86 |

* For critical $F$ values refer to Shaw and Wheeler (1985, p. 349 and 350). Degrees of freedom are calculated by using the total number of independent variables ($v_1$ = 6), and $N$ (27) subtracted by the total number of variables (7) = $v_2$ = 20.

** For critical $t$ values refer to Shaw and Wheeler (1985, p. 339). Degrees of freedom are calculated by subtracting the total number of variables (7) from $N$ (27) = $v$ =20.

Table 6.11 Statistical output from the multiple regression of geologic and marine environment variables with karren density.

| Variable | Beta ($B$) | $Sr^2$ | $t$ |
|---|---|---|---|
| **Density ($N$ = 27)** | | | |
| Onshore Gradient | 0.6239 | 0.36 | 3.90 |
| Offshore Gradient | 0.3267 | 0.09 | 1.94 |
| Insoluble Residue | -0.2081 | 0.03 | 1.14 |
| Exposure Index | 0.0660 | 0.00 | 0.35 |
| Grain Size | -0.0340 | 0.00 | 0.25 |
| Dip | 0.0305 | 0.00 | 0.18 |
| Constant = -1.08<br>$e$ = 9.89 | Multiple $R^2$ = 0.59<br>Adjusted $R^2$ = 0.45 | $F$ = 4.09<br>*$F$ critical (0.05) = 3.10<br>(0.01) = 4.94 | ** $t$ critical<br>(0.05) = 2.09<br>(0.01) = 2.86 |

* For critical $F$ values refer to Shaw and Wheeler (1985, p. 349 and 350). Degrees of freedom are calculated by using the total number of independent variables ($v_1$ = 6), and $N$ (27) subtracted by the total number of variables (7) = $v_2$ = 20.

** For critical $t$ values refer to Shaw and Wheeler (1985, p. 339). Degrees of freedom are calculated by subtracting the total number of variables (7) from $N$ (27) = $v$ =20.

Table 6.12 Total $Sr^2$ values for marine environment and geologic variables in relation to karren diameter, microrelief and density in the supratidal swash zone.

| Variable | Total $Sr^2$ |
| --- | --- |
| **Marine Environment** | |
| Onshore Gradient | 0.40 |
| Exposure Index | 0.13 |
| Offshore Gradient | 0.12 |
| Total | 0.65 |
| **Geologic** | |
| Insoluble Residue | 0.10 |
| Grain Size | 0.09 |
| Dip | 0.09 |
| Total | 0.28 |

be more important than geology in explaining overall intersite variations in karren development, although there are some sites where geology may be more significant. In order to verify the proposed results, there needs to be more sites which have similar marine environments, but are different in terms of geology. It also would have been good if there existed several very exposed sites (e.g. Cook's Harbour region) and very sheltered sites (e.g. Bay of Islands area near Cornerbrook; Figure 3.1) which possess a similar geology, so that the effects of the marine environment on karren development can be better isolated. There were no such comparisons provided from the western Newfoundland study sites.

# CHAPTER 7

# CONCLUSIONS AND FUTURE RESEARCH

## 7.1 Intrasite Karren Variation

Across the onshore littoral zone karren diameter and microrelief generally increase in size with increasing height above the MLWM (excluding the supratidal spray zone). This produces a corresponding inverse relationship between karren density and height above the MLWM, although a slightly different combination of sites was used for density. In all cases the $r^2$ values would probably be higher, as indicated by the strong morphologic trends presented in Section 5.2.1., if it wasn't necessary to combine sites with different lithologies and marine environments into one data set. Although maximum karren dimensions are often found in the backshore, karren are more abundant and consistently spectacular in the supratidal swash zone. This may be because the bedrock in that zone receives maximum wave/swash energy on a more regular basis than the backshore and intertidal zones. There may also be some correlation between karren development and degree of subaerial exposure, with the supratidal swash zone providing an optimum balance between subaerial and subaqueous exposure necessary for maximum karren development. More detailed process work would be required to verify if any such relationship exists.

This intrasite trend in karren development is different from those studied at other temperate region karren sites. The karren models at Galway Bay, the Bristol Channel and Vancouver Island all reveal maximum karren development in the mid-intertidal zone, decreasing in size both seaward and landward from that point. This is probably due to the larger meso- and macro tidal ranges at these regions, allowing a higher magnitude of erosion to be concentrated in the intertidal zone, as opposed to the supratidal swash and backshore zones. The horizontal extent of the intertidal zone was very limited for many of the western Newfoundland study sites, due to the microtidal regime of the Gulf of St. Lawrence and the morphology of some of the shorelines. Also, karren zones for Galway Bay are directly correlated with bioerosion, and biological species colonization within the intertidal zone, and it is clear that bioerosion is not as important in developing karren at western Newfoundland.

There were no established relationships between SpC or pH and karren development, despite variations in these seawater properties across the littoral zone. This does not discount the importance of ionic strength (SpC), or acidity level (pH), on rates of chemical dissolution of limestone and dolomite solubility, as geologic and marine environment factors probably obscure the existence of a more significant association. The general increase in alkalinity towards the backshore may be indicative of more aggressive waters, necessary to facilitate chemical erosion in these isolated rock pools. The diurnal study at the Pointe Riche Peninsula reveals an increase in concentrations of $Ca^{2+}$ and $HCO_3^-$ in association with the increase in pH during the day, at least in the upper-intertidal and supratidal swash zone rock pools, which is an indication that extra limestone dissolution is occurring during this time.

## 7.2 Intersite Karren Variation

Variations in karren development between the four major study regions were studied with respect to variations in geologic and marine environment factors. Average karren dimensions are significantly smaller on dolomite and calcareous siltstones than on the different types of limestone, due to the reduced solubility of these rocks. Dolomite produces consistently small, high density pitting upon the rock surface, regardless of the littoral zone location of the rock. An increase in the percent dolomite of a limestone will produce a corresponding decrease in the size of the karren. Karren are somewhat larger than expected in association with calcareous siltstones, for larger karren will form where there is a reduced amount of insoluble silt present in the rock. An inverse relationship was defined with insoluble residue and karren development, especially in the supratidal swash zone, with an increased percentage of impurities producing smaller karren, until a point is reached (about 10-12%) where the insoluble residue is high enough to completely retard karren formation.

Even though finer-grained rocks are considered the most soluble, a positive, logarithmic relationship was established between karren development and grain size, which is strongest in the supratidal swash zone. That is, an increase in the average grain size of a rock is associated with larger karren formations. This may also be a function of the increased heterogeneity existing in many of the grain-supported rocks found at western Newfoundland, as the amount of surface area exposed to the erosion processes is increased. Many fine-grained mudstone and wackestone rocks possess a relatively uniform texture throughout the rock sample reducing rock solubility. The increased percentage of micrite existing in many of these finer-grained rocks, also reduces the size of the karren in all littoral zones. Results were inconclusive when comparing karren development with different types of allochems present in limestone.

The only significant relationship with platform structure and karren development occurred in the intertidal zone, where an increase in dip produces an exponential increase in karren diameter and microrelief. This may be a function of increased surface roughness produced from the steeper platform slope, thereby helping focus wave energy upon these areas and enhancing karren development. At the same time, though, there was minimal correlation with dip and the size of karren in supratidal swash and backshore zones, with the largest karren forming on horizontal or gentle dipping strata. Direction of dip is not a factor in influencing karren development in any littoral zone.

When comparing the effects of the marine environment on karren development, it was evident that degree of exposure ($\Delta E$, overall fetch and $EI$ ) is more important than offshore and onshore gradient on an interregional level. There was almost no correlation with offshore gradient and karren development in any zone. Analyses of $\Delta E$ effects on karren development produced some relation with diameter, but the $\Delta E$ data set only takes into account sites where there existed shingle, so it is not a complete representation of the study area. Overall fetch and $EI$ also have some marginally significant relationships with karren morphology in the supratidal swash and backshore zones. Overall fetch explains karren variation significantly better than $EI$ in the backshore, even though *EI* takes into account wind velocity and frequency. Analyses of all exposure variables revealed an increase in karren size with increased exposure, yet this trend did not always hold true on the intraregional level. There were several significant relationships on an intraregional level between measures of exposure and gradient, and karren development even though the scale of analysis involved a very small number of observations.

The multivariate analyses in Chapter 6 revealed some interesting results for the supratidal swash zone. Geologic factors, especially insoluble residue, are the most important factor in determining whether karren will develop beyond the scale of micropits at a given coastal site, regardless of how exposed that shoreline is to the open marine environment. This was evident in the $r^2$ values derived from the bivariate regressions in Chapter 5, as well as comparing the difference in karren development between limestone and dolomite rock. When only comparing sites where karren do exist at a measurable scale, however, then the marine environment may be more important than geology in explaining variations in karren development. More research is required to verify these findings, preferably at a region where the separate effects of geology and the marine environment on karren development can be better studied.

It was found from field observations that there appears to be no effect of the seasonal sea ice on karren development. Instead the sea ice acts as a buffer when it is fast to the shore, protecting the karren assemblages from the harsh winter climate of Atlantic Canada.

## 7.3 Future Research

It is clear that the conclusions derived here can only be considered preliminary results. Many of the bivariate regressions involved small data sets, as sites were aggregated together in an attempt to try and minimize the effects that other variables may have on karren development. The multivariate analyses, in particular, should really be based on much larger data sets than the regressions presented in Chapter 6. It would have been ideal if western Newfoundland provided enough study sites (at least 30) with approximately the same geology and marine environment, to establish more statistically sound intrasite trends in karren development. The intersite karren analysis would have been much improved if one or two regions possessed shorelines with the same geology, but quite different marine environments, so as to better study the effects of the marine environment on karren development. Conversely, more sites are needed with similar marine environments, but different carbonate rock types to better analysis geologic effects on karren.

There are three major projects for possible future research that were not undertaken in this thesis. First, this work is a morphology-based project which did not involve detailed measurements of the erosion processes forming the karren. There is the potential for significant amounts of work in this area at western Newfoundland, especially with an accurate determination of the importance of chemical dissolution in producing karren. Detailed water chemistry analysis of the littoral zone rock pools can be performed *in situ,* taking into account the complex chemistry of seawater, so that accurate littoral, and diurnal, patterns of chemical variation can be produced and correlated with karren development. Second, a much more detailed survey of karren offshore could be performed, to determine whether karren are present at sites and depths not surveyed for this project. Lower subtidal and offshore bioerosion may also be more of a factor in forming karren (Figure 4.34) than it is above the MLWM. Third, there appear to be some sites where the karren are significantly higher than the present MLWM, even allowing for the intense late autumn storms that western Newfoundland experiences (e.g. Lower Head). There may be a correlation with these karren formations and relative sea level changes for western Newfoundland since the Wisconsinan glaciation, but this possibility was not explored in this project.

# APPENDIX A

## PETROLOGICAL CLASSIFICATION AND DESCRIPTION OF INDIVIDUAL ROCK SAMPLES

**Table A1** Rock samples taken from the western Newfoundland karren study sites.

| Site (sample) | Rock Type* | % Carbonate | % Dolomite | Allochems Type | Allochems Size (mm) Avg./ Max. | Matrix |
|---|---|---|---|---|---|---|
| **Port au Port Pen.** | | | | | | |
| Long Pt. | | | | | | |
| LP1 | calcareous siltstone | 20 - 25 | < 5 | lithoclasts<br>pellets | 0.4 / 4.5<br>0.15 / 0.25 | > 95% spar |
| LP2 | argillaceous wackestone | 70 - 75 | < 5 | peloids | 0.6 / 1.0 | > 95% spar |
| LP3 | wackestone | 90 - 95 | < 5 | peloids + bioclasts<br>pellets | 0.8 / 2.0<br>0.2 / 0.6 | > 95% spar |
| LP4 | calcareous siltstone | 30 - 40 | < 5 | NA | NA | > 95% spar |
| LP5 | wackestone | 90 - 95 | < 1 | peloids + bioclasts | 0.4 / 1.4 | > 95% spar |
| LP6 | wackestone | 90 - 95 | < 1 | peloids | 1.3 / 2.0 | > 95% spar |
| LP7 | wackestone | > 95 | < 1 | peloids + bioclasts | 1.6 / 10.9 | > 95% spar |

* based on the Embry and Klovan (1971) classification of limestone rocks

**Table A1** Continued.

| Site (sample) | Rock Type* | % Carbonate | % Dolomite | Allochems Type | Allochems Size (mm) Avg./ Max. | Matrix |
|---|---|---|---|---|---|---|
| The Bar | | | | | | |
| TB1 | grainstone | > 95 | trace | aggregrate grains and peloids | 1.6 / 4.5 | > 90% spar |
| TB2 | grainstone | > 95 | < 5 | lithoclasts<br>peloids | 2.2 / 5.0<br>0.6 / 1.4 | > 90% spar |
| TB3 | grainstone | > 95 | trace | aggregate grains and peloids | 0.7 / 3.0 | > 90% spar |
| TB4 | packstone | 90 - 95 | < 5 | lithoclasts<br>peloids | 5.1 / 6.5<br>0.8 / 2.2 | > 90% spar |
| TB5 | grainstone | > 95 | < 5 | aggregate grains and peloids | 0.7 / 2.3 | > 95% spar |
| TB6 | wackestone | > 95 | trace | peloids + bioclasts | 0.15 / 0.90 | > 70% spar |
| TB7 | argillaceous wackestone | 85 - 90 | < 5 | peloids | 0.30 / 0.65 | > 85% spar |
| TB8 | grainstone | 90 - 95 | < 5 | peloids + bioclasts | 1.3 / 2.0 | > 95% spar |
| TB9 | argillaceous wackestone | 80 - 85 | < 5 | peloids | 0.3 / 1.0 | > 70% spar |
| TB10 | argillaceous wackestone | 50 - 60 | < 5 | clay ?<br>Bioclasts | 0.6 / 3.2<br>0.5 / 1.0 | Silt + clay |
| TB11 | dolomitic siltstone | 15 - 20 | 15 - 20 | dolomite rhombs | 0.8 / 1.17 | Silt + quartz |

* based on the Embry and Klovan (1971) classification of limestone rocks

**Table A1** Continued.

| Site (sample) | Rock Type* | % Carbonate | % Dolomite | Allochems Type | Allochems Size (mm) Avg./ Max. | Matrix |
|---|---|---|---|---|---|---|
| Three Rock Pt. | argillaceous wackestone | 80 - 85 | < 5 | peloids | 0.4 / 1.4 | > 95% spar |
| Jerrys Nose | dolomite | 90 - 95 | > 90 | dolomite rhombs | 0.15 / 1.45 | dolomite |
| Ship Cove | | | | | | |
| SC1 | argillaceous mudstone | 60 - 70 | 5 - 10 | peloids + dolomite rhombs | 0.12 / 0.17 | > 95% micrite |
| SC2 | wackestone | > 95 | 5 - 10 | peloids | 1.6 / 4.0 | > 95% micrite |
| Lower Cove | | | | | | |
| LC1 | rudstone | 90 - 95 | < 5 | peloids | 2.3 / 5.4 | > 70% micrite |
| LC2 | grainstone-packstone | > 95 | 5 - 10 | peloids | 1.7 / 12.0 | > 90% micrite |
| LC3 | mudstone | > 95 | trace | pellets | 0.3 / 0.5 | > 70% micrite |
| LC4 | rudstone | > 95 | < 5 | peloids + bioclasts | 3.6 / 10.8 | > 95% spar |
| LC5 | dolomitic packstone - grainstone | > 95 | 20 - 30 | peloids + bioclasts | 1.4 / 5.0 | > 70% micrite |
| LC6 | dolomitic rudstone | > 95 | 20 - 30 | peloids | 1.9 / 6.0 | > 75% spar |

* based on the Embry and Klovan (1971) classification of limestone rocks

**Table A1** Continued.

| Site (sample) | Rock Type* | % Carbonate | % Dolomite | Allochems Type | Allochems Size (mm) Avg./ Max. | Matrix |
|---|---|---|---|---|---|---|
| LC7 | rudstone - floatstone | > 95 | < 5 | peloids + bioclasts | 2.4 / 7.2 | > 70% spar |
| Port au Port East Bay | | | | | | |
| PE1 | mudstone | > 95 | < 1 | peloid | NA / 1.1 | > 70% micrite |
| PE2 | wackestone | > 95 | trace | peloids | 0.3 / 8.0 | > 85% micrite |
| PE3 | mudstone | 90 - 95 | < 5 | peloid | NA / 1.4 | > 70% micrite |
| PE4 | argillaceous rudstone - floatstone | 75 - 80 | trace | peloids + bioclasts | 12.2 / 45.0 | > 90% micrite + silt |
| PE5 | argillaceous mudstone | 70 - 75 | NA | peloid | NA / 1.2 | > 95% micrite + silt |
| **Cow Head Peninsula Region** | | | | | | |
| Cow Head Peninsula | | | | | | |
| CH1 | rudstone | 90 - 95 | < 5 | peloids | 9.5 / 29.0 | > 95% spar |

* based on the Embry and Klovan (1971) classification of limestone rocks

**Table A1** Continued.

| Site (sample) | Rock Type* | % Carbonate | % Dolomite | Allochems Type | Allochems Size (mm) Avg./ Max. | Matrix |
|---|---|---|---|---|---|---|
| CH2 | rudstone | 90 - 95 | < 5 | peloids + bioclasts | 10.0 / 56.0 | > 95% spar |
| CH3 | rudstone | > 95 | < 5 | peloids + grainstone clasts | 14.2 / 37.0 | 100% spar |
| CH4 | rudstone | 90 - 95 | NA | peloids + bioclasts | 7.5 / 23.0 | > 95% spar |
| CH5 | rudstone | 90 - 95 | 5 - 10 | peloids + bioclasts | 9.0 - 26.0 | > 70% silt and dolomite |
| CH6 | chert | 25 | < 5 | aggregate grains | 0.3 / 1.0 | > 70% chert |
| Stearing Island | floatstone | 90 - 95 | NA | peloids | 8.0 / 19.0 | > 80% micrite |
| Lower Head | floatstone | > 95 | NA | peloids | 4.3 / 9.0 | > 80% micrite |
| Broom Pt. | | | | | | |
| BP1 | argillaceous dolomitic mudstone | 85 - 90 | 20 - 30 | dolomite rhombs + peloids | 0.4 / 0.9 | > 95% micrite |
| BP2 | rudstone | 90 - 95 | NA | peloids | 10.5 / 33.0 | > 90% spar |
| Daniel's Harbour | packstone | > 95 | < 5 | peloids, bioclasts and aggregate grains | 0.40 / 1.8 | > 60 % spar |

* based on the Embry and Klovan (1971) classification of limestone rocks

**Table A1** Continued.

| Site (sample) | Rock Type* | % Carbonate | % Dolomite | Allochems Type | Allochems Size (mm) Avg./ Max. | Matrix |
|---|---|---|---|---|---|---|
| **Port au Choix Peninsula Region** | | | | | | |
| Port au Choix Peninsula | | | | | | |
| PC1 | rudstone | > 95 | < 5 | bioclasts + peloids | 1.6 / 9.0 | > 90% spar |
| PC2 | argillaceous wackestone | 75 - 80 | < 5 | bioclasts + peloids | 1.0 / 5.5 | > 70% spar |
| PC3 | calcareous siltstone | 20 - 30 | NA | NA | NA | > 95% silt |
| PC4 | calcareous siltstone | 40 - 50 | < 5 | NA | NA | > 90% silt / micrite |
| PC5 | dolomitic wackestone | > 95 | 20 - 25 | peloids | 0.9 / 2.5 | > 85% spar |
| PC6 | grainstone - packstone | 90 - 95 | < 5 | peloids + aggregate grains | 1.0 / 3.6 | 50% spar + micrite |
| PC7 | argillaceous dolomitic mudstone | 80 - 90 | 10 - 15 | peloid | NA / 2.7 | > 90% micrite |
| PC8 | dolomite | 90 - 95 | > 90 | dolomite rhombs | 0.2 / 0.7 | dolomite |

* based on the Embry and Klovan (1971) classification of limestone rocks

**Table A1** Continued.

| Site (sample) | Rock Type* | % Carbonate | % Dolomite | Allochems Type | Allochems Size (mm) Avg./ Max. | Matrix |
|---|---|---|---|---|---|---|
| PC9 | dolomite | > 95 | > 95 | dolomite rhombs | NA / NA | dolomite |
| PC10 | dolomitic mudstone | > 95 | 15 - 20 | peloids | 0.4 / 2.8 | > 90% micrite |
| Ingorna-choix Bay | | | | | | |
| IB1 | mudstone | > 95 | < 5 | bioclast | NA / 3.0 | > 80% micrite |
| IB2 | wackestone | 90 - 95 | 5 - 10 | peloids + bioclasts | 0.3 / 1.1 | >80% micrite |
| Pointe Riche Pen. | | | | | | |
| PR1 | dolomitic mudstone | 90 - 95 | 20 - 25 | NA | NA / NA | > 90% micrite |
| PR2 | calcitic chert | 30 - 40 | NA | NA | NA / NA | >90% chert - micrite |
| PR3 | dolomitic wackestone | 90 - 95 | 10 - 15 | peloids + bioclasts | 0.4 / 1.6 | > 70% micrite |
| PR4 | mudstone | 90 - 95 | 5 - 10 | peloid | NA / 6.0 | > 80% micrite |
| PR5 | mudstone | 90 - 95 | < 5 | peloids+ bioclasts | 0.3 / 3.4 | > 60% micrite |

* based on the Embry and Klovan (1971) classification of limestone rocks

**Table A1** Continued.

| Site (sample) | Rock Type* | % Carbonate | % Dolomite | Allochems Type | Allochems Size (mm) Avg./ Max. | Matrix |
|---|---|---|---|---|---|---|
| New Ferrolle Peninsula | | | | | | |
| NF1 | dolomite | > 95 | > 95 | dolomite rhombs | 0.2 / 0.5 | dolomite |
| NF2 | dolomite | > 95 | > 95 | dolomite rhombs | 0.5 / 0.8 | dolomite |
| **Cook's Harbour Region** | | | | | | |
| Cape Norman | | | | | | |
| CH1 | mudstone | > 95 | 5 - 10 | peloids | 0.1 / 0.3 | > 75% micrite |
| CH2 | dolomite | > 95 | > 95 | dolomite rhombs | 0.3 / 0.9 | dolomite |
| East Cape Norman | | | | | | |
| CNE1 | mudstone | > 95 | < 5 | peloid | NA / 2.3 | > 75% micrite |
| CNE2 | dolomitic mudstone | 90 - 95 | 25 - 30 | NA | NA / NA | > 90% micrite |

* based on the Embry and Klovan (1971) classification of limestone rocks

**Table A1** Continued.

| Site (sample) | Rock Type* | % Carbonate | % Dolomite | Allochems Type | Allochems Size (mm) Avg./ Max. | Matrix |
|---|---|---|---|---|---|---|
| West Cape Norman | | | | | | |
| CNW1 | mudstone | > 95 | < 5 | NA | NA / NA | > 80% micrite |
| CNW2 | dolomite | > 95 | > 95 | dolomite rhombs | NA / NA | dolomite |
| CNW3 | dolomite | 90 - 95 | > 90 | dolomite rhombs | NA / NA | dolomite |
| CNW4 | mudstone | 90 - 95 | < 5 | NA | NA / NA | > 85% micrite |
| Boat Harbour | dolomite | 90 - 95 | > 90 | dolomite rhombs | 0.4 / 1.1 | dolomite |

* based on the Embry and Klovan (1971) classification of limestone rocks

# APPENDIX B

# INSOLUBLE RESIDUE CALCULATIONS

The technique used to determine the insoluble residue of the 100 chip samples, taken from western Newfoundland, follows the standard method described in Carver (1971, p.483-484), with the results presented in Table B1. The location of the chip sample within the littoral zone are provided with the code for each sample. Thus, inter/swash k indicates a sample taken from a karren zone spanning the inter-and supratidal zones. If a sample has nk beside it then it was taken from a zone where there was no karren, and the term entire platform indicates a rock sample taken from a homogenous lithological area where karren existed, or was absent, throughout the littoral zone of the platform area. More samples were taken for insoluble residue calculations than for petrological analysis. Therefore, rocks with the same sample codes in this appendix compared with Appendix A may not refer to the same rock.

Weathered surfaces were first removed from the rock and about 50 g of the sample were sawn into small pieces to aid in the acid digestion of the rock. The rock was oven dried over a period of 24 hours to remove any moisture, with the resultant dry weight recorded in the first column. The rock pieces were then placed inside a large beaker and 9N (30%) hydrochloric acid (HCl) was poured over the sample until it was immersed in acid. Watch glasses covered the top of the beakers, to prevent any loss of sample when there was a vigorous reaction with the acid. Spent acid was decanted into a flask and fresh acid was added until no further reaction with the sample occurred. The contents of each beaker was decanted through filter paper and cleansed with distilled water. The filter paper containing the solid residue was oven dried for 24 hours and weighed (column two), with the weight of the filter paper then subtracted (column three). This produced the weight of the insoluble residue for the rock, which is then converted to a percentage of the original rock weight (column four) used in Chapter 5.

Table B1 Insoluble residue calculations for rock samples taken from the karren study sites along the coast of western Newfoundland.

| Sample (location) | Initial Dry Weight (g) | Dry Weight of Residue and Filter Paper (g) | Weight of Insoluble Residue (g) | Insoluble Residue % |
|---|---|---|---|---|
| **Port au Port Peninsula** | | | | |
| Long Point | | | | |
| LP1 (inter/swash - nk) | 50.0409 | 23.6176 | 21.6657 | 43.30 |
| LP2 (inter/swash - nk) | 50.0723 | 5.6544 | 4.1317 | 8.25 |
| LP3 (inter/swash - k) | 50.1180 | 6.7129 | 5.2653 | 10.51 |
| LP4 (inter/swash - nk) | 48.9055 | 26.8896 | 24.9377 | 51.00 |
| LP5 (inter/swash - k) | 50.1520 | 5.1939 | 3.6968 | 7.37 |
| LP6 (inter/swash - k) | 50.0147 | 6.2837 | 4.7440 | 9.49 |
| LP7 (inter/swash - nk) | 49.9952 | 3.3137 | 1.82273 | 3.65 |
| The Bar | | | | |
| TB1 (swash - k) | 50.3746 | 3.0575 | 1.4975 | 2.97 |
| TB2 (back - nk) | 50.2613 | 3.4898 | 1.9811 | 3.94 |
| TB3 (inter/swash - k) | 49.7975 | 2.6894 | 1.2291 | 2.47 |
| TB4 (back - nk) | 50.0676 | 4.1209 | 2.5983 | 5.19 |
| TB5 (inter/swash - k) | 49.8293 | 2.6289 | 1.1395 | 2.28 |
| TB6 (back - nk) | 50.0222 | 4.8589 | 3.3361 | 6.67 |
| TB7 (inter/swash - k) | 49.6155 | 6.5124 | 4.9835 | 10.04 |
| TB8 (inter/swash - k) | 49.7991 | 6.0746 | 4.6117 | 9.26 |
| TB9 (inter/swash - nk) | 49.2785 | 3.7914 | 2.2577 | 4.58 |
| TB10 (inter/swash - nk) | 50.0090 | 9.8754 | 8.3601 | 16.72 |
| TB11 (inter/swash - nk) | 49.2143 | 40.1274 | 38.1755 | 77.57 |

**Table B1** Continued.

| Sample (location) | Initial Dry Weight (g) | Dry Weight of Residue and Filter Paper (g) | Weight of Insoluble Residue (g) | Insoluble Residue % |
|---|---|---|---|---|
| Three Rock Point | | | | |
| TR1 (entire platform - nk) | 49.9775 | 7.8469 | 6.3586 | 12.72 |
| Port au Port East Bay | | | | |
| PE1 (inter/swash - k) | 50.1709 | 3.0565 | 1.4993 | 3.00 |
| PE2 (back - nk) | 50.2275 | 5.3465 | 4.0210 | 8.01 |
| PE3 (inter/swash - k) | 50.3695 | 2.7832 | 1.2715 | 2.52 |
| PE4 (back - nk) | 50.2465 | 4.3490 | 2.9467 | 5.86 |
| PE5 (inter/swash - k) | 50.3330 | 2.8926 | 1.3607 | 2.70 |
| PE6 (inter/swash - k) | 50.2271 | 7.8459 | 6.3306 | 12.60 |
| PE7 (entire platform - nk) | 49.4472 | 10.5468 | 9.0089 | 18.22 |
| Lower Cove | | | | |
| LC1 (inter/swash - k) | 49.7824 | 3.9350 | 2.4274 | 4.88 |
| LC2 (swash - k) | 49.9019 | 3.5408 | 2.0388 | 4.09 |
| LC3 (back - nk) | 49.5543 | 4.1028 | 2.5955 | 5.24 |
| LC4 (inter/swash - k) | 50.0593 | 2.7727 | 1.2587 | 2.51 |
| LC5 (swash - nk) | 50.1269 | 3.4589 | 1.9665 | 3.92 |
| LC6 (swash - nk) | 50.0507 | 3.6035 | 2.0905 | 4.18 |
| LC7 (inter/swash - nk) | 49.7852 | 4.8823 | 3.3739 | 6.78 |
| LC8 (inter/swash - k) | 49.8877 | 4.0162 | 2.4758 | 4.96 |
| LC9 (back - nk) | 49.8157 | 4.6074 | 3.1125 | 6.25 |
| LC10 (back - nk) | 49.8235 | 3.4417 | 1.9422 | 3.90 |
| LC11 (back - nk) | 50.0930 | 3.8795 | 2.3795 | 4.74 |

**Table B1** Continued.

| Sample | Initial Dry Weight (g) | Dry Weight of Residue and Filter Paper (g) | Weight of Insoluble Residue (g) | Insoluble Residue % |
|---|---|---|---|---|
| Ship Cove | | | | |
| SC1 (swash - k) | 50.2842 | 3.3918 | 1.8828 | 3.74 |
| SC2 (swash - nk) | 50.0521 | 6.6676 | 5.1355 | 10.26 |
| Jerrys Nose | | | | |
| JN1 (entire platform - nk) | 49.7150 | 4.5104 | 3.0421 | 6.12 |
| **Cow Head Peninsula Region** | | | | |
| Cow Head Peninsula | | | | |
| CH1 (inter/swash - k) | 49.2201 | 7.6815 | 6.1534 | 12.50 |
| CH2 (back - nk) | 49.8434 | 3.8133 | 2.3650 | 4.74 |
| CH3 (back - nk) | 50.4038 | 4.3238 | 2.8863 | 5.73 |
| CH4 (back - k) | 49.6021 | 3.4080 | 1.8949 | 3.82 |
| CH5 (back - nk) | 49.2104 | 8.2657 | 6.7976 | 13.81 |
| CH6 (back - nk) | 50.0476 | 4.6323 | 3.1022 | 6.20 |
| CH7 (inter/swash - nk) | 49.9417 | 44.6294 | 43.1610 | 86.42 |
| CH8 (swash - k) | 50.0773 | 5.4575 | 3.9501 | 7.89 |
| CH9 (entire platform - nk) | 49.7501 | 5.9209 | 4.4746 | 8.99 |
| CH10 (swash/back - k) | 50.0637 | 2.9470 | 1.5025 | 3.00 |
| CH11 (swash - nk) | 49.3475 | 39.5658 | 38.0414 | 77.09 |
| Stearing Island | | | | |
| ST1 (inter/swash - k) | 49.804 | 3.9798 | 2.4573 | 4.93 |

**Table B1** Continued.

| Sample (location) | Initial Dry Weight (g) | Dry Weight of Residue and Filter Paper (g) | Weight of Insoluble Residue (g) | Insoluble Residue % |
|---|---|---|---|---|
| Lower Head | | | | |
| LH1 (back - k) | 49.9222 | 2.7749 | 1.2657 | 2.54 |
| Daniel's Harbour | | | | |
| DH1 (swash/back - k) | 49.5796 | 3.8855 | 2.3568 | 4.76 |
| Broom Point | | | | |
| BP1 (swash/back - k) | 50.0681 | 6.3545 | 4.8605 | 9.71 |
| BP2 (inter - k) | 50.7343 | 6.5668 | 5.0980 | 10.05 |
| BP3 (entire platform - nk) | 50.2516 | 8.8778 | 7.3551 | 14.64 |
| **Port au Choix Peninsula Region** | | | | |
| Port au Choix Peninsula | | | | |
| PC1 (inter - k) | 49.8191 | 9.1025 | 7.6598 | 15.38 |
| PC2 (back - k) | 50.4019 | 3.4516 | 2.0054 | 3.98 |
| PC3 (entire platform - nk) | 49.7252 | 4.8826 | 3.3606 | 6.76 |
| PC4 (inter/swash - k) | 50.0981 | 6.1035 | 4.6717 | 9.33 |
| PC5 (entire platform - nk) | 49.9078 | 6.1855 | 4.6729 | 9.36 |
| PC6 (inter/swash - k) | 50.3538 | 5.7644 | 4.3216 | 8.58 |
| PC7 (entire platform - nk) | 50.3807 | 10.3554 | 8.8797 | 17.63 |
| PC8 (inter/swash - k) | 50.3073 | 4.1036 | 2.6520 | 5.27 |
| PC9 (back - nk) | 49.9739 | 2.9787 | 1.4787 | 2.96 |
| PC10 (swash - k) | 49.8501 | 3.3106 | 1.8758 | 3.76 |
| PC11 (back - nk) | 49.7877 | 6.9119 | 5.4371 | 10.92 |

**Table B1** Continued.

| Sample | Initial Dry Weight (g) | Dry Weight of Residue and Filter Paper (g) | Weight of Insoluble Residue (g) | Insoluble Residue % |
|---|---|---|---|---|
| PC12 (inter/swash - k) | 49.7918 | 7.7691 | 6.3273 | 12.71 |
| PC13 (inter/swash - nk) | 50.0117 | 6.2573 | 4.7398 | 9.48 |
| PC14 (back - k) | 50.0084 | 5.2205 | 3.7621 | 7.52 |
| PC15 (back - k) | 50.0267 | 3.9709 | 2.4699 | 4.94 |
| Pointe Riche Peninsula | | | | |
| PR1 (swash - k) | 50.6499 | 4.4012 | 2.9049 | 5.74 |
| PR2 (back - k) | 50.0171 | 4.4877 | 3.0189 | 6.04 |
| PR3a (swash - nk) | 49.6749 | 6.5074 | 4.9800 | 10.03 |
| PR3b (swash - nk) | 49.8810 | 43.8259 | 42.3200 | 84.85 |
| PR4 (inter - k) | 50.2705 | 5.2352 | 3.8352 | 7.63 |
| PR5 (back - k) | 50.0696 | 5.5850 | 4.1499 | 8.29 |
| PR6 (back - nk) | 50.0412 | 4.2516 | 2.7075 | 5.41 |
| Ingornachoix Bay | | | | |
| IB1 (entire platform - k) | 50.0479 | 3.5473 | 2.0201 | 4.04 |
| IB2 (inter/swash - nk) | 49.8933 | 8.2065 | 7.0055 | 14.04 |
| IB3 (back - nk) | 50.2379 | 4.3030 | 2.9370 | 5.85 |
| New Ferrolle Peninsula | | | | |
| NF1 (swash - nk) | 49.6889 | 2.7944 | 1.3259 | 2.67 |
| NF2 ( back - k) | 49.9194 | 3.4294 | 1.9681 | 3.94 |
| NF3 (back - nk) | 49.7593 | 5.2733 | 3.7681 | 7.57 |
| NF4 (back - k) | 50.1858 | 2.9858 | 1.5407 | 3.07 |

**Table B1** Continued.

| Sample | Initial Dry Weight (g) | Dry Weight of Residue and Filter Paper (g) | Weight of Insoluble Residue (g) | Insoluble Residue % |
|---|---|---|---|---|
| **Cook's Harbour Region** | | | | |
| Cape Norman | | | | |
| CN1 (swash - k) | 49.4144 | 2.8914 | 1.3515 | 2.74 |
| East of Cape Norman | | | | |
| CNE1 (swash - nk) | 49.8811 | 4.4789 | 3.0345 | 6.09 |
| CNE2 (swash/back - k) | 49.6380 | 2.9712 | 1.4627 | 2.95 |
| CNE3 (swash/back - k) | 49.9345 | 3.4133 | 1.9576 | 3.92 |
| West of Cape Norman | | | | |
| CNW1 (swash - k) | 49.7853 | 2.4673 | 0.9857 | 1.98 |
| CNW2 (back - k) | 49.5945 | 2.1548 | 0.6429 | 1.30 |
| CNW3 (inter - k) | 50.2408 | 4.8171 | 3.3856 | 6.74 |
| CNW4 (back - k) | 49.6724 | 4.1704 | 2.6788 | 5.39 |
| CNW5 (swash/back - nk) | 49.9553 | 7.6931 | 6.2035 | 12.41 |
| Boat Harbour Area | | | | |
| BH1 (entire platform - nk) | 49.7821 | 4.5338 | 3.0814 | 6.19 |

# APPENDIX C

## TABLES OF PLATFORM SLOPE ANGLE AND DIRECTION WITH KARREN DATA FOR EACH LITTORAL ZONE

Table C1 Dip Angles and Slope direction for platform rock hosting karren in the intertidal zone.

| Site | Dip Angle (°) | Slope Direction* | Average Diameter (cm) | Average Microrelief (cm) | Average Density (per $m^2$ quadrat) |
|---|---|---|---|---|---|
| **Port au Port Peninsula** | | | | | |
| Long Point T2** | 14.5 | scarp | 6.34 | 2.85 | 14.00 |
| Long Point T3 | 10 | scarp | 12.46 | 5.23 | 30.00 |
| The Bar T1 | 25 | scarp | 17.84 | 10.13 | 7.00 |
| The Bar T2 | 25 | scarp | 21.14 | 12.50 | 30.00 |
| Port au Port East Bay T1 | 17 | dip | 11.69 | 5.80 | 10.00 |
| Port au Port East Bay T2 | 20 | dip | 7.93 | 4.98 | 40.00 |
| Lower Cove T1 | 12 | dip | 6.33 | 3.12 | 25.00 |
| **Cow Head Peninsula Region** | | | | | |
| Cow Head Peninsula T1 | 20 | scarp | 18.59 | 8.38 | 4.00 |
| Broom Point T1 | 55 | dip | 8.18 | 3.84 | 6.00 |

* slope direction refers to the direction the dip angle is facing; scarp is a platform dip of the rock towards the land and dip slopes are towards the sea

** refers to the numbered transect (or quadrat) code for that site possessing intertidal karren

**Table C1** Continued.

| Site | Dip Angle (°) | Slope Direction* | Average Diameter (cm) | Average Microrelief (cm) | Average Density (per $m^2$ quadrat) |
|---|---|---|---|---|---|
| **Port au Choix Peninsula Region** | | | | | |
| Port au Choix Peninsula T1** | 5 | horizontal | 4.64 | 1.48 | 20.00 |
| Port au Choix Peninsula T2 | 4 | horizontal | 10.65 | 2.00 | 8.50 |
| Port au Choix Peninsula T3 | 0 | horizontal | 3.69 | 1.04 | 55.00 |
| Port au Choix Peninsula T4 | 14 | scarp | 4.50 | 2.12 | 20.00 |
| Pt. Riche Pen. T1 | 0 | horizontal | 3.98 | 1.33 | 50. 00 |
| Pt. Riche Pen. T2 | 10 | scarp | 11.85 | 2.46 | 8.50 |
| Pt. Riche Pen. T3 | 20 | dip | 8.28 | 4.28 | 18.50 |
| Pt. Riche Pen. T4 | 20 | dip | 13.00 | 2.09 | 8.00 |
| Pt. Riche Pen. T5 | 10 | dip | 27.97 | 7.50 | 6.50 |
| Ingornachoix Bay Study Area Avg. | 3 | horizontal | 5.02 | 2.55 | 52.54 |
| Gargamelle Cove Study Area Avg. | 3 | horizontal | 6.95 | 1.60 | 46.67 |
| **Cook's Harbour Region** T1 | 2 | horizontal | 3.51 | 1.44 | 100.00 |

* Slope direction refers to the direction the dip angle is facing; scarp is a platform dip of the rock towards the land and dip slopes are towards the sea. A platform slope of 5° or less is considered horizontal.

** refers to the numbered transect (or quadrat) code for that site possessing intertidal karren

Table C2 Dip angles and slope directions for platform rock hosting karren in the supratidal swash zone.

| Site | Dip Angle (°) | Slope Direction* | Average Diameter (cm) | Average Microrelief (cm) | Average Density (per $m^2$ quadrat) |
|---|---|---|---|---|---|
| **Port au Port Peninsula** | | | | | |
| Long Point T1** | 22 | scarp | 12.42 | 7.98 | 17.50 |
| Long Point T2 | 25 | scarp | 6.89 | 2.41 | 6.50 |
| Long Point T3 | 26 | scarp | 7.28 | 2.97 | 16.50 |
| The Bar T1 | 13 | scarp | 16.15 | 6.94 | 7.00 |
| The Bar T2 | 24 | scarp | 5.76 | 3.64 | 22.00 |
| The Bar T3 | 20 | scarp | 13.96 | 8.26 | 30.00 |
| The Bar T4 | 15 | scarp | 11.75 | 5.08 | 35.00 |
| The Bar T5 | 22 | dip | 16.50 | 6.03 | 8.00 |
| Port au Port East Bay T1 | 20 | dip | 3.06 | 1.37 | 15.00 |
| Port au Port East Bay T2 | 27 | dip | 5.88 | 3.95 | 13.00 |
| Ship Cove T1 | 12 | dip | 16.93 | 6.67 | 3.00 |
| Lower Cove T1 | 13 | dip | 7.21 | 2.81 | 16.00 |
| Lower Cove T2 | 12 | dip | 6.33 | 3.12 | 30.00 |

* Slope direction refers to the direction the dip angle is facing; scarp is a platform dip of the rock towards the land and dip slopes are towards the sea. A platform slope of 5° or less is considered horizontal.

** refers to the numbered transect (or quadrat) code for that site possessing supratidal swash karren

**Table C2** Continued.

| Site | Dip Angle (°) | Slope Direction* | Average Diameter (cm) | Average Microrelief (cm) | Average Density (per $m^2$ quadrat) |
|---|---|---|---|---|---|
| **Cow Head Peninsula Region** | | | | | |
| Cow Head Peninsula T1** | 10 | scarp | 14.12 | 6.10 | 10.00 |
| Cow Head Peninsula T2 | 12 | scarp | 13.97 | 6.82 | 16.50 |
| Cow Head Peninsula T3 | 18 | dip | 29.92 | 15.25 | 4.50 |
| Cow Head Peninsula T4 | 20 | dip | 11.77 | 10.00 | 7.00 |
| Broom Point T1 | 36 | dip | 3.43 | 1.97 | 12.00 |
| Broom Point T2 | 0 | horizontal | 31.00 | 18.50 | 4.00 |
| Belldowns Island | 30 | dip | 5.52 | 3.03 | 40.00 |
| Stearing Island | 12 | dip | 18.46 | 8.58 | 13.00 |
| **Port au Choix Peninsula Region** | | | | | |
| Port au Choix Peninsula T1 | 10 | scarp | 18.08 | 3.24 | 7.00 |
| Port au Choix Peninsula T2 | 20 | scarp | 6.10 | 2.83 | 12.00 |
| Port au Choix Peninsula T3 | 0 | horizontal | 5.42 | 2.83 | 23.00 |

* Slope direction refers to the direction the dip angle is facing; scarp is a platform dip of the rock towards the land and dip slopes are towards the sea. A platform slope of 5 ° or less is considered horizontal.

** refers to the numbered transect (or quadrat) code for that site possessing supratidal swash karren

**Table C2** Continued.

| Site | Dip Angle (°) | Slope Direction* | Average Diameter (cm) | Average Microrelief (cm) | Average Density (per $m^2$ quadrat) |
|---|---|---|---|---|---|
| **Port au Choix Peninsula Region Continued** | | | | | |
| Pointe Riche Peninsula T1 | 17 | scarp | 10.53 | 4.32 | 7.67 |
| Pointe Riche Peninsula T4 | 20 | dip | 24.33 | 6.43 | 3.00 |
| Pointe Riche Peninsula T5 | 3 | horizontal | 25.63 | 5.50 | 6.00 |
| Ingornachoix Bay Study Area Avg. | 10 | dip | 15.64 | 5.54 | 9.30 |
| Gargamelle Cove Study Area Avg. | 2 | horizontal | 13.25 | 3.25 | 4.00 |
| **Cook's Harbour Region** | | | | | |
| Cape Norman Avg. | 3 | horizontal | 12.16 | 2.38 | 68.00 |
| West Cape Norman Avg. | 0 | horizontal | 36.02 | 28.06 | 6.00 |
| East Cape Norman Avg. | 0 | horizontal | 27.21 | 20.25 | 3.00 |

* Slope direction refers to the direction the dip angle is facing; scarp is a platform dip of the rock towards the land and dip slopes are towards the sea. A platform slope of 5° or less is considered horizontal.

** refers to the numbered transect (or quadrat) code for that site possessing supratidal swash karren

Table C3 Dip angles and slope direction for platform rock hosting karren in the backshore zone.

| Site | Dip Angle (°) | Slope Direction* | Average Diameter (cm) | Average Microrelief (cm) | Average Density (per $m^2$ quadrat) |
|---|---|---|---|---|---|
| **Cow Head Peninsula Region** | | | | | |
| Cow Head Peninsula T1** | 22 | dip | 19.58 | 8.33 | 3.00 |
| Lower Head T1 | 16 | dip | 9.90 | 7.51 | 12.00 |
| **Port au Choix Peninsula Region** | | | | | |
| Port au Choix Peninsula T1 | 20 | dip | 2.56 | 1.00 | 12.00 |
| Port au Choix Peninsula T2 | 5 | horizontal | 7.25 | 3.00 | 2.00 |
| Port au Choix Peninsula T3 | 15 | scarp | 18.00 | 6.50 | 3.00 |
| Port au Choix Peninsula T4 | 13 | scarp | 6.00 | 2.44 | 10.00 |
| Port au Choix Peninsula T5 | 0 | horizontal | 17.46 | 8.67 | 6.00 |
| Pointe Riche Peninsula T2 | 26 | scarp | 12.41 | 3.51 | 9.88 |
| Pointe Riche Peninsula T3 | 11 | dip | 24.10 | 2.20 | 5.00 |

* Slope direction refers to the direction the dip angle is facing; scarp is a platform dip of the rock towards the land and dip slopes are towards the sea. A platform slope of 5° or less is considered horizontal.

** refers to the numbered transect (or quadrat) code for that site possessing backshore karren

**Table C3** Continued.

| Site | Dip Angle (°) | Slope Direction* | Average Diameter (cm) | Average Microrelief (cm) | Average Density (per $m^2$ quadrat) |
|---|---|---|---|---|---|
| **Port au Choix Peninsula Region Continued** | | | | | |
| Ingornachoix Bay Study Area Avg.** | 4 | horizontal | 24.35 | 12.94 | 2.50 |
| New Ferrolle Peninsula T1 | 0 | horizontal | 6.47 | 4.87 | 18.00 |
| **Cook's Harbour Region** | | | | | |
| Cape Norman Avg. | 0 | horizontal | 8.54 | 3.41 | 34.60 |
| West Cape Norman T1 | 25 | scarp | 16.00 | 6.36 | 2.33 |
| East Cape Norman T2 | 2 | horizontal | 47.54 | 37.88 | 9.72 |

* Slope direction refers to the direction the dip angle is facing; scarp is a platform dip of the rock towards the land and dip slopes are towards the sea. A platform slope of 5 ° or less is considered horizontal.

** refers to the numbered transect (or quadrat) code for that site possessing backshore karren

# APPENDIX D

# FETCH CALCULATIONS FOR THE MAJOR STUDY REGIONS

Tables D1 and D2 present the data involved in producing a total fetch value for each of the major sites where transects were located. Transects were aggregated together for shorelines, where there existed multiple transects possessing the same coastal configuration and lines of fetch (e.g. The Bar). Regional maximum fetch provides the distance, and direction, of the line of maximum fetch from each coastal site seaward, measured from maps of the Gulf of St. Lawrence. Platform orientation refers to the compass angle of the shore-normal transect line measured in the field. The component of regional fetch determines the relative strength of the dominant waves, for that region, acting upon that shoreline and possibly influencing karren development. This is done by multiplying the distance of maximum fetch, with the cosine, of the angle ($\alpha$) of deviation, of that shoreline from that line of maximum fetch. This angle of deviation is determined by subtracting the platform orientation from the direction of the line of maximum fetch. If a negative value is encountered then a value of zero is given, indicating that the regional fetch has no effect on that shoreline. For example, for the southeast side of Long Point $\alpha$ is 22.5° (NNE fetch) minus 125° (platform orientation) to equal -102.5. The cosine of this angle is -0.2164, which is multiplied by 300 km (distance of maximum fetch) to equal -64.93 (or 0 km). Conversely, the northwest side of Long Point has a regional fetch component of 87 km, indicating that this shoreline is somewhat affected by maximum fetch waves.

Local fetch distances are determined from regional topographic maps, with these distances indicating the maximum shore-normal local fetch for that shoreline. Total fetch for each site is produced by summing the regional fetch component (coastal configuration) with local fetch, giving an overall fetch used in Section 5.4.2. In some instances the maximum local fetch is the same direction as the line of maximum regional fetch (e.g. several sites in the Cow Head Peninsula region), indicating a very exposed site, as the shoreline is shore-normal to the line of maximum fetch. Therefore, both the regional fetch and local fetch components are the same distances, doubling the distance of the total fetch.

Table D1 Fetch calculations for sites from the Port au Port Peninsula and Cow Head Peninsula region.

| Site | Regional Max. Fetch (km/dir.) | Platform Orientation (° ) | Component of Regional Fetch (km) | Local Fetch (km/dir) | Overall Fetch (km) |
|---|---|---|---|---|---|
| **Port au Port Pen.** | | | | | |
| Long Point SE | 300 (NNE) | 125 | 0 | 13 (SE) | 13 |
| Long Point NW | 500 (SW) | 305 | 87 | 220 (NW) | 307 |
| The Bar | 300 (NNE) | 137 | 0 | 11 (SE) | 11 |
| Three Rock Pt. | 465 (SW) | 270 | 329 | 365 (W) | 694 |
| Lower Cove | 470 (SW) | 300 | 126 | 1 (NW) | 127 |
| Ship Cove | 470 (SW) | 300 | 126 | 1 (NW) | 127 |
| Port au Port E. Bay | | | | | |
| E shore | 310 (NNE) | 290 | 0 | 13 (WNW) | 13 |
| Aguathuna S shore | 310 (NNE) | 0 | 286 | 275 (N) | 561 |
| **Cow Head Peninsula Region** | | | | | |
| Cow Head Pen. | | | | | |
| N shore | 610 (SW) | 0 | 0 | 170 (N) | 170 |
| WNW shore | 610 (SW) | 320 | 0 | 340 (W) | 340 |
| SW shore | 610 (SW) | 225 | 610 | 610 (SW) | 1220 |
| SSE shore | 610 (SW) | 168 | 332 | 2 (SE) | 334 |
| Stearing Island | 610 (SW) | 225 | 610 | 610 (SW) | 1220 |
| Belldowns Islands | 610 (SW) | 100 | 0 | 1.5 (ESE) | 1.5 |
| Lower Head | 610 (SW) | 270 | 437 | 225 (W) | 656 |

Table D2 Fetch calculations for sites from the Port au Choix Peninsula and Cook's Harbour regions.

| Site | Regional Max. Fetch (km/dir.) | Platform Orientation (° ) | Component of Regional Fetch (km) | Local Fetch (km/dir) | Overall Fetch (km) |
|---|---|---|---|---|---|
| Broom Point N | 600 (SW) | 0 | 0 | 180 (N) | 180 |
| Broom Point S | 600 | 180 | 424 | 2.5 (S) | 427 |
| Daniel's Harbour | 650 (SW) | 225 | 650 | 650 (SW) | 1300 |
| **Port au Choix Peninsula Region** | | | | | |
| Port au Choix Peninsula | | | | | |
| E Shore | 700 (SW) | 85 | 0 | 3.5 (ENE) | 3.5 |
| N Shore | 700 (SW) | 355 | 0 | 80 (N) | 80 |
| NW Shore | 700 (SW) | 328 | 0 | 90 (NW) | 90 |
| W Shore | 700 (SW) | 308 | 85 | 110 (W) | 195 |
| Pointe Riche Peninsula | | | | | |
| NW Shore | 700 (SW) | 308 | 85 | 75 (WNW) | 160 |
| W Shore | 700 (SW) | 266 | 528 | 110 (W) | 638 |
| S Shore | 700 (SW) | 185 | 536 | 12 (S) | 548 |
| Ingornachoix Bay | 700 (SW) | 226 | 700 | 700 (SW) | 1400 |
| Gargamelle Cove | 700 (SW) | 327 | 0 | 0.25 (NW) | 0.25 |
| New Ferrolle Peninsula | 740 (SW) | 313 | 26 | 60 (NW) | 86 |

Table D2 Continued.

| Site | Regional Max. Fetch (km/dir.) | Platform Orientation (° ) | Component of Regional Fetch (km) | Local Fetch (km/dir) | Overall Fetch (km) |
|---|---|---|---|---|---|
| **Cook's Harbour Region** | | | | | |
| Cape Norman | 1000 (NE) | 0 | 707 | 500 (NNE) | 1207 |
| E Cape Norman | 1000 (NE) | 20 | 980 | 500 (NNE) | 1480 |
| W. Cape Norman | 1000 (NE) | 340 | 423 | 500 (NNE) | 923 |

# APPENDIX E

# SEA WATER PROPERTY CALIBRATIONS

Field measurements of temperature, conductivity and salinity were conducted with the use of a standard YSI model 33 meter. The meter was calibrated, before and after the field season, with known solutions of sodium chloride (NaCl) for salinity, and potassium chloride (KCl) for conductivity. These known solutions of NaCl and KCl covered the entire range of measurement that the meter provided, so that salinity recordings were taken from 5 to 40 ‰, and conductivity recordings were taken from 0 to 50,000 $\mu$mhos cm$^{-1}$. Temperature was calibrated with the use of a standard mercury thermometer, with the water temperature ranging from near 0° C, through to 30° C and recordings taken at regular intervals

The amount of deviation of the measured values from the meter, which was the same for both before and after field season calibrations, compared with the actual values (1:1 line), can now be observed (Figure E1). A regression equation for meter recordings of salinity, conductivity and temperature is calculated, and provides a correction factor for field measurements. Thus, for example, a field recording for salinity of 35.00 ‰ would actually be 33.64‰ from the equation

$$Y = 0.74 + 0.94\,(X) \tag{E1}$$

so that

$$Y = 0.74 + 0.94\,(35) = 33.64\text{ ‰} \tag{E2}$$

Field recordings for conductivity and salinity, and their corrected values are provided in Table E1. Conductivity is a sensitive function of temperature (White, 1988) and all measurements are usually corrected to a standard reference temperature of 25° C, by using the following equation from Gardiner and Dackombe (1983),

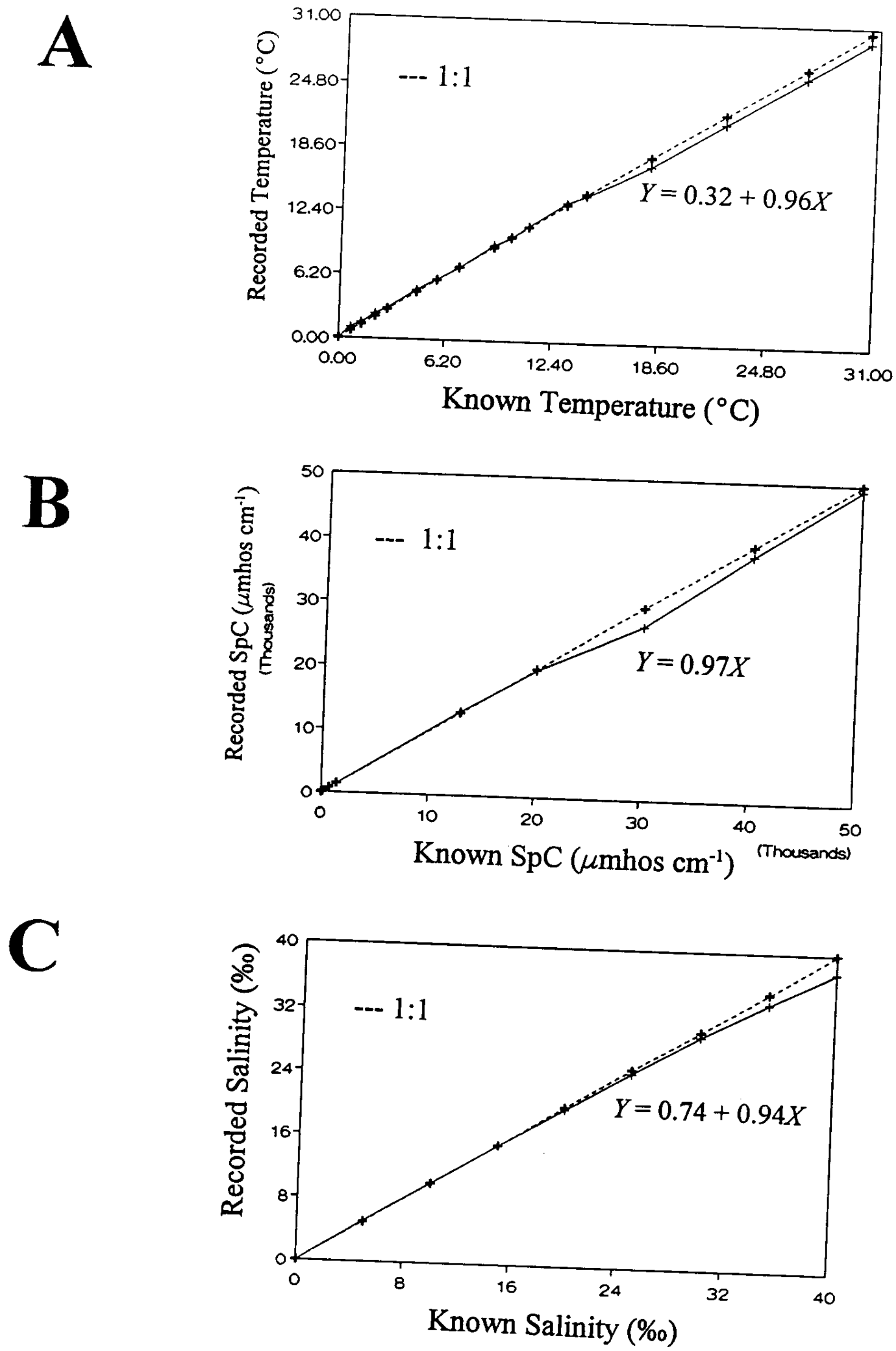



Figure E1 Derived calibration equations used to correct field recordings of A) temperature, B) SpC and C) salinity with the YSI meter.

$$L_R = L_T - 0.02\,(T - R)\,L_T \tag{E3}$$

where

$L_R$ = conductivity at reference temperature
$L_T$ = conductivity at sampled temperature
$R$ = reference temperature (°C)
$T$ = sample temperature (°C)

Thus, a conductivity recording in the field is first corrected by the calibration equation and is then referenced to 25°C, which represents the results presented in Chapter 5.

Table E1 Field recordings for conductivity and salinity measurements of littoral pools, with an associated correction for meter variation.

| Pool Location | Conductivity (μmhos/cm) Field Recording | Metre Correction | Referenced to 25°C | Salinity (‰) Field Recording | Metre Correction |
|---|---|---|---|---|---|
| **Port au Port Peninsula** | | | | | |
| Long Point | | | | | |
| Intertidal | 36,500 | 35,400 | 42,622 | 29.40 | 28.38 |
| Intertidal | 37,800 | 36,670 | 43,124 | 28.40 | 27.44 |
| Intertidal | 41,300 | 40,000 | 44,480 | 29.20 | 28.19 |
| Intertidal | 36,100 | 35,020 | 42,024 | 28.20 | 27.25 |
| Supratidal | 43,500 | 42,200 | 45,238 | 29.50 | 28.47 |
| Supratidal | 40,200 | 39,000 | 43,290 | 28.50 | 27.53 |
| Supratidal | 35,000 | 33,950 | 37,549 | 24.00 | 23.30 |
| Supratidal | 18,900 | 18,335 | 19,655 | 11.90 | 11.93 |
| Supratidal | 42,800 | 41,520 | 45,257 | 29.60 | 28.56 |
| Supratidal | 41,300 | 40,000 | 44,560 | 29.20 | 28.19 |
| Supratidal | 37,800 | 36,670 | 43,124 | 28.40 | 27.44 |
| Supratidal | 42,800 | 41,520 | 46,835 | 31.00 | 29.88 |
| Supratidal | 44,000 | 42,680 | 49,000 | 32.50 | 31.29 |
| Supratidal | 38,100 | 36,960 | 43,465 | 29.00 | 28.00 |
| Backshore | 46,800 | 45,400 | 51,300 | 34.70 | 33.36 |
| Backshore | 11,800 | 11,450 | 12,114 | 7.00 | 7.32 |
| Backshore | 31,200 | 30,265 | 32,989 | 20.90 | 20.39 |
| The Bar | | | | | |
| Intertidal | 37,400 | 36,280 | 42,375 | 27.20 | 26.31 |
| Supratidal | 48,100 | 46,660 | 46,380 | 34.10 | 32.79 |
| Supratidal | 42,000 | 40,740 | 37,399 | 24.00 | 23.30 |
| Supratidal | 38,400 | 37,250 | 42,838 | 28.20 | 27.25 |
| Supratidal | 38,900 | 37,735 | 43,697 | 29.00 | 28.00 |
| Supratidal | 41,100 | 39,870 | 44,256 | 29.10 | 28.09 |
| Supratidal | 37,100 | 35,990 | 40,957 | 28.20 | 27.25 |
| Supratidal | 36,500 | 35,410 | 37,960 | 24.00 | 23.30 |

Table E1 Continued.

| Pool Location | Conductivity (μmhos/cm) Field Recording | Metre Correction | Referenced to 25°C | Salinity (‰) Field Recording | Metre Correction |
|---|---|---|---|---|---|
| **The Bar** | | | | | |
| Backshore | 40,500 | 39,285 | 41,249 | 26.50 | 25.65 |
| Backshore | 48,800 | 47,340 | 48,003 | 31.10 | 29.97 |
| Backshore | 2,700 | 2,620 | 2,856 | 1.40 | 2.06 |
| Backshore | 1,750 | 1,700 | 1,754 | 0.10 | 0.83 |
| **Port au Port East Bay** | | | | | |
| Intertidal | 33,000 | 32,010 | 38,604 | 26.00 | 25.18 |
| Intertidal | 38,200 | 37,050 | 42,459 | 28.00 | 27.06 |
| Supratidal | 31,600 | 30,650 | 36,657 | 24.00 | 23.30 |
| Supratidal | 38,000 | 36,860 | 40,840 | 26.20 | 25.37 |
| Backshore | 250 | 245 | 300 | 0 | 0 |
| Backshore | 1,000 | 970 | 1,207 | 0.05 | 0.78 |
| **Lower Cove** | | | | | |
| Supratidal | 39,000 | 37,830 | 44,185 | 29.20 | 28.19 |
| Backshore | 750 | 730 | 735 | 0.10 | 0.83 |
| Backshore | 900 | 875 | 903 | 0.10 | 0.83 |
| Backshore | 450 | 440 | 531 | 0 | 0 |
| **Ship Cove** | | | | | |
| Supratidal | 38,400 | 37,250 | 44,328 | 29.90 | 28.85 |
| Supratidal | 40,000 | 38,800 | 46,793 | 31.50 | 30.35 |
| Supratidal | 40,100 | 38,900 | 46,836 | 32.00 | 30.82 |
| Backshore | 14,000 | 13,580 | 16,160 | 10.00 | 10.14 |

Table E1 Continued.

| Pool Location | Conductivity (μmhos/cm) Field Recording | Metre Correction | Referenced to 25°C | Salinity (‰) Field Recording | Metre Correction |
|---|---|---|---|---|---|
| **Cow Head Peninsula Region** | | | | | |
| Cow Head Peninsula | | | | | |
| Intertidal | 37,900 | 36,765 | 42,574 | 28.10 | 27.15 |
| Intertidal | 35,800 | 34,730 | 41,884 | 28.20 | 27.25 |
| Supratidal | 45,500 | 44,140 | 46,877 | 31.00 | 29.88 |
| Supratidal | 46,900 | 45,495 | 48,771 | 32.10 | 30.91 |
| Supratidal | 47,500 | 46,075 | 50,222 | 33.20 | 31.95 |
| Supratidal | 35,800 | 34,730 | 41,884 | 28.20 | 27.25 |
| Supratidal | 35,100 | 34,050 | 41,677 | 28.10 | 27.15 |
| Supratidal | 39,100 | 37,930 | 43,620 | 29.00 | 28.00 |
| Backshore | 6,000 | 5,820 | 6,181 | 3.50 | 4.03 |
| Backshore | 2,820 | 2,740 | 2,839 | 1.50 | 2.15 |
| Backshore | 1,920 | 1,865 | 2,000 | 1.00 | 1.68 |
| Backshore | 9,300 | 9,025 | 10,325 | 6.10 | 6.47 |
| Broom Point | | | | | |
| Supratidal | 32,400 | 31,430 | 36,019 | 23.20 | 22.55 |
| Supratidal | 32,000 | 31,040 | 35,324 | 22.80 | 22.17 |
| Backshore | 41,500 | 40,260 | 43,883 | 28.80 | 27.81 |
| Backshore | 45,200 | 43,845 | 46,563 | 30.80 | 29.69 |
| Backshore | 38,000 | 36,860 | 41,431 | 26.80 | 25.93 |
| Backshore | 43,800 | 42,490 | 44,784 | 29.00 | 28.00 |

Table E1 Continued.

| Pool Location | Conductivity (μmhos/cm) Field Recording | Metre Correction | Referenced to 25°C | Salinity (‰) Field Recording | Metre Correction |
|---|---|---|---|---|---|
| **Port au Choix Peninsula Region** | | | | | |
| Port au Choix Peninsula | | | | | |
| Intertidal | 41.300 | 40,065 | 42,950 | 28.00 | 27.06 |
| Intertidal | 36,900 | 35,795 | 42,811 | 28.50 | 27.53 |
| Supratidal | 46,000 | 44,620 | 46,048 | 29.90 | 28.85 |
| Supratidal | 44,100 | 42,780 | 44,063 | 28.20 | 27.25 |
| Supratidal | 37,800 | 36,670 | 43,857 | 29.10 | 28.09 |
| Supratidal | 28,600 | 27,745 | 26,802 | 16.20 | 15.97 |
| Supratidal | 34,500 | 33,465 | 39,154 | 25.80 | 24.99 |
| Supratidal | 49,200 | 47,725 | 53,834 | 36.10 | 34.67 |
| Supratidal | 38,500 | 37,345 | 47,353 | 34.00 | 32.70 |
| Backshore | 50,000 | 48,500 | 50,052 | 40.00 | 38.34 |
| Backshore | 50,000 | 48,500 | 48,500 | 38.90 | 37.31 |
| Backshore | 38,400 | 37,250 | 37,921 | 24.00 | 23.30 |
| Backshore | 50,000 | 48,500 | 45,396 | 30.00 | 28.94 |
| Backshore | 11,800 | 11,450 | 13,374 | 8.00 | 8.26 |
| Backshore | 3,500 | 3,395 | 3,938 | 2.20 | 2.81 |
| Backshore | 2,000 | 1,940 | 2,153 | 1.10 | 1.77 |
| Backshore | 1,450 | 1,410 | 1,647 | 0.90 | 1.59 |
| Backshore | 365 | 355 | 420 | 0 | 0 |
| Backshore | 325 | 320 | 379 | 0 | 0 |
| Backshore | 620 | 605 | 675 | 0.50 | 1.21 |

Table E1 Continued.

| Pool Location | Conductivity ($\mu$mhos/cm) Field Recording | Metre Correction | Referenced to 25°C | Salinity (‰) Field Recording | Metre Correction |
|---|---|---|---|---|---|
| Pointe Riche Peninsula | | | | | |
| Intertidal | 34,800 | 33,760 | 41,930 | 28.20 | 27.25 |
| Intertidal | 38,300 | 37,155 | 44,735 | 30.00 | 28.94 |
| Supratidal | 30,100 | 29,200 | 39,712 | 29.00 | 28.00 |
| Supratidal | 32,000 | 31,040 | 41,532 | 29.60 | 28.56 |
| Supratidal | 30,900 | 29,975 | 40,766 | 29.00 | 28.00 |
| Supratidal | 31,000 | 30,070 | 40,775 | 29.80 | 28.75 |
| Supratidal | 39,400 | 38,220 | 46,093 | 29.00 | 29.97 |
| Supratidal | 35,500 | 34,435 | 42,700 | 29.60 | 28.09 |
| Supratidal | 21,800 | 21,150 | 25,930 | 29.00 | 16.44 |
| Supratidal | 34,900 | 33,855 | 42,116 | 29.80 | 27.15 |
| Supratidal | 40,000 | 38,800 | 45,318 | 31.10 | 29.03 |
| Supratidal | 20,000 | 19,400 | 22,659 | 29.10 | 14.65 |
| Supratidal | 37,900 | 36,765 | 43,971 | 16.70 | 28.09 |
| Supratidal | 31,700 | 30,750 | 37,392 | 28.10 | 24.15 |
| Backshore | 30,900 | 29,975 | 40,226 | 28.90 | 27.91 |
| Backshore | 32,200 | 31,235 | 40,668 | 28.80 | 27.81 |
| Backshore | 33,000 | 32,010 | 41,613 | 29.20 | 28.19 |
| Backshore | 32,000 | 31,040 | 41,283 | 29.50 | 28.47 |
| Backshore | 35,000 | 33,950 | 42,913 | 29.90 | 28.85 |
| Backshore | 30,900 | 29,975 | 38,428 | 26.50 | 25.65 |
| Backshore | 32,500 | 31,525 | 42,559 | 27.90 | 26.97 |
| Backshore | 37,900 | 36,765 | 43,971 | 29.10 | 28.09 |
| Backshore | 2,000 | 2,940 | 2,468 | 1.50 | 2.15 |
| Backshore | 2,100 | 2,040 | 2,464 | 1.20 | 1.87 |
| Backshore | 450 | 440 | 531 | 0.80 | 1.49 |
| Backshore | 325 | 320 | 385 | 0.80 | 1.49 |
| Backshore | 280 | 275 | 326 | 0.10 | 0.83 |
| Backshore | 270 | 265 | 319 | 0.10 | 0.83 |
| Backshore | 380 | 370 | 432 | 0.10 | 0.83 |

Table E1 Continued.

| Pool Location | Conductivity ($\mu$mhos/cm) Field Recording | Metre Correction | Referenced to 25°C | Salinity (‰) Field Recording | Metre Correction |
|---|---|---|---|---|---|
| Ingornachoix Bay | | | | | |
| Intertidal | 32,200 | 31,235 | 38,107 | 28.00 | 27.06 |
| Intertidal | 35,900 | 34,825 | 40,954 | 27.00 | 26.12 |
| Intertidal | 34,400 | 33,370 | 41,512 | 28.80 | 27.81 |
| Supratidal | 33,000 | 32,010 | 38,924 | 26.00 | 25.18 |
| Supratidal | 36,200 | 35,115 | 39,680 | 26.00 | 25.18 |
| Supratidal | 39,700 | 38,510 | 41,591 | 26.90 | 26.03 |
| Supratidal | 35,900 | 34,825 | 40,118 | 27.00 | 26.12 |
| Supratidal | 16,000 | 15,520 | 17,507 | 11.50 | 11.55 |
| Supratidal | 32,900 | 31,915 | 39,064 | 26.00 | 25.18 |
| Supratidal | 39,200 | 38,025 | 46,391 | 32.00 | 30.82 |
| Supratidal | 36,100 | 35,020 | 41,604 | 29.20 | 28.19 |
| Supratidal | 34,800 | 33,760 | 40,039 | 26.50 | 25.65 |
| Supratidal | 38,100 | 36,960 | 42,060 | 27.90 | 26.97 |
| Supratidal | 50,000 | 48,500 | 54,432 | 40.00 | 39.34 |
| Backshore | 39,800 | 38,610 | 42,934 | 27.80 | 26.87 |
| Backshore | 10,800 | 10,480 | 11,444 | 6.80 | 7.13 |
| Backshore | 50,000 | 48,500 | 54,320 | 38.00 | 36.46 |
| Backshore | 36,900 | 35,795 | 39,804 | 25.20 | 24.43 |
| Backshore | 22,000 | 21,340 | 26,035 | 16.90 | 16.63 |
| Backshore | 27,300 | 26,485 | 32,894 | 21.90 | 21.33 |
| Backshore | 970 | 945 | 1,130 | 0.50 | 1.21 |
| Backshore | 360 | 350 | 435 | 0 | 0 |
| Backshore | 285 | 280 | 325 | 0 | 0 |
| New Ferrolle Peninsula | | | | | |
| Intertidal | 34,900 | 33,855 | 43,793 | 29.50 | 28.47 |
| Supratidal | 19,600 | 19,015 | 23,198 | 14.90 | 14,75 |
| Supratidal | 3,510 | 3,405 | 4,236 | 2.50 | 3.09 |

Table E1 Continued.

| Pool Location | Conductivity ($\mu$mhos/cm) Field Recording | Metre Correction | Referenced to 25°C | Salinity (‰) Field Recording | Metre Correction |
|---|---|---|---|---|---|
| New Ferrolle Peninsula | | | | | |
| Backshore | 9,700 | 9,410 | 11,518 | 5.30 | 5.72 |
| Backshore | 2,500 | 2,425 | 2,929 | 1.80 | 2.43 |
| Backshore | 2,090 | 2,030 | 2,505 | 1.20 | 1.87 |
| **Cook's Harbour Region** | | | | | |
| Cape Norman | | | | | |
| Supratidal | 37,000 | 35,890 | 43,642 | 29.20 | 28.19 |
| Supratidal | 38,700 | 37,540 | 45,123 | 30.10 | 29.03 |
| Backshore | 4,500 | 4,365 | 5,247 | 3.70 | 4.22 |
| Backshore | 5,400 | 5,240 | 6,330 | 2.20 | 2.81 |
| East of Cape Norman | | | | | |
| Supratidal | 31,800 | 30,850 | 39,241 | 26.80 | 25.93 |
| Supratidal | 36,200 | 35,115 | 43,683 | 29.90 | 28.85 |
| Backshore | 15,000 | 14,550 | 18,973 | 3.00 | 3.56 |
| West of Cape Norman | | | | | |
| Intertidal | 40,000 | 38,800 | 43,766 | 29.00 | 28.00 |
| Supratidal | 38,700 | 37,540 | 42,946 | 28.20 | 27.25 |
| Supratidal | 39,100 | 37,930 | 44,985 | 30.00 | 28.94 |
| Supratidal | 4,000 | 3,880 | 4,454 | 2.50 | 3.09 |

Table E1 Continued.

| | Conductivity ($\mu$mhos/cm) | | | Salinity (‰) | |
|---|---|---|---|---|---|
| Pool Location | Field Recording | Metre Correction | Referenced to 25°C | Field Recording | Metre Correction |
| West of Cape Norman | | | | | |
| Backshore | 3,950 | 3,835 | 4,403 | 12.50 | 12.49 |
| Backshore | 5,800 | 5,630 | 6,193 | 3.50 | 4.03 |
| Backshore | 4,300 | 4,175 | 4,634 | 2.20 | 2.81 |
| Backshore | 50,000 | 48,500 | 52,865 | 40.00 | 38.41 |

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