COASTAL EROSION AT MISTAKEN POINT ECOLOGICAL RESERVE, AVALON PENINSULA, NEWFOUNDLAND

by

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Abstract

The purpose of the project at Mistaken Point Ecological Reserve (MPER) was to investigate coastal processes through qualitative assessment as well as to create a measurable baseline for future quantitative measures at four distinct sites. Analysis started in the spring of 2009 and was completed in the fall of 2011. The sites were chosen based on previously observed erosion, as well as age and number of Ediacaran fossils present at each site. MPERs coastline is known for having the oldest known soft-bodied multi-cellular organisms, and is believed to provide critical information about biological evolution in the Ediacaran Period. As a result, MPER was nominated for UNESCO World Heritage Site Status in 2004. However, under the UNESCO Operational Guidelines, appropriate management of the site and its fossils must be procured in order for full heritage status to be granted.

Four sites were chosen (PC Site 1, PC Site 2, MP Site 3 and MP Site 4) for analysis within MPER. Qualitatively, field and ground photographs of the four sites were analyzed. Visitation statistics were recorded for MP Site 3. To create a baseline for future research on coastline erosion, data was collected using Real Time Kinematic (RTK) GPS. Additional quantitative methods include strike/dip/sense measures which were later mapped to stereonets to provide a comprehensive view of the geological structure, and its response to physical processes.

Much of the bed rock along MPERs coastline is greywacke. Differences such as structural geology, wave aspect, human impact, and therefore type and level of erosion occurring vary among sites. Observed physical processes included wave impact, storms, freeze/thaw, and gravitational failure resulting in mass movement. Human factors include foot traffic due to increased visitation and individual casting projects of the fossils.

Due to time constraints of the project, no quantitative rates were identified. However, qualitative observations pointed to two primary contributing factors of erosion at all four sites. The first was the inherent structural geology, and the second was intense wave impact. Although the qualitative observations made from 2009-2011 document visible movement or removal of bedrock clasts, to adequately understand rates of erosion along a consolidated hardrock coastline, a minimum of 60 years of data collection is required. Therefore, to quantitatively understand rate of erosion along MPERs coastline, further and ongoing assessment of MPERs coastline is recommended.

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1. Introduction

Coastal geomorphology is primarily focused on the understanding of processes that cause erosion and accretion along coastlines. Understanding the nature of coastal geomorphology of bedrock shorelines is not only based on observation and analysis of presently active site-specific and regionally induced processes and their effects on the coastline, but also necessitates comprehension of the inherent geological structure, as well as past physical processes. Although qualitative observations are important in understanding processes that contribute to the erosion of any particular coastline, quantitative rates of erosion provide important pieces of information, especially with respect to coastal zones of human interest.

Globally, there are two broad classifications of coastlines: *allomorphic* or sediment-dominated coastlines, and *automorphic* or bedrock coastlines (Finkl, 2004). Although automorphic coastlines such as rock platforms and cliffs represent ~ 80% of the world's coastlines, they have received relatively little attention (Emery and Kuhn, 1982; Sunamura, 1992; Finkl, 2004).

Automorphic coastlines have generally been subject to limited human occupation, because they commonly do not provide easy accessibility to the shoreline. They do, however, have attractive features that make them popular tourist destinations. As well, with the expectation of increased frequency and intensity of storms in the North Atlantic (Woodroffe and Grime, 1999), more attention has been given to erosional rates on automorphic coasts (Hall *et al.*, 2006; Etienne and Paris, 2010). Erosion along these coastlines can cause increased risk of slope failures, such as rotational slumps and rock toppling. Increased visitation can accelerate anthropogenically -induced erosion. Unlike allomorphic coastlines, where artificial nourishment can temporarily replenish sediment to a coastline, the erosion of automorphic coasts is an irreversible process (Philpott, 1984; Sunamura, 1992).

The rate at which coastal recession occurs as well as the size and distribution of the population along a coastline contributes to an understanding of the possible economic impact. Along the morphologically complex and variable coastlines of England and Wales, it is projected that by 2050, £7.7 billion of coastal assets will be lost due to coastal erosion (Hall *et al.*, 2008).

Much of Newfoundland's 9655 km of coastline is subjected to various forms of erosion, with an estimated 90% of its inhabitants living close to the sea (Economics and Statistics Branch, 2002; Batterson *et al.*, 2010). The Avalon Peninsula coastline has been recently recognized as one of the world's most attractive tourist destinations (National Geographic, 2011), and is one of the most dynamic and physically variable coastlines in Canada (Catto *et al.,* 2003; Catto, 2011). Coastal zones in Newfoundland are not classified strictly on lithology but are defined by an array of physical characteristics including structural geology, surficial material, and the vegetation and climate (eco-region). Along the southeast Avalon Peninsula, near the tip of the Southern Shore, much of the coast is a resistant automorphic shore composed of shale, argillite, and siliceous sandstone (King, 1988). Mistaken Point Ecological Reserve represents a segment of this coastline.

1.1 Purpose and Objectives

The purpose of the project is to investigate the coastal processes and rates of erosion along the coast of Mistaken Point Ecological Reserve (MPER), through qualitative and quantitative assessment of four sites. MPER contains some of the oldest fossilized soft-bodied multi-cellular organisms (Narbonne and Gehling, 2003), and provides critical information about biological evolution in the Ediacaran Period (565 Ma). The term "Ediacaran" is named for the Ediacara Hills of South Australia, where the first primitive metazoans were first discovered in 1946 (Turner *et al.,* 2007). The fossils from the Ediacaran period are described by palaeontologists as organisms that not only differ substantially from modern animals, but also from the organisms of the Cambrian Period (beginning 550 Ma) (Fedonkin, 2007). It has been suggested that these fossils document an evolutionary transition from microbial ecosystems of the Precambrian Era to animal ecosystems of the Phanerozoic Era (Clapham *et al*. 2003). Thus, studying the Ediacaran fossils aids in understanding of how life was organized, and the processes that may have contributed to global evolution and/or extinction at this time (Clapham *et al*. 2003; Fedonkin, 2010). In recognition of the significance of the fossil assemblages, the Newfoundland and Labrador Ministry of Environment and Conservation, and palaeontologists from Canada and England are dedicated to preserving these fossils for future research.

In 1968, MPER Ediacaran fossils were discovered by Memorial University of Newfoundland student S.B. Misra (assisted by P. Thompson) during geological mapping (Anderson and Misra, 1968). Subsequently, the southeast tip and its Ediacaran assemblage received relatively little attention until 1987 when the Government of Newfoundland and

Labrador (NL) established Mistaken Point as an Ecological Reserve (2.95 km^2) to protect the fossils (Government of Newfoundland and Labrador, 2009). Since 1998, paleontologists from Queen's University, Memorial University, and Oxford University, amongst others, have investigated multiple distinct fossil assemblages within the sequence of MPER's sedimentary rocks, noting that (to date) MPER contains:

- Some of the world's oldest architecturally complex fossils (Narbonne, 2005; Sperling *et al.* 2011);
- One of the largest (nearly 2 m length) known Ediacaran fossils (Narbonne and Gehling, 2003);
- Abundant, dense and diverse Ediacaran fossil assemblages;
- Possibly the oldest known Ediacaran trace fossil (Liu *et al.* 2010); and
- Rock strata suitable for uranium-lead dating (Benus *et al.* 1988);

The Ediacaran fossils along the MPER coastline are not only considered significant by NL Environment and Conservation for their scientific value, but are regarded as a tourist attraction. It is therefore in the interest of the provincial government to create a sustainable visitor site within the reserve boundaries (Government of Newfoundland and Labrador, 2009). In 2004, MPER was nominated for UNESCO World Heritage Site Status (UNESCO, 2010).

The coastline along MPER has been subjected to various physical processes that results in erosion and modification, including storms, wave impact, freeze/thaw, mass movement, and foot traffic by visitors. Although erosion along the MPER coastline has been observed by various researchers qualitatively, an analysis of processes and quantitative rates will contribute to effective management of MPER's coastline. Therefore, this thesis will address the following questions:

- What are the dominant erosional processes at the MPER sites?
- What baseline data will provide a better understanding of rates of erosion?
- What specific factors or combinations of factors generate and control these processes at each site?
- What differences in physical processes, bedrock structure, exist between the sites?
- How does anthropogenic activity influence erosion at MPER?

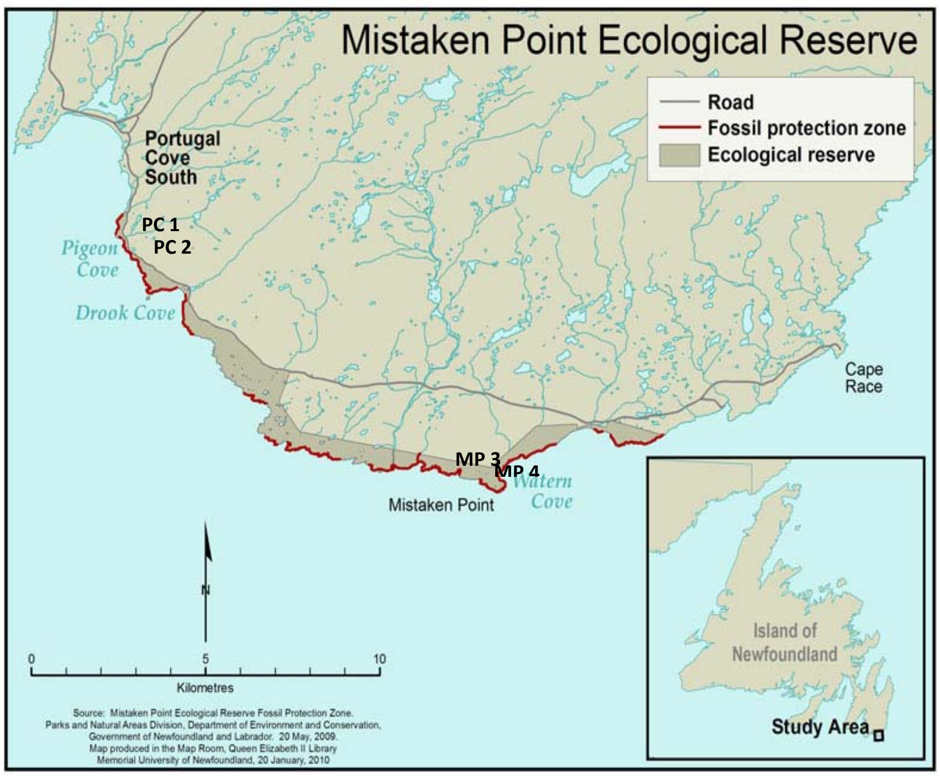

Figure 1.1: Map of Mistaken Point Study Area Study sites at Pigeon Cove (PC1, PC2) and Mistaken Point (MP3, MP4) are indicated.

The funding received for this project was provided by The Government of Newfoundland and Labrador, Environment and Conservation. This research will benefit Mistaken Point Ecological Reserve, and may also enhance understanding of automorphic coastline erosion at other sites in Atlantic Canada.

For MPER to receive designation as a UNESCO World Heritage Site, it must fulfill certain requirements and have a management plan that includes adequate long-term legislative, regulatory, institutional or traditional protection (UNESCO Operational Guidelines, 2011). Long-term management cannot be undertaken if the physical processes that affect this coastal area over time are not fully understood. Secondly, understanding of the processes affecting MPERs coastline can be applied to the study of erosion in other locations. Ongoing geological processes that have and continue to contribute to its erosion have been noted by researchers for a number of years. However, no previous coastal research has been focused on MPERs bedrock coastline. As this coastline is more frequently utilized, and visitation as well as development increases, knowledge of the processes that contribute to its development will be of importance for effective management and conservation.

1.2 Thesis Structure

The following thesis consists of 7 chapters, of which this is the Introduction. Chapter 2 is a literature review of previous work, focusing on bedrock coastlines and erosion processes, and also considers some geological sites that have received UNESCO World Heritage Status, and some of the management approaches taken to protect their integrity. Chapter 3 examines the physical location and setting of MPER. The Methodology is presented in Chapter 4. Chapter 5 presents the results of the study of the four specific locations investigated at MPER. Chapter 6 provides the Discussion concerning the erosional processes active along this coastline. The final chapter presents the Conclusion as well as Recommendations for future management of this area.

2. Previous Work

2.1 Factors influencing Geomorphology of Rocky Coasts

Coastal geomorphology of an automorphic coastline is the study of cliff systems composed of consolidated material, regardless of hardness (Sunamura, 1992) and is in part the product of processes such as plate tectonics. As a multi-dimensional science, coastal geomorphology provides explanations concerning the origin and development of coastal formations in response to physical, chemical, and biological processes that occur over time (Sunamura, 1992).

Although in the past cliffs were perceived as a habitat reasonably free from human disturbance, the abundance of scenic vistas common in cliff environments has provided the incentive for the establishment of parks and nature reserves, necessitating a more thorough understanding of the processes (Larson *et al.,* 2000; Turner, 2002; Reynard *et al.,* 2007). Pressure placed on coastlines due to increased human presence can lead to coastline erosion, leading to the greater occurrence of hazards along the coastline. Until recently, coastal cliffs, which comprise ~ 80% of the world's coastlines, received little attention from scientific research (Emery and Kuhn, 1982). However, due to observed coastal recession in response to physical processes, especially in areas where population is growing, research along these coastal zones has increased to provide a better understanding of the processes acting on bedrock coastlines as well as the rates of retreat (Bray and Hooke, 1997; Benumof and Griggs, 1999; Foote *et al*., 2006; Hall *et al*., 2008; Matsuoka, 2008; Recorbet, 2010). To adequately understand or quantify rates of erosion along an automorphic coastline largely depends on the temporal component. The observed change to an automorphic coastline, such as cliff recession, can be described as a process related to its "memory", suggesting that present and future behavior is influenced by the effects of past events on the system (Lee, 2008). The influences on a coastal cliff system can be organized and described by the environmental controls of the system, also referred to as independent variables or boundary conditions. These components that are the inheritance of past processes include cliff height and slope angle determining gravitational attraction, sea-level, tectonic history and the post-glacial effects of isostatic readjustment, and the existing geology, topography and sediment availability. Other environmental controls are those that represent the system's state at present, such as established landforms (Lee, 2008). The controls drive or weaken the energy regime (forcing factors) within the system: rainfall, wind regime, temperature, tidal range, wave action and relative sea level, contributing to a dynamic, non-linear zone of constant change.

Although the morphology of cliffs can include a number of sections: adjacent beach area, including the shoreline, nearshore, foreshore, and backshore; the cliff system includes both the vertical and horizontal cliff planes (platforms, cliff face) as well as the cliff top (Lee, 2008). As well, these evolve over time often leading to cliff retreat (characterized as the recession rate with respect to the cliff top), deposition or erosion along the cliff base, as well as the volumetric changes of the entire cliff face (Young *et al*. 2009). The variations observed in recession rates, either annually or over longer periods of time, frequently reflect variations in those factors that control strength of cliff materials and kinetic energy of waves at the cliff base (Lee, 2008).

The geological structure of a coastline contributes to its erosion over time in a number of ways. Specific geomorphological features of an outcrop surface are related to the pattern of structural weaknesses and inhomogeneities, including its joint pattern (Scheidegger, 2001). Joints are defined as cracks or fissures from 10 cm to several meters in length, which do not show perceptible lateral movement. Joints are produced by the application of stress to consolidated rock (Scheidegger, 1978, 1985; Hancock and Engelder, 1989; Hancock, 1991) and occur in a wide variety of rock types and tectonic environments. Joint systems may involve a single orientation, or two or more linked (conjugate) orientations. Where a single or conjugate joint pattern has been developed, neotectonics as well as gravitational and weathering processes can further develop the joints into extension fractures. On outcrops, this can result in rock toppling, wedging, sliding, or creep.

Budetta et al. (2000) discussed the relationship between erosional processes and the compressive strength of rocks, depending on the mechanical properties of joints affecting rock masses. In addition, research conducted by Hampton (2002) observed the gravitational failure of sea-cliffs along the segments of the California coastline, highlighting that cliff stability was primarily influenced by the tensional stresses generated during the release of horizontal confining stress, therefore weakening of the cliff structure. Undercutting by waves is one of the most significant factors in coastal retreat. Waves erode the cliff toe, undercutting and oversteepening it, which destabilize the overlying slope, causing it to collapse, a cycle that typically repeats at time scales of years to decades (USGS, 2004). In addition, depending on the structure, wave energy impacting the base of a cliffed coastline contributes pneumatic and hydraulic pressures that may lead to weakening of weathered rocks, resulting in levering and detachment from the cliff face (Trenhaile, 1987).

With respect to wave impact, there are four primary variables that influence the erosion of a cliff face: 1) fetch (Lim, 2011); 2) wave angle on impact; 3) significant wave height (Hall *et al*, 2008); and 4) frequency of high magnitude wave events and storms (Haslett, 2009; Nunes *et al*. 2011). The energy received at the base of the cliffs is also influenced by offshore bathymetry and the location of wave break.

Fetch distance determines the size of waves that impact a coastline. A longer fetch can result in larger and more energetic waves, causing increased erosion on the coastline (Sunamura, 1992; Larson *et al.* 2000). An additional influence on wave energy is the bathymetric slope. Relatively steep bathymetry allows higher energy waves to impact the coastline, whereas low slope bathymetry causes waves to dissipate further offshore, reducing the amount of direct energy and impact on the coastline (Sheppard, 1997).

Sea level change also influences coastal erosion. Factors that affect global sea-level rise include the accelerated melting of ice sheets, ice caps, and mountain glaciers (Alley *et al.*, 2005, 2008; Velicogna and Wahr, 2006; Rignot *et al.*, 2008; Dahl-Jensen *et al.*, 2009; Pritchard *et al.*, 2009; Radić and Hock, 2011). Although the estimates for global sea level rise (SLR) from GCMs (Global Circulation Climate Models; e.g. http://www.cics.uvic.ca/scenarios) vary widely, the Special Report on Emissions Scenarios of the Intergovernmental Panel on Climate Change (IPCC, 2011) has presented a range of projections varying from 0.18 to 0.59 m globally averaged sea-level rise at the end of the 21st

century with a median value of 40 cm. These are values for change in global ‘absolute’ sea level, rather than ‘relative’ sea level at a particular locality.

Along the coastlines of the Avalon Peninsula, anticipated sea level changes will be determined by a combination of continued glacioisostatic adjustment, and volumetric increase of the oceans waters that result from glacial melting (e.g. James *et al.*, 2010). The observed rates of relative sea level rise observed from tide gauges for locations in southern Newfoundland are 3.0-3.5 mm/y (Catto, 2006, 2011; Catto *et al*., 2006).

Along the Canadian Atlantic coastline, frost action is significant in modifying exposed bedrock. Frost action is effective in well-jointed bedding planes, resulting in fracture and joint expansion (Ritter, 1978; White, 2002; Catto, 2011). The mechanism of frost action along coasts is evident in the angular structures observed where erosion has occurred.

Frost action contributes to erosion of hardrock during freeze-thaw intervals and is especially effective when coastal bedrock is exposed and devoid of ice, snow, or vegetation cover. The rate of formation is controlled by the number of freeze-thaw cycles, with each freezing event subjecting the rock to stress as confined ice expands its volume by 9.2% (Trenhaile and Mercan, 1984; Tharp, 1987; Trenhaile, 1987; Bloom, 1998). Effective frost wedging requires that the freezing water be confined within a fracture or area of weakness, and that the surrounding rock be saturated, so that water cannot migrate (Tharp, 1987). In micro-fractures and joints, confinement is more likely, producing more effective frost wedging.

2.2 Case studies

Hall et al. (2008) studied rates of erosion induced by wave action at The Grind of the Navir, a coastal headland in the Shetland Islands, north of Scotland. The approach was to create and analyze detailed time series maps, ground photography and observe the distribution of *Verrucaria maura* and two other lichen species to understand the processes, patterns and rates of erosion.

During storms, high-energy waves may impact and overtop cliffs as high as ~ 15 m above sea level. The principal vertical joint sets, spaced at ~ 0.3 m in plan view, define the geometry of this headland. The joints are mostly orthogonal, allowing wave quarrying to produce tabular blocks to > 1 m^3.

Recent fractures within the cliff face and top indicate that wave force exceeds the tensile strength of the rock (ignimbrite, 1.5 MPa) propagating cracks inwards and upwards within the rock. While the impact of waves was able to move boulders across the cliff top, the upward and inward movement of water through cavities contributed to the removal of blocks from the vertical faces of the cliffs. Although block removal occurred over a year, total block removal was most likely during large Atlantic storm events.

Although classic models (Sunamara, 1977; Trenhaile, 1987) suggest that cliff erosion is concentrated where wave attack is at the waterline, promoting basal notching and therefore failure of overlying material, at this location the combination of the geology, and high-energy wave impact (especially during storm season) cause erosion to occur along both cliff face and top, moving blocks inland, or out to sea. Rates of erosion were 1.9 - 6.0 mm/y for the cliff face, and 5 mm/y for parts of the of the cliff top. This study illustrates that while wave impact at the waterline can contribute to cliff face erosion, when wave power is intense enough under storm conditions, and where structural strength of rock cliff is compromised by jointing systems, the removal of cliff top material is also highly feasible.

Based on a middle-Cretaceous chalk cliff, the research conducted by Wolters and Müller (2008) addresses the undercutting of a vertical cliff face by considering the gravity-induced stresses found within the cliff face. The method employed by the researchers was Finite Element Modelling (FEM) of the stress distribution of cliff face geometry with respect to slope angle, cliff height, influence of a cliff base cavity, front face loading, and cliff surcharge loading.

The investigation of cliff face erosion included measurement of slope angles and tension cracks along the cliff top, to understand shear stresses. Contributing mechanisms such as the effect of undercutting and cavity formation, influence of cliff height (ratio of gravity-induced stress), external loading (if bedding plane exfoliates, load decreases decreasing stress) as well as vertical and horizontal wave impact were considered. The numerical analysis showed that wave undercutting that altered rock cliff geometry from a slope to a vertical face resulted in the development of very high local stresses, which can exceed the shear strength of the material. The authors concluded that with steepening of the cliff face, based on contributing stress factors (geometry, ratio of gravity induced stress, and material strength) contributed to an unstable equilibrium condition contributing to sudden cliff failure. The primary influences to cliff face erosion dependent upon material composition of cliff, inherent geological structure (geometry) as well as the processes (wave, storm impact) at which the coastal cliffs are subjected to. Resultant vertical cliffs may also emphasize wave power therefore contributing to erosion along the cliff face and cliff top.

2.3 Geological Heritage Sites: Physical and Human Integrity

Every cliffline should be viewed as a unique environment due to its inherent variability of cliff materials as well as the numerous potential combinations in response to the environmental controls of the system in question (Lee, 2008). However, the dynamics that result in a coastline's uniqueness are not limited to physical processes alone, but also the policy and management plans that affect the coastline. As well, effectiveness of a management plan dictates to a certain degree the integrity of a coastline for future generations.

Geodiversity can be defined as a natural range (diversity) of geomorphological and geological (landform, physical processes) conditions, together with rocks, minerals, and/or soil features, including their assemblages (plants, fossils), relationships, properties, and interpretations as well as their systems (Gray, 2004). The Earth's biodiversity may be strongly influenced by its geological diversity (Gray, 2005). For that reason, if land management is to be effective, a holistic understanding and approach is necessary considering changes over time.

Although geodiversity was first created as the geological equivalent to biodiversity to encapsulate the many geological and geomorphological features and processes preserved within terrestrial lands, the concept does not necessarily summarize the dynamic relationships that actually occur within these sites (Vasiljević *et al.,* 2010). These relationships include the diverse nature of the perceived values such as those deemed intrinsic, cultural, aesthetic, economic, functional and scientific. Thus, while geodiversity specifically encapsulates the scientific, educational, and aesthetic physical components of a site, the term “geoheritage” includes those components of geodiversity as well as the cultural or human components (Dixon, 1996). The term “geoconservation” refers to the type of management that might be used to maintain the quality of a particular geological heritage site (Burek and Prosser, 2008).

In response to the growing recognition and widespread activity of geoconservation in recent decades, the concept is now well established in many parts of the world (Burek and Prosser, 2008). Defined as the active management of geodiversity and/or geoheritage sites (Sharples, 2002), geoconservation has been undertaken to preserve and promote geological and geomorphological features, processes, sites and specimens (Burek and Prosser, 2008). However, in the case of irreversible geological processes that might be identified in sites deemed more vulnerable and sensitive to external pressures, approaches of preservation rather than conservation might be required (Burek and Prosser, 2008; Vasiljević *et al.,* 2010).

The basic aim of geoconservation is to conserve well-developed and well-preserved representative examples of important elements of the geodiversity found in a region. In terms of its application, geoconservation is important in that its practice helps to maintain threatened areas in the face of encroaching and increasing human activity and presence. One example of this management approach is the concept of a Geopark (Burek and Prosser, 2008).

Developed in 1996, a Geopark can be defined as a protected (or designated) area containing a number of geological heritage sites of particular importance, rarity or aesthetic appeal. The goal of a Geopark is to integrate concepts of protection, education and sustainable development as well as to promote geotourism (Zouros 2004; McKeever and Zouros, 2005;

Turner, 2010). The use of a Geopark as a management tool has been well recognized. These political entities include the European Geoparks Network initiated in 2000 (Zouros, 2004), as well as the Initiative on Geoparks adopted by the United Nations Educational, Scientific and Cultural Organization (UNESCO) in 2003 (Reynard et al. 2007), and has spread to countries such as China and Iran (Turner, 2006). However, another primary goal of a Geopark is to stimulate economic activity and sustainable development through Geotourism. By generating tourism potential, a Geopark stimulates local socio-economic development through the promotion of local natural heritage. It encourages the creation of local enterprises and cottage industries. However, depending on the sensitivity of the geological component of interest, UNESCO sites may also fall under more conservative management criteria due to provincial legislation. For example, the Ecological Reserve Act classifies a site as a permanent sanctuary maintaining a more tenuous balance between conservation and education.

While Geo-sites are considered to be "universally" significant to all of humanity with respect to their geodiverse components, Geoparks openly enhance increased visitation for economic growth. In contrast, Ecological Reserves more aptly benefit from a more conservative management approach, including only guided tours to visitors, and low impact recreational activities such as wildlife viewing and/or nature photography. With a stronger approach to conservation, the NL Ecological Reserve Act prohibits the presence of motorized vehicles and the establishment of buildings with the site boundaries. While sites managed by either approach may be entitled to UNESCO World Heritage Site Status, goals of site maintenance and therefore management conditions are very different.

The World Heritage Convention of UNESCO first convened in 1972. Its purpose was to recognize both cultural and natural heritage sites that are considered "priceless" as well as irreplaceable as assets to humanity as a whole. These properties are defined as having "outstanding universal value" and are noted as being worthy of special protection by UNESCO due to their vulnerability. It is also the intention of the UNESCO World Heritage convention to ensure the respect and protection of natural and cultural heritage that contributes to international and social cohesion (UNESCO Operational Guidelines, 2011). However, whether the site is of cultural or natural significance, it must satisfy a set of criteria stated within the Operational Guidelines for the World Heritage Convention. The following criteria are expected to be established before designation as a geological heritage site:

- The site is to be an outstanding example representing one or more major stages of Earth's history, with respects to the record of life, significant ongoing geological processes in the development of land forms, or significant geomorphic or physiographic features (Criterion a (i)).
- "The sites listed in a(i) should contain all or most of the key interrelated and interdependent elements in their natural relationships" (Criterion b (i))
- The site should have a management plan (Criterion b (v))
- The site should have adequate long-term legislative, regulatory, institutional or traditional protection. (Criterion b (vi)). (UNESCO Operational Guidelines, 2011).

  Once inscribed, it is the mission of UNESCO to support the World Heritage Site, and:

- "Encourage States Parties to establish Management Plans and set up reporting systems on the state of conservation of their World Heritage Sites";
- "Help States Parties safeguard World Heritage properties by providing technical assistance and professional training";
- "Provide emergency assistance for World Heritage Sites in immediate danger";
- "Support States Parties' public awareness-building activities for World Heritage conservation";
- "Encourage participation of the local population in the preservation of their cultural and natural heritage";
- "Encourage interaction and cooperation in the conservation of our world's cultural and natural heritage".

A total of 936 properties have received UNESCO World Heritage Status (UNESCO, 2012). An application to designate Mistaken Point Ecological Reserve as a World Heritage site is currently in preparation by World Heritage Lead, Dr. Richard Thomas, Department of Environment and Conservation, Newfoundland and Labrador. The following three geological World Heritage sites provide relevant comparative examples to MPER, with respect to geological value and possible strategies of use for protection of MPER fossils.

Rocky Mountain Parks World Heritage site (Burgess Shale) is located in Yoho National Park, British Columbia (UNESCO, 2012). The Burgess Shale is a fossil locality representative of Middle Cambrian age (~ 540 Ma), and was inscribed as a World Heritage property in 1984. The shale contains a wide diversity of soft-bodied fossil invertebrate animals, living when the continental margin of North America was located near the equator.

To reach the Burgess Shale, visitors are required to take a guided tour. The tour is quite popular, so visitors are expected to book months in advance. Although the site is remote, the fossils can be easily removed, and their location and presence is well known. As a result, Yoho National Park has had issues with fossil theft in the past (UNESCO, 2012). Similarly to MPER, the Burgess Shale fossil site is unique in its diversity and abundance and one of the few sites in the world representative of its geological age.

The Dorset and East Devon Coast World Heritage site, located on the south coast of England, displays a combination of internationally renowned geological features that provide an almost continuous sequence of rock formations spanning the Mesozoic (Triassic, Jurassic and Cretaceous). This easily accessible coastline is highly populated with residents and a popular destination for tourists. The undeveloped cliffs and beaches between Orcombe Point near Exmouth in East Devon and Studland Bay near Poole in Dorset were inscribed on the World Heritage List by UNESCO in 2001 (Dorset and East Devon Coast UNESCO, 2009). Ammonite fossils can be viewed along this coastline during low tide, and are imbedded into a hardrock platform. Although the practice is discouraged by locals, there is no regulation stopping visitors from removing the ammonite fossils. In the past, visitors removed loose fossils at the site, but presently few to none of these remain: the embedded fossils are difficult to remove unless cut out with a diamond saw. Hence, due to the nature of the substrate, the fossils that remain at this site remain comparatively protected.

Joggins Fossil Cliffs World Heritage site is located in Nova Scotia. The coastal cliffs at Joggins received World Heritage status in 2008, and according to Criterion (viii), represent the best and most complete known fossil record of the Pennsylvanian period, including plant, invertebrate and vertebrate fossils. The fossils at Joggins were noted in both the Principles of Geology (1830-33) by Charles Lyell and The Origin of the Species (1859) by Charles Darwin, and the site has come to be known as a "Coal Age Galápagos" (UNESCO, 2010).

The fossil specimens at Joggins are both embedded within its soft cliffs and lie along the beach. Prior to 2007, visitors were allowed to remove fossils from the beach area. To ensure fossil conservation, an interpreter now supervises visitors along the fossilized beach and prevents fossil removal. While the removal of fossil specimens is prohibited, it is within Joggins' mandate to allow for the rescue of fossils if they are at risk of erosion from the cliff due to physical processes such as storm impact.

The Burgess Shale site, based on fossil age and global distribution, is possibly the most comparable to the MPER site. However, geomorphogical differences influence accessibility and conservation. MPERs fossils are firmly embedded into the bedrock, whereas Burgess Shale fossil specimens may be easily removed without drilling or diamond saw use.

Relative to Joggins and the Devon/Dorset coasts, MPER may be perceived as a reasonably inaccessible and remote site. Although the hike over the barrens is flat and reasonably short (3.5 km), visitors also need to drive 16 km on a poorly graded road to get to the start of hiking trails. Visiting the Burgess Shale requires a lengthy hike up-mountain, and bookings need to be made in advance. Access to the MPER fossil sites is only available through free guided tours. Due to limited staff, guided tours are limited to one per day, 15 people per tour, in order to reduce the impact on MPERs coast. Nonetheless, with increasing recognition since 2007, guided tours in 2012 have to be booked up to months in advance. In 2011, MPER employees turned away 215 visitors.

3. Setting

3.1 Location and Physical Setting of Study Area

Mistaken Point Ecological Reserve (MPER) is situated on the Southern Shore of the Avalon Peninsula, Newfoundland (46˚37’45.03”N; 53˚10’29.78”W). It is located between the community of Portugal Cove South and the Heritage Site of Cape Race. Portugal Cove South has a population of 160 people (Statistics Canada, 2012). With the cessation of the cod fishery with the 1992 Cod Moratorium, Portugal Cove South has few local economic resources to sustain itself. However, it is positioned on a popular tourist route, the “Irish Loop”, and in 2007, an Interpretive Centre was designed and built within its boundaries. The intent for the centre is to promote knowledge and educate visitors about conservation of MPER’s Ediacaran fossils, as well as to contribute to the area’s development as a tourist attraction. Thus, MPER will not only be considered valuable scientifically, but also economically with increased visitation.

The four study areas within MPER include: Pigeon Cove (PC) Site 1, PC Site 2, Mistaken Point (MP) Site 3, and MP Site 4. PC Site 1 (46˚41’05.58”N; 53˚15’33.17”W) is 3 km east of Portugal Cove South. PC Site 1 contains one of the oldest assemblages of Ediacaran fossils within the Mistaken Point Ecological Reserve (Narbonne and Gehling, 2003). The most abundant fossils at the site are commonly referred to as “pizza discs” (Narbonne *et al*., 2001), irregular collections of lobes and troughs that have recently been synonymised, along with ‘lobate discs’ and ‘bubble discs’ (see Narbonne *et al.*, 2001), within the Ivesheadiomorphs (Liu *et al.,* 2011; A. G. Liu, personal communication).

PC Site 2 is located ~100 m south of PC Site 1 across a pebble-cobble- boulder beach (46˚41’00.43”N; 53˚15’31.80”W). PC Site 2 was chosen as a reference site with respect to wave angle of attack and structural geology, as well as the efficacy of the adjacent potentially protective headlands. PC Site 1 and PC Site 2 bedding planes are extremely accessible, located less than 50 m from the road across gentle topography. Both sites are subjected to long fetch southwest winds. They are situated along a geological fold, increasing their structural complexity. The angles of wave and wind impact, geological structure, and the location of the headlands vary for each site.

Southeast along the coastline from Pigeon Cove is Mistaken Point (MP), where an additional two sites were chosen for the project. Access to Mistaken Point from the land involves a 16 km drive along a graded road from Portugal Cove South, followed by a ~ 3.5 km hike through the Eastern Hyper-Oceanic Barren Eco-region. The bedrock at each of the Mistaken Point sites is composed of the D (lower) and E (upper) surfaces. The D surface on MP Site 3 is situated ~ 10 metres above sea level and is west of the adjacent E surface. The E surface of MP Site 3 is accessible from D, and is situated ~ 9 metres above sea level. MP Site 4 is separated by a 10 metre wide ravine from MP Site 3. The MP sites flank a narrow inlet of the ocean, and are capped by low Quaternary bluffs, approximately 2 – 3 metres in height.

The bedding planes at each of the Mistaken Point sites include numerous and diverse Ediacaran fossils of varying relief. The Ediacaran taxa at MP include: *Fractofusus* ('Spindle'); 'Ostrich Feather', *Charniadiscus*; *Bradgatia*; *Pectinate*s; and *Thectardis* (Clapham *et al*., 2003) among others. MP Site 3 (west side) is considered as the more significant due to the prominence of the fossils on these bedding planes. At present, guided tours for visitors are allowed on the E and D surfaces of MP Site 3, but not onto the less accessible MP Site 4. Understanding the presence of fossils in terms of abundance and diversity at each site not only determines the significant value of each site, but fossil morphology and distribution on the rock bed also contribute to differential erosion.

3.2 Bedrock Geology

The geological units in Mistaken Point Ecological Reserve include bedrock and Quaternary deposits. The dipping bedrock at Pigeon Cove is part of the Ediacaran Drook Formation, and that exposed at Mistaken Point is within the Ediacaran Mistaken Point Formation. Both units are included in the Conception Group (Canfield *et al.,* 2007).

Group	Formation	Age
St. John’s	 Renews Head Fermeuse Trepassey	
Conception MP Site 3 & 4 PC Site 1 & 2	 Mistaken Point Briscal Drook Gaskiers Mall Bay	 565 ± 3 Ma ☆ MP 575 ± 1 Ma ☆ PC

Figure 3.1: Group, Formation and age of study sites. MP Site 3 and 4 are exposures of the Mistaken Point Formation, while PC Site 1 and 2 are exposures of the Drook Formation.

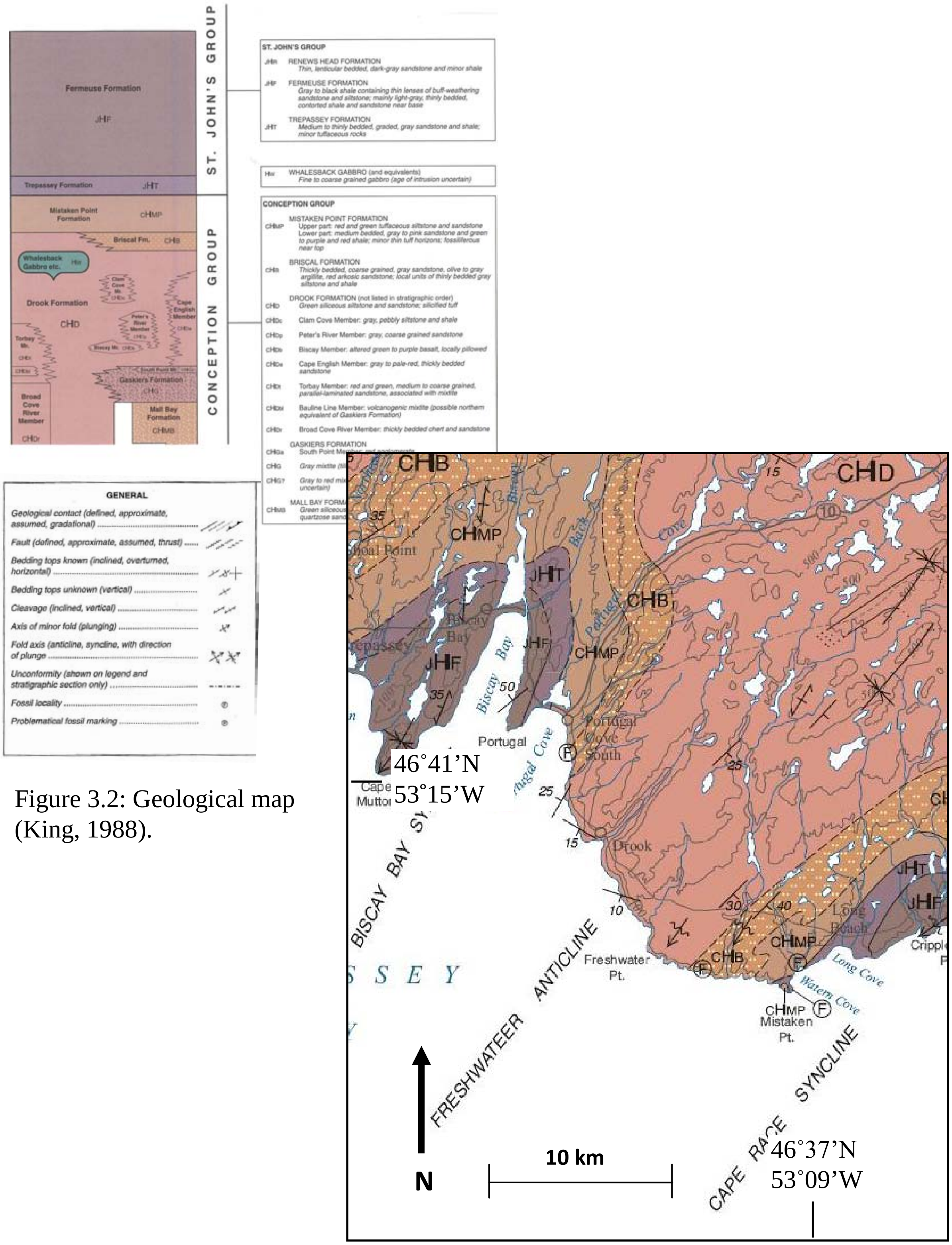

Figure 3.2: Geological map (King, 1988).

The Conception Group is more than 4 km thick, and consists mainly of medium to very thick bedded, grey to green, siliceous, turbiditic sandstones, with associated mudstones, siltstones, and argillites (Benus, 1988; Gardner and Hiscott, 1988; King, 1988). Volcaniclastic deposits, including airfall and reworked tuff, and modified tephra, are also present. The Conception Group has generally been interpreted as a submarine fan – basin plain deposit derived from a tectonically active volcanic terrain (Gardner and Hiscott, 1988). Units within the Conception Group include the Drook Formation (Pigeon Cove) and the Mistaken Point Formation (Mistaken Point).

Both the Mistaken Point and Drook Formations consist primarily of medium-bedded sandstones and mudstones (Benus, 1988.) The Mistaken Point Formation as a whole displays the turbiditic character that typifies the entire Conception Group (Williams and King, 1979; King *et al.,* 1988); all of the graded beds have regular thickness, and sharp upper and lower contacts. Current ripples in the turbidites yield a consistent paleocurrent direction toward the southeast. At Mistaken Point, a millimetre- to centimetre- thick tephra is present on the exposed fossil bedding plane and is responsible for moulding the Ediacaran fossils.

3.3 Quaternary History

The Mistaken Point area of the southern Avalon Peninsula was glaciated several times during the Quaternary. The most recent glaciation, during Marine Isotope Stage (MIS) 2, involved ice flow to the south and southeast (Catto, 1998). Glacial deposits include coarse diamicton, dominated by pebbles and cobbles with a mixture of sandy matrices, forming veneers and blankets over the bedrock. Deglaciation occurred approximately 12,000 BP (Catto and Taylor, 1998, Figure 3.3).

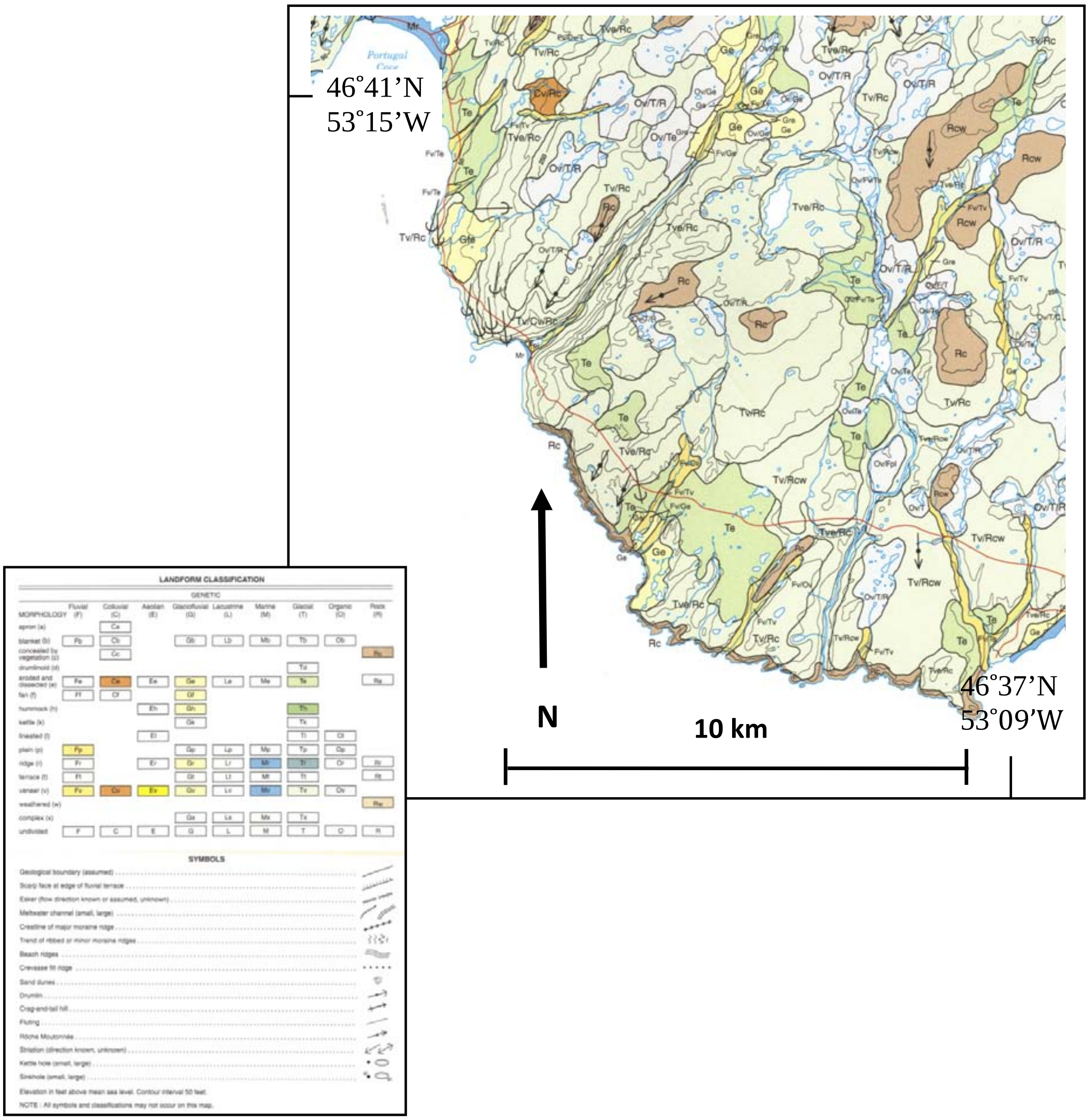

Figure 3.3: Legend and map of surficial geology, (Catto and Taylor, 1998).

Quaternary sediments exposed in coastal bluffs, as well as those present adjacent to the beaches at Pigeon Cove, potentially contribute to erosion of the fossils in the bedrock in a number of ways. Mechanical erosion due to the impact of fallen material via gravity, as well as the hydraulic force upon pebbles and cobbles of harder materials such as granite and quartz thrown up by waves, may scour and/or shatter the brittle and siliceous materials along the MPER coastline. In addition, the wedging of these materials within joint systems resulting from their deposition via slope failure also contributes to erosion. As well, although much of the eroded bedrock material along certain areas of MPERs coastline is lost to the ocean, some of the material resulting from rock fall lands on bedding planes.

When deglaciation commenced, isostatic uplift occurred (Liverman, 1994; Daly *et al.*, 2007). Glacioisostatic neotectonic activity potentially could result in reactivation of previous joint systems, which could accentuate erosion.

At the Last Glacial Maximum in MIS 2, the sea level along the coast of eastern Newfoundland was lower than it is at present (Catto *et al.,* 2003). Following deglaciation, relative sea level along the southernmost Avalon Peninsula was either at or very slightly above the present level, with a maximum inundation of less than 5 m (Catto, 2011). No deposits or landforms associated with elevated relative sea level are present at Mistaken Point or Pigeon Cove. Following a decline of relative sea level in the early to mid-Holocene (Forbes and Shaw, 1995), renewed transgression has marked the latest Holocene. Terrestrial peat deposits at modern sea level, drowned forests, and archaeological sites indicate that transgression has continued throughout the latest Holocene (Catto, 2006). The rate of relative sea level rise over the past 1,000 years in the southeastern Avalon Peninsula is approximately 3 mm/y (Catto, 2011).

3.4 Terrestrial Climate

Eastern Newfoundland has a mid-boreal climate (Köppen-Geiger Dfb) which describes the overall region as being relatively cool with seasonally consistent precipitation (Banfield, 1981).

Mean Annual Precipitation	1548.1 mm
Mean Annual Rainfall	1406.4 mm
Mean Annual Snowfall	141.65mm
Mean February Temperature	-4.05˚C
Mean July Temperature	13.25˚C
Prevailing Wind Direction	Winter NW ; Summer SW

Table 3.1: Climate data, St Shotts, Newfoundland, 40 km SW of Portugal Cove South (Environment Canada, 2011).

A large part of the climate along the southern shore is controlled by the dominant westerly winds of the mid-latitude Northern Hemisphere, and the proximity of the relatively cold waters of the Labrador Current system (Banfield, 1981). Fog commonly results from the interaction of cold Labrador Current and warm Gulf Stream waters southwest of MPER, as well as local occurrences of both advective and radiative fog.

The spring season along the south coast of the Avalon Peninsula is relatively long (March through June) followed by cool, wet summers with the driest and hottest month being in August (Environment and Canada, 2011). Normally autumn is quite short, and the winters are moderately mild and wet with the coldest month being February (Catto *et al.,* 2003).

Due to the southwesterly winds blowing from the terrestrial land westward of the South Coast and Avalon zone is subjected to more of a maritime influence rather than continental. This contributes to mean February sea surface temperatures that are less than 0°C along the majority of the coastline at shoreline sites. Daily mean temperatures in February vary from -3°C to -5°C. August daily mean temperatures vary from 14°C to 16°C (Environment and Canada, 2011). Those areas that are directly exposed to southwesterly winds, such as MPER, experience more variable temperature regimes resulting in freeze-thaw cycles throughout the winter months starting from mid-December to early April. However, frost events may very well occur at any time from early September to June (Catto *et al.*, 2003). Along the coastal areas of the southern shore roughly 15-25% of the precipitation falls as snow. Aspect and differences in the proportion of precipitation types also contribute to variation in distribution (Catto *et al.,* 2003).

A primary influence on the storm activity in this area is the North Atlantic Oscillation (NAO); a cyclic variation in pressure regimes that influences northern North Atlantic environments and communities (Hurrell, 1995; Topliss, 1997; Drinkwater *et al.*, 2003; Hurrell *et al*., 2003; Vasseur and Catto, 2008). A positive NAO phase contributes to the presences of strong northwesterly to northeasterly winds, which vary depending on latitude. The negative

NAO phase produces the opposite effects, resulting in warmer drier winters, possibly reducing protective snow and ice cover alone the coastlines of Newfoundland (Catto, 2006; Vasseur and Catto, 2008).

3.5 Marine Environment

Wave action results in three primary variables that influence the erosion of a cliff face: 1) fetch direction and wave angle on impact; 2) significant wave height; and 3) frequency of high magnitude wave events (storms) (Haslett, 2009; Forbes *et al*., 2004). Effectiveness on coastal recession is a product of wave power; increased wave height contributes to the level of wave impact. Increased wave power not only implies that waves are able to move further inland, but can overtop in areas of higher elevation as well.

Waves breaking onto bedded, jointed or faulted rocks can create hydraulic as well as pneumatic pressure in the structural gaps within the fractures and joint systems along bedding planes (Trenhaile, 1987). The geological structure of the coastline as well as the wave energy impacting the coastline influences the pneumatic and hydraulic pressures that may lead to weakening and readying of rocks for detachment. Detached blocks may break down under wave activity, gradually rounding the clasts and reducing their size. Sediment that is provided by the process of quarrying may also contribute to mechanical weathering in conjunction with the waves to further erode rock through abrasion (Robinson 1977a, b).

3.6 Increased Intensity and Frequency of Storms

Although coastal material and morphology determines the sensitivity of a coastline to climatic events, intensity and frequency of storm activity has a major influence on coastal recession (Forbes *et al.*, 2004). The more significant storms impacting Atlantic Canada are mainly extratropical in origin (Forbes *et al.*, 2004; Vasseur and Catto, 2008; Catto, 2011). Extratropical storms usually form at mid-latitudes and migrate in a west-east direction. Although extratropical storms are commonly less intense than hurricanes, they are much larger in size and have a tendency to impact a larger geographic area (Hayden *et al.*, 2000). Tropical storms originating from more southern latitudes also occur, and may interact with extratropical events to form extratropical transitions (Catto and Batterson, 2011). Understanding the nature of storm impacts on a coast within a particular region is fundamental to understanding long-term coastal response (Forbes *et al*., 2004).

3.7 Vegetation

The type and distribution of vegetation, including moss, lichens, grasses, shrubs and trees on the backshore, and marine nearshore (intertidal) vegetation can influence the level of erosion and/or stability along a coastal segment. A sparsely vegetated backshore might indicate that there has been recent and high energy wave attack. In addition, the presence of vegetation can also reduce surface flow rates during storms, contributing to stabilization.

3.7.1 Terrestrial

The terrestrial vegetation at MPER is classified under the Eastern Hyper-Oceanic Barren Ecoregion. The poor drainage and high precipitation contributes to stream erosion and gullying. Blanket bogs are common throughout the topography.

The Eastern Hyper-Oceanic Barrens Ecoregion, including the extreme southern part of the Avalon Peninsula, is almost completely devoid of tree cover, with the exception of low-lying balsam fir (*Abies balsamea*) tuckamore (dwarf krummholz), black spruce (*Picea mariana*), and white spruce (*Picea glauca*). The eco-region is dominated by bog, which contains crowberry (*Empetrum nigrum*), blueberry (*Vaccinium uliginosum*), partridgeberry (*Vaccinium vitis-idaea*), bakeapple (*Rubus chamaemorus*) alpine azalea (*Loiseleuria procumbens*), moss campion (*Silene acaulis*), and heath moss (*Rhacomitrium lanuginosum*) as well as a variety of lichens (Damman, 1983).

3.7.2 Marine

The marine vegetation at MPER was defined as being within the intertidal zone or below. The dominant species is *Ascophyllum nodosum* (rockweed), which is observed as extensive carpets of yellow-brown seaweeds growing on bedrock within the tidal zone (Catto *et al*., 2003). The upper intertidal zone with MPER was marked by terrestrial crustose lichens such as *Verrucaria maura* species (Catto *et al*., 2003) as well as *Xanthoria sp*., both common along many North Atlantic coastlines. Lichens may either physically erode rock by loosening it with their thalli or protect the rock by acting as a barrier against the elements. Observing the surface distribution of lichens can also be helpful in understanding which parts of the coastline receive the greatest amount of wave impact.

3.7.3 Study Sites

The two primary MPER sites (PC Site 1 and MP Site 3) were chosen for analysis for the following reasons. Significant paleontological research has been conducted at these two sites, and they are considered by paleontologists as being scientifically valuable with respects to their contribution to the geological time scale. Erosion has been observed by researchers and MPER staff at these two sites in recent years. An additional factor is the anticipated increase in visitation to MP Site 3, as this is the only site within MPER where the public is allowed access through guided tours.

The two additional sites chosen (PC Site 2 and MP Site 4) were chosen as reference sites to assess relative differences in physical processes and extents and responses to types of erosion. PC Site 1 and 2 included folded bedrock, and are situated within the same cove, adjacent to a pebble-cobble-boulder beach. However, the differences in relation to the presence of headlands, the angle of the dipping folded plane, and their aspects, suggest that each site could be subject to differences in type and significance of physical processes. MP Site 3 is higher in elevation, and thus less exposed to wave impact, than the comparative MP Site 4, in addition to being the only segment of fossilized coastline open to public visitation. MP Site 3 and MP Site 4 have almost identical geological structure and lithology.

4. Methodology

The area of Mistaken Point Ecological Reserve is 5.7 km^2, with a coastline length of 24 kilometres. Within this area, four coastal sites were chosen for analysis to help better understand erosion along this coastline. Between June 2009 and August 2011, MPER was visited on 13 occasions. No visits occurred during the winter months from January to March, due to weather conditions and difficulty of access. Although quantitative long-term rates of erosion could not be determined due to time and funding constraints, qualitative information was acquired and was coupled with the use of quantitative methods to strengthen observations concerning the processes causing erosion along MPERs coastline. The four sites include two locations within Pigeon Cove; PC Site 1 (north) and PC Site 2 (south), and two sites at Mistaken Point; MP Site 3 (west) and MP Site 4 (east). At PC Site 1 and PC Site 2, research was primarily focused on a single bedding plane of the larger area. At MP Site 3 and MP Site 4, observations were made on two bedding planes at each of the sites; the 'E' and 'D' surfaces (Table 4.1).

Bedding Planes	PC Site 1	PC Site 2	MP Site 3 'D'	MP Site 3 'E'	MP Site 4 'D'	MP Site 4 'E'
Area (m^2)	~150	~170	~130	~115	~100	~115

Table 4.1: Estimates of exposed bedding plane area at PC Site 1 and 2, MP Site 3 and 4.

The methods chosen to assess coastal erosion along this part of MPERs coastline include the following:

- Photographs were taken during each visit, and aerial photographs from 1966 and 2008 were analyzed for changes over time at each of the project sites. The steepness of the cliffs along the MPER coastline, coupled with the 42-year time span between the most recent and the oldest aerial photographs, limited the potential value of orthorectification;
- Bedding plane, fracture, and joint strike/sense/dip measurements were taken using a Brunton precision compass. Additional measures were taken of their width, length, opening and spacing;
- Measurements of bedding planes and joint attitudes were plotted on equal-area Stereonets with the use of GEOrient© 9.2, 2006;
- Observations of wave dynamics (wave period (T), and angle of impact (α)) were recorded during each visit, to determine wave regime;
- Base-line measures were taken using a measuring tape from fixed points inland to the bluff-line of each site, to provide baseline data. Future surveys in subsequent years could be used to assess any ongoing recession of unconsolidated Quaternary deposits; Real Time Kinematic Global Positioning System (RTK GPS) (Ashtech©, 2011) surveying was conducted for each site, in order to provide baseline data. Surveys in subsequent years, based on the established RTK reference points inland, could be used to assess any ongoing erosion during future research;

- Map sketches and the pattern of lichen cover as well as distribution along rock surfaces was used as supplemental method to assess human and wave impact; and
- Visitation statistics recorded at the Portugal Cove South Visitor Centre were analyzed to assess possible impacts resulting from tourist use.

4.1 Photographs

Field photographs of all four sites were taken during each visit from June, 2009 until August 2011, including repetitive photography from the same location in some instances. Additional photographs were provided by NL Environment and Conservation. Photographs are helpful in that they provide evidence of physical change at the coastal sites. These physical changes may include rock removal caused by physical processes or human impact.

Two sets of aerial photographs were obtained. One set taken in 1966 (Mistaken Point to Portugal Cove South, 19761, September 1966, 1:15 840) was acquired through Memorial University's Map library, and another taken in 2008 (Mistaken Point to Portugal Cove South, 2008, 1:11 500) was acquired from the Department of Environment and Conservation, Surveys and Mapping Division, Newfoundland and Labrador. Although the cliff line in the aerial photography is discernible, the exact vertical surface of the cliff-face area does not show up on (normally-oriented) aerial photographs and maps. This distortion makes it difficult to conduct orthorectification. Nonetheless, the aerial photographs can be helpful in providing information concerning large scale mass changes occurring at each of the sites; as well as aerial photographs can help understand regional strike (orientation direction) patterns that may complement measurements taken on the ground.

4.2 Strike and Dip Measurements

Adhering to strike/dip sense convention used to measure the geological structure at each site, a Brunton compass was used to take geometrical measures including the orientation of the joint systems identified at each site. Folds were identified, and faults intersecting the bedding planes were observed and recorded. Each of the primary and secondary joint measurements were designated within Sectors at Pigeon Cove Sites, related to position with respect to folding; and Coastal (south) and Inland (north) positions at Mistaken Point Sites related to the presence of direct wave impact from the south. The measurements along these surfaces were further grouped into zones. The geometrical measurements taken were then plotted on Lambert azimuthal equal-area projection stereonets, using GEOrient © 9.2, Version date, November 1st, 2006, and analyzed to understand the relationship between geological structure and the configuration of the eroding coastline.

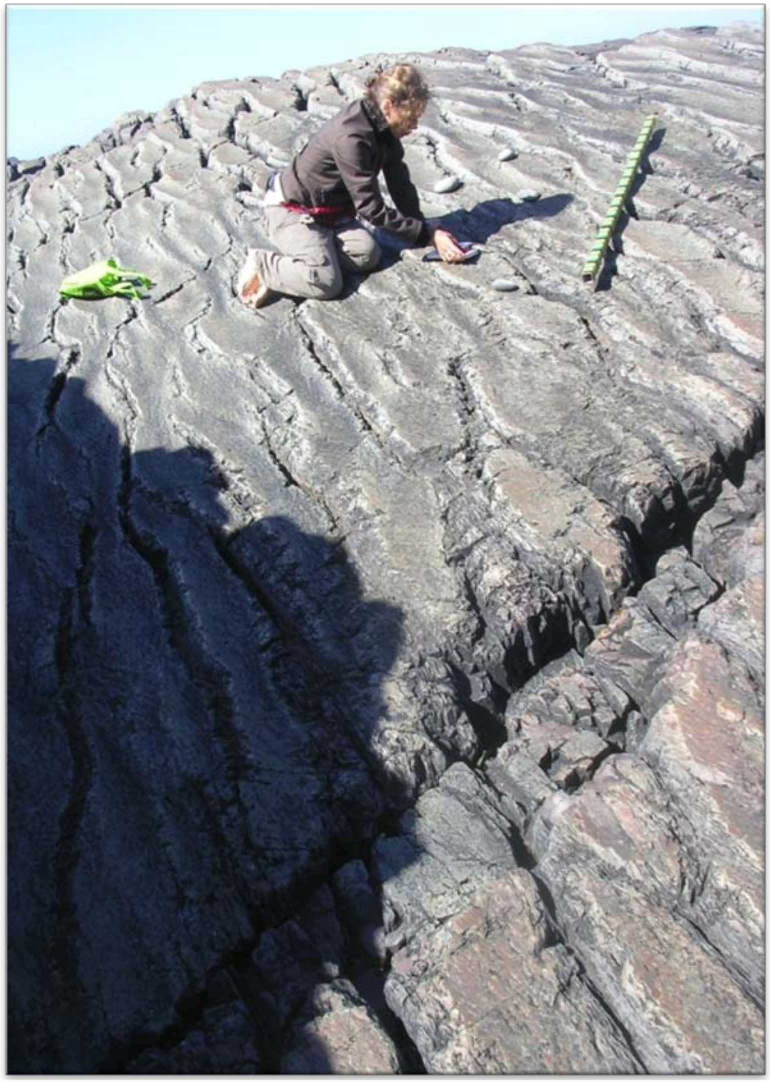

Figure 4.1: Measuring joint sets on D surface, MP Site 4.

4.3 Wave dynamics

During each on-site visit, measurements were taken of the following wave dynamic properties:

- Wave-period (T)
- Wave-angle (α) **–**visually determined using a Brunton compass, by measuring the impact angle of the nearshore wave crests.

4.4 Map Sketches

Each of the four sites observed from 2009-11 and their relevant features were mapped to paper. Three such relevant features include: 1) chemical weathering due to oxidization along the surfaces of bedding planes; 2) discolouration (e.g. rock scars) from mechanical erosion due to rock fall impacts; and 3) the presence of marine flora along the coastal surfaces. The width, length, opening, and spacing of joint systems were also mapped.

Weathering discolouration caused by the chemical action of oxidization was characterized at each site using a Munsell Soil-Color Chart (2009). Areas where Munsell hues were darker have either been exposed for greater lengths of time, have been subjected to greater intensity of weathering, and/or have not been subjected to recent erosional processes (Hall, *et al.*, 2008). In addition, discolouration of rock surfaces such as rock scars resulting from rockfalls was also observed and plotted on the polygon maps. Marine flora including lichens can be used as a relative indicator revealing patterns and rates of erosion (e.g. block removal post-storm, or spray zone) along the cliff face (Dalby *et al.*, 1978; Hall *et al.*, 2008).

4.5 Bluff Recession Measurements

The initial method used to assess erosion of the Quaternary bluff line was measurements at right-angles from the soft coastline edge to fixed inland reference points using a 50 metre measuring tape. Position and bearing from a fixed reference point were taken and recorded using a handheld GPS (Garmin eTrex Venture ®). Once the coastline was reached with the measuring tape, a photograph of both the bluff edge and tape measure was taken. The intent in conducting these measurements was to record the position of the bluff edge, thereby providing baseline data that could allow rates of coastal erosion to be determined by surveys in future years.

In July, 2009 at Pigeon Cove, the starting point was chosen 3 metres north of the 'Mistaken Point Ecological Reserve' sign located at 90° to the shoreline at PC Site 1. To cover the length of both PC Site 1 and PC Site 2, 61 measurements were taken at 3 metre intervals using the road as a point of reference.

In July, 2009 measurements at Mistaken Point were taken using the same method using a fence post along the bluff as a point of reference. However, as concern was expressed that the fence posts may not be stable or permanent, permission was received from Ecological Reserve Manager Dr. Richard Thomas to place stainless steel tent pegs with orange plastic tops at the base of each fence post. Fence posts were roughly 3 metres apart. A total of 32 measurements covered the length of bluff line directly above the Mistaken Point fossil assemblages.

4.6 Real Time Kinematic Global Positioning System (RTK GPS), Ashtech©

RTK GPS was subsequently used to provide data to contribute to the understanding of erosion along the Quaternary bluff materials above the bedding planes at each of the Reserve sites. RTK GPS was used to survey the bluff position at Pigeon Cove on March 15th, 2011, and at Mistaken Point on May 13th, 2011. The intent in conducting these measurements was to record the position of the bluff edge, thereby providing baseline data that could allow rates of coastal erosion to be determined by surveys in future years.

RTK GPS is used as a Canadian spatial referencing system that has an accuracy within five centimetres. Dual frequency RTK GPS involves the use of two GPS receivers, the stationary Base Station and a Rover. While the two receivers communicate with one another via radio link, the dual frequency allows for an increase in accuracy of the chosen target point (Natural Resources Canada, 2011). The precision of the instrument is measured by the Rover's relative baseline-length from the Base station, and therefore the baseline distance was kept as short as possible (< 10 km).

A total of 192 target points was surveyed along the Pigeon Cove coastline (Figure 4.2). The target points were initially recorded with RTK GPS along the road at 3-metre intervals and were also taken along the bluff line edge at 3-metre intervals, beginning at the bluff line and oriented at 90° to the starting position at the road. The starting position was 3 m north of the 'Mistaken Point Ecological Reserve' sign used in the original tape measurements. The Base station was situated east across the road from the 'Mistaken Point Ecological Reserve' sign. A control point referenced by a PVC pipe pushed into the ground, surrounded by a pile of rocks collected from the surrounding area, and located by GPS, was established.

Figure 4.2: Air photo of the 192 target RTK points (red) measured along the bluff at the Pigeon Sites.

A total of 121 RTK GPS target points was measured at Mistaken Point (Figure 4.3). Half of these were kinematic (running) RTK points taken along the bluff line, while individual (static) points were taken along the fence line. The base station was located ~ 3 km NE with coordinates of 334904.277146928 E, 5168051.90779353 N. Both base stations were located outside of the Ecological Reserve boundaries.

Figure 4.3: Air photo of 121 RTK GPS target points (red) measured along the bluff at the Mistaken Point sites.

4.7 Visitation statistics

Visitation statistics from 2007 to 2011 were acquired from the Portugal Cove South Interpretive Centre. The Interpretive Centre for MPER has only been present since 2007, and has recorded numbers through a guest book that employees of the centre diligently request each visitor to sign. However; because the Reserve remains relatively open to the public, and has had little active management between the years 2007-2012, actual visitation numbers are not known.

5. Results

5.1 Pigeon Cove (PC Sites 1 and 2)

Pigeon Cove is flanked by two headlands that extend approximately 100 m seaward, oriented NE-SW. Inshore from these headlands is a morphologically complex coastline composed of a pebble-cobble-boulder -beach framed by two folded masses of resistant bedrock.

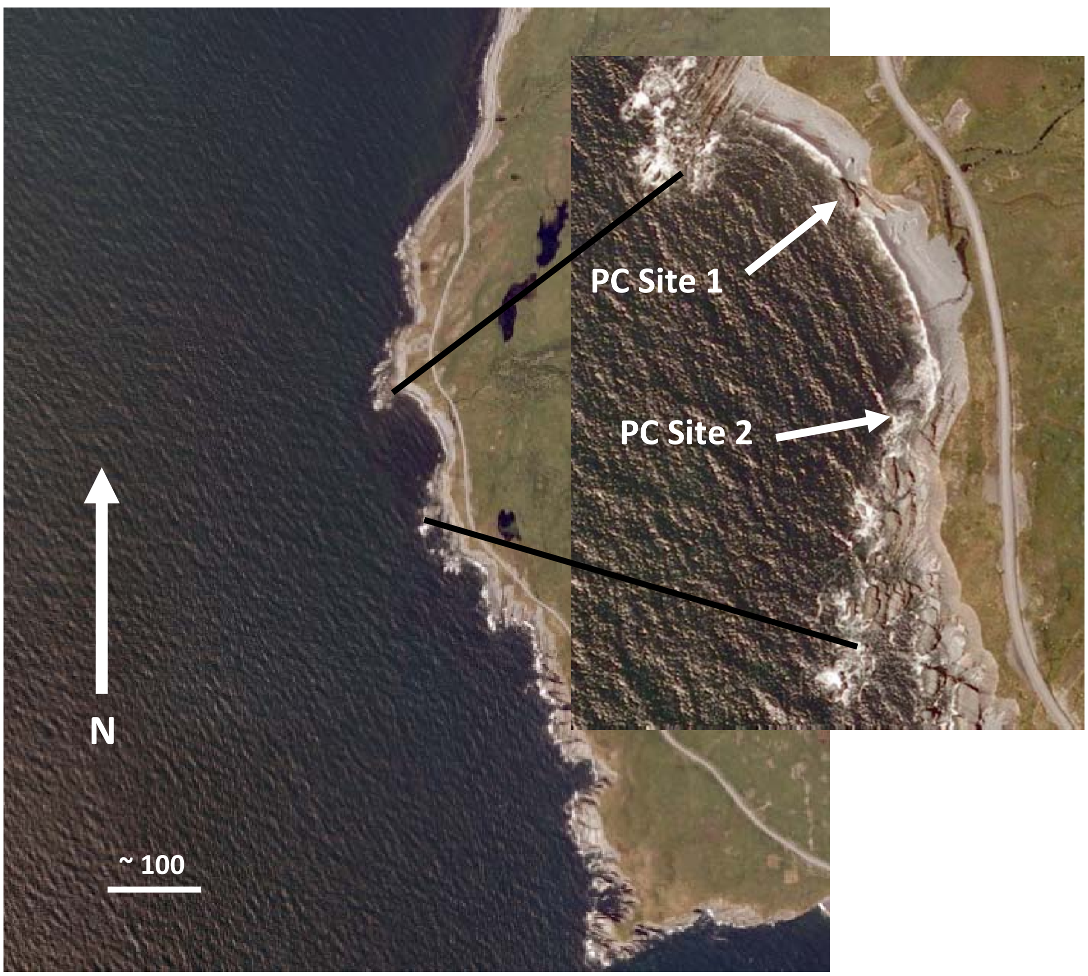

Figure 5.1: Air photograph of Pigeon Cove, PC Site 1 and PC Site 2.

Both Pigeon Cove sites are located roughly 50 m west of a graded road (Figure 5.1). The intervening terrain is composed of a peaty organic veneer, locally with earth hummocks, which supports heathland vegetation. Although access from the road is easy, people are not permitted to enter Pigeon Cove (a restricted fossil zone) unless they have a special permit.

The prevailing wind is southwesterly reaching Pigeon Cove coastal front at a 45° angle impacting the beach at 90° to the trend of the shoreline. The system is dominated by shore-normal, swash-aligned, reflective conditions. Strong southwesterly winds generated by storms of both tropical and extra-tropical origin produce high energy conditions along the coastline.

The rock types exposed at the Pigeon Cove Sites bedding planes are greyish green siliceous sandstone, mudstone, and siltstones, representing multiple turbidites (Benus, 1988; Gardner and Hiscott, 1988; King, 1988). A second rock type noted was weaker and porous tephra, volcanic debris including clay-sized ("dust"), and silt-sized and fine sand-sized ("ash") particles.

Observations along the bedrock surfaces in Pigeon Cove included measurement of faults, orientation and spacing of joints and intersecting joint systems, as well as joint opening width. Dominant (primary) and secondary joint systems were recognized based on their extent and consistency of spacing, resulting in intersection with adjacent fractures and other planes of weakness. PC Site 1 and 2 each divided into zones from north to south (Table 5.1, Figure 5.8).

5.1.1 PC Site 1: Geological Structure

The coordinates for PC Site 1 are 46° 41’06.39” N; 53° 15’31.40” W. The bedding plane observed in detail is termed PC 1 IBP (Pigeon Cove 1 Ivesheadia bedding plane). Primary structural details are listed in Table 5.1. Due to the complexity of the structure and erosion at this site, field observations of the bedding plane were grouped into 14 zones (A through N) within the North, Central, and South Sectors (Figure 5.2). Fifty-three joint sets were measured.

PC 1 IBP contains the most prominent and important fossil assemblage of the four bedding planes noted within PC Site 1. The other three bedding planes from west (coastline) to east (inland) are termed: upper (PC 1 UBP), middle (PC 1 MBP), and lower (PC 1 LBP) stratigraphic layers, the latter overlying PC 1 IBP (Figure 5.3). These three exposed overlying stratigraphic layers cover the northwestern part of PC Site 1. Aside from PC 1 IBP, Ediacaran fossils have also been noted on PC 1 LBP, and PC 1 UBP.

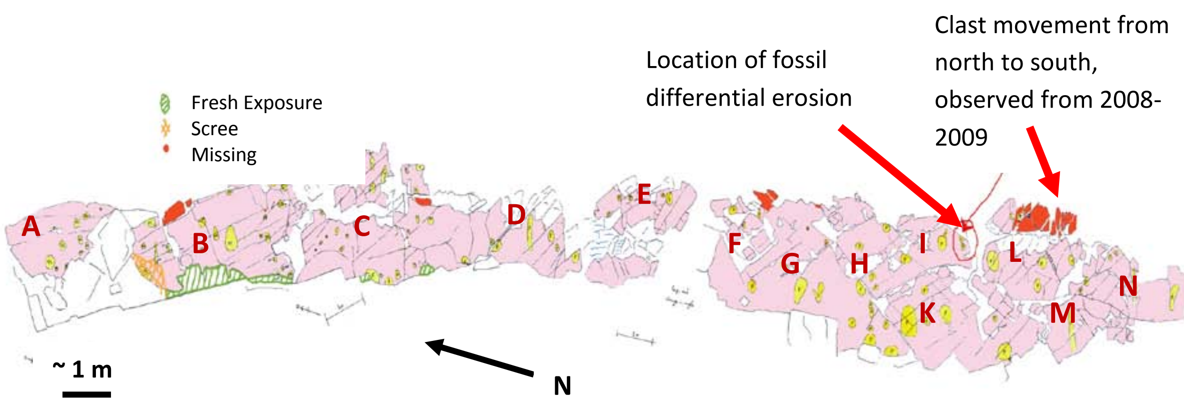

Figure 5.2: Map with measured SDS Zones (A through N) and changes observed from 2008 to 2009 at PC Site 1. Courtesy of Alex Liu (assisted by Jack Matthews) (modified from Liu 2011, fig. A4.2b).

In addition to these harder stratigraphic layers of rock, two weaker layers of tephra were noted. An upper tephra layer is located directly below PC 1 LBP and above PC 1 IBP. A lower tephra layer is located directly below PC 1 IBP (Figure 5.3).

Figure 5.3: Exposed stratigraphic layers and their thickness overlying and including the *Ivesheadia* BP (PC 1 IBP), North and Central sectors.

Unit PC 1 UBP had strike-dip sense (SDS) of 358˚/52˚. No loose clasts were noted on this surface, although it is highly eroded by wave impact. Unit PC 1 MBP had a SDS of 343˚/47 E and had on its surface large eroded clasts with highly weathered surfaces. The lowermost stratigraphic layer (PC 1 IBP) shares the same orientation as PC 1 MBP and is the most extensively exposed of the six stratigraphic surfaces (Figure 5.3).

PC 1 IBP had a total exposed perimeter of 86 m, 37 m of which are along the inland length of the site, 2 m to the north, 7 to the south and 40 m along the coastal edge. The irregular, fractured surface is located on a large fold extending from north to south.

5.1.1.1 PC Site 1: Orientations, Width and Spacing of Joints

Although the NW-SE, and NE-SW oriented populations are similar, additional joints are aligned N-S (Figure 5.4).

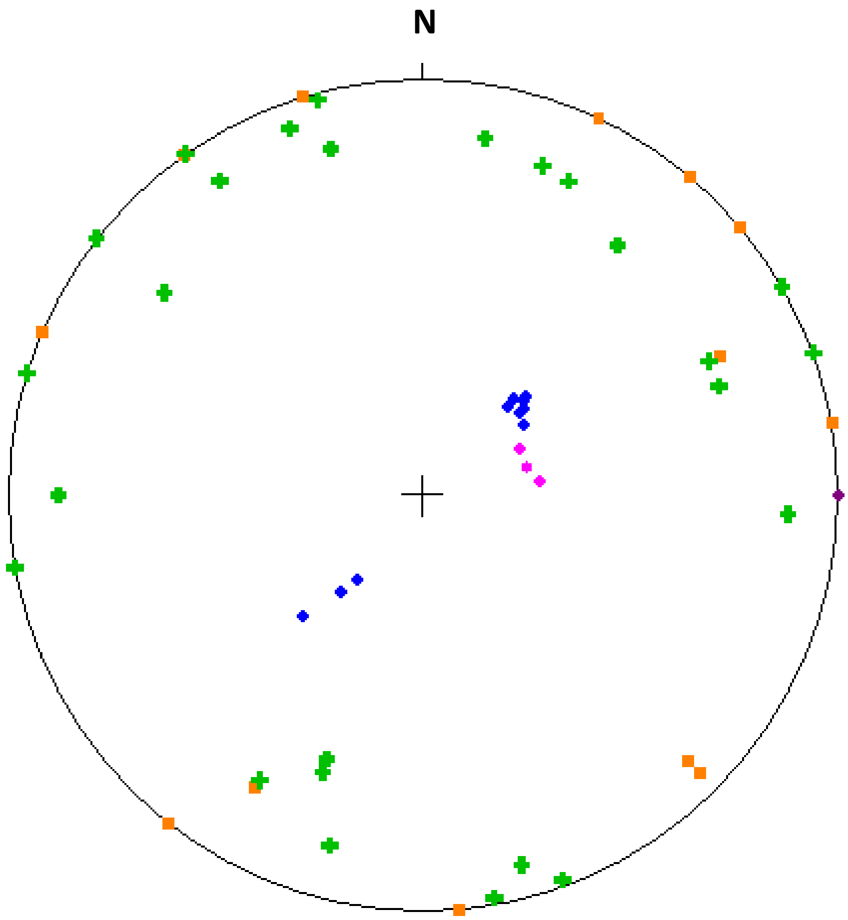

Figure 5.4: Pole-to-plane stereonet of joint sets measured at PC 1 IBP. The data on the following page indicate the joint systems measured as well as their mean principal orientation.

No. of Data = 10
Mean Principal Orientation = 141/13W
Mean Resultant dir'n = 11-232

South Side Joints (green cross)
No. of Data = 38
Mean Principal Orientation = 95/83S
Mean Resultant dir'n = 57-197

South Side BP (blue circles)

PC 1 IBP	Bedding Plane	Primary Joint Set	Opening Width (mm)	Spacing (cm)	Secondary Joint Set	Opening Width (mm)	Spacing (cm)
North Sector							
Zone A	353˚/23˚ SW	360˚/90˚	1	2 -3	N/A	N/A	N/A
Zone B	353˚/23˚ SW	310˚/90˚	1	15 - 25	235˚/90˚	1	4 - 20
Zone C	345˚/21˚ SW	308˚/90˚	1	8 - 15	235˚/90˚	1	5 - 25
Central Sector							
Zone D	335˚/21˚ SW	300˚/70˚ SE	1	15 – 30	225˚/84˚ NW	1	5 - 10
Zone E	314˚/24˚ S	308˚/77˚ S	1	10 – 20	260˚/88˚ W	1	4
Zone F	325˚/24˚ S	290˚/60˚ E	1	4 - 15	235˚/90˚	1	3 - 15
Zone G	319˚/26˚ W	350˚/68˚ S	1	15 - 30	237˚/79˚ SW	1 – 3	4 - 12
South Sector							
Zone H	320˚/25˚ NW	300˚/76˚ NW	1 – 60	6 – 15	340˚/65˚ NW	1	1 - 2
Zone I	316˚/28˚ NW	255˚/88˚ SW	1 – 10	6 – 15	360˚/90˚	1	10 - 15
Zone J	317˚/27˚ NW	290˚/57˚ E	1 – 10	2 – 8	360˚/90˚	1	4 - 15
Zone K	310˚/25˚ E	255˚/75˚ S	1 – 10	10 -40	340˚/90˚	1 – 3	50
Zone L	315˚/34˚ E	242˚/90˚S W	1 – 10	25 - 45	335˚/75˚ W	1	15
Zone M	313˚/26˚ S	240˚/71˚ E	1 – 20	20 - 30	332˚/90˚	1 – 10	50
Zone N	308˚/21˚ NW	250˚/74˚SE	1 – 3	2 – 10	338˚/83˚NW	10 -20	30 - 40

Table 5.1: Primary and Secondary joint sets along Pigeon Cove (PC 1 IBP).

North Side BP (pink circles)

No. of Data = 4
Mean Principal Orientation = 167/22W
Mean Resultant dir'n = 22-257

North Side Joints (orange square)

No. of Data = 13
Mean Principal Orientation = 290/88N
Mean Resultant dir'n = 68-245

5.1.1.2 PC Site 1: North Sector

The North sector includes the northwest ~ 10 m of PC 1 IBP as exposed along the coastal side. Except for Zone C (SDS of 345˚/21˚SW) the North sector surface has a primary SDS orientation of 353˚/23˚SW. In Zone A, a single major joint system was identified as trending 360˚ with a vertical dip. The joints are continuous, extending across the entire exposed bedding plane of prominent *Ivesheadiomorph* fossils to the edge of the lower stratigraphic layer. The spacing between the joints within this system was ~ 2-3 cm. Width of the surface openings of individual joints ranged from < 1 mm to 1 mm. A small amount of accentuated widening due to plucking was visible to the NE (exposed) part of PC 1 IBP. *Ivesheadia* fossils were subject to plucking, but plucking was also apparent in areas where fossils were not present. The upper surfaces of many of the fossils with higher relief were broken off.

The upper tephra layer along the North Sector of PC IBP is eroded ~ 20-30 cm inward, creating a notch. The consistency of the upper tephra when saturated with water was soft and viscous to a few centimetres inward. After recent wave events, the eroded void may be filled with pebbles and cobbles. An additional tephra lower layer, 8 cm thick, lies below PC 1 IBP and extends along the full length of PC 1 IBP. Although it was not notched, it was saturated and viscous along its outer beach- exposed edges.

Figure 5.5: Wave impact to the north of PC Site 1.

Zone B and C shared the same dominant joint system with a SDS of 310˚/90˚, but with a much wider spacing of 8 to 25 cm (Figure 5.6). Both these Zones had a secondary intersecting joint set of 235˚/90˚. Irregular tensile fractures with a spacing of ~ 1 cm and width of 1 mm trend roughly normal to the dominant joint system. Where the dominant joint system intersects with these fractures, plucking and erosion was observed.

This part of surface is much less exposed to the beach, and is not directly adjacent to the Quaternary bluff, and therefore little material from these was observed. However, parts of PC 1 IBP were visibly eroded, in addition to erosion of the overlying stratigraphic layers. As well, scree derived from PC 1 UBP had fallen onto the bedding plane.

The eroded pieces from PC 1 IBP form orthogonal blocks, whereas the eroded scree pieces from the overlying planes are irregular shapes. Erosional scars in the overlying bedding planes are conchoidal in nature. In this part of the North Sector, the upper tephra is not eroded, and extends onto the exposed unit of PC 1 IBP.

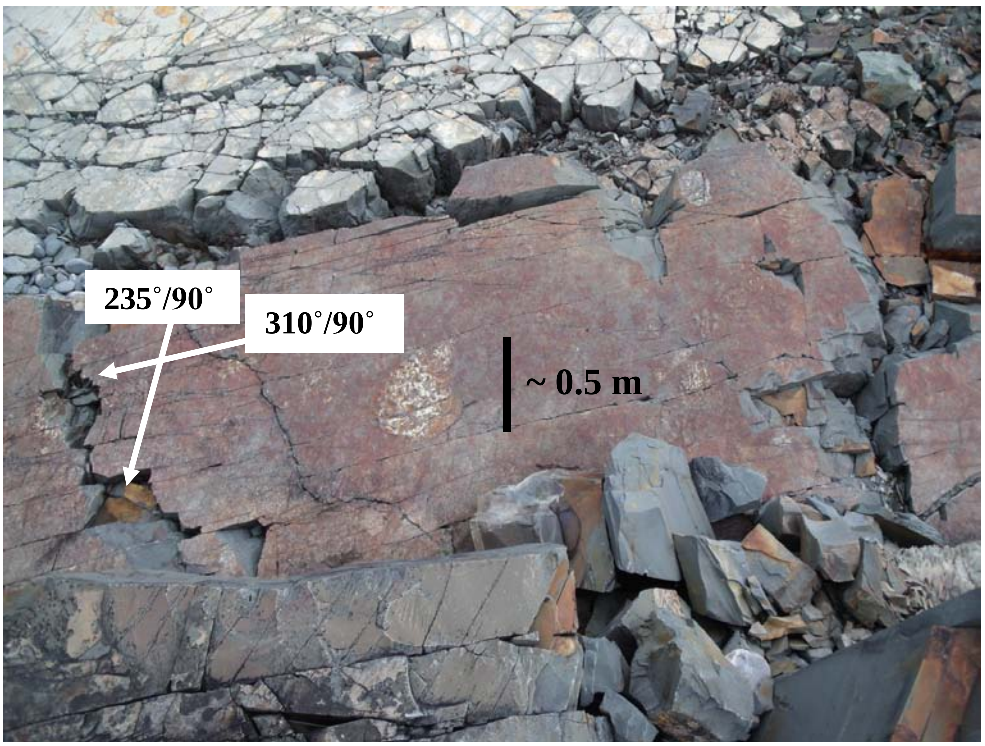

Figure 5.6: Conjugate joint sets (310˚/90˚ and 235˚/90˚) Zone B and C, North Sector PC 1 IBP.

5.1.1.3 PC Site 1: Central Sector

In general, the central part of PC 1 IBP is one of the most complex areas, both coastal and inland, possessing some of the most prominent and variable joint patterns.

With a complex fractured system, the Central Sector has a mean bedding plane orientation of 323˚/24˚ SW. The dominant joint system within the D Zone has a strike and dip of 300˚/70˚ SE. A series of eroded blocks fallen the overlying strata was observed over PC 1 IBP within the central sector. The inland (east) part of this bedding plane is marked by freshly eroded clasts from PC 1 MBP, interspersed with finer Quaternary bluff material. PC 1 LBP, to the southwest of PC 1 IBP, shows eroded bedrock, with various shapes and sizes of rounded

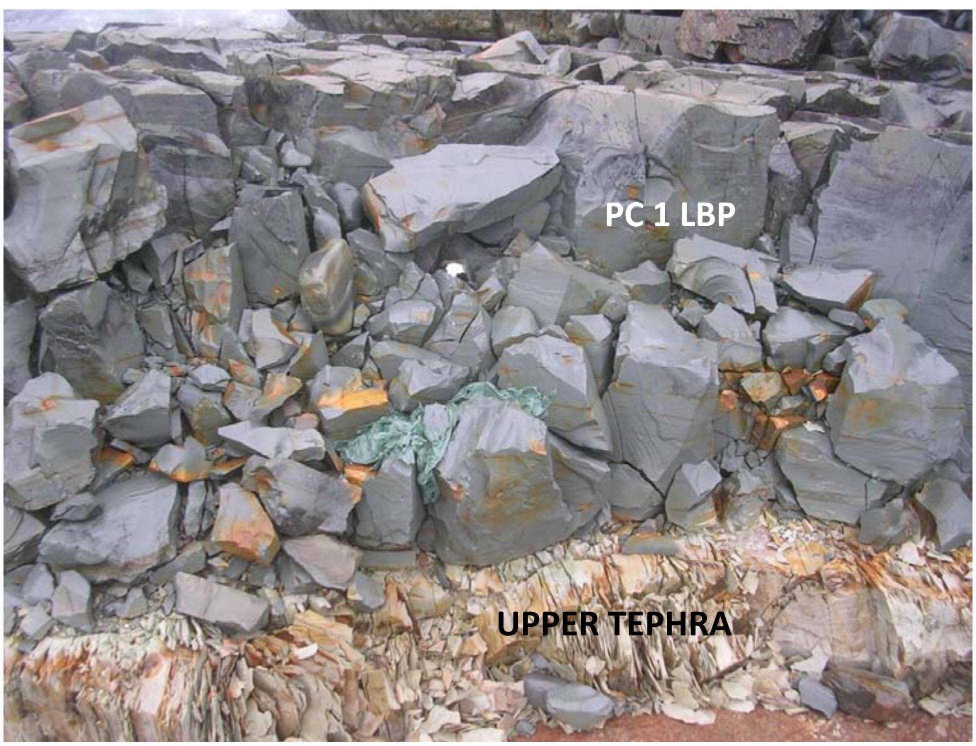

Figure 5.7: Orthogonal block erosion and platy tephra layer, PC 1 LBP, exposed at the North and Central Sectors, PC Site 1.

clasts, suggesting a number of different factors acting on this surface. The lower stratigraphic layer adjacent to PC 1 IBP has receded through erosion much more than the upper tephra layer. The upper tephra layer along the Central Sector is platy (Figure 5.7). To the south, the upper tephra layer is covered by clast debris deposited from PC 1 LBP. Over much of the Central Sector, the surface area of the lower tephra layer below PC 1 IBP is exposed 2 to 5 cm inland.

In the southern part of the Central Sector, the dominant joint systems vary. The most prominent joint systems are oriented at 308˚/77˚ S (Zone E), 290˚/60˚ E (F), and 350˚/68˚ (G). Secondary joint systems are aligned 260˚/88˚ W (E), 235˚/90˚ (F), and 237˚/79˚ SW (G). Surface weathering and erosion was observed along this part of PC 1 IBP. Spacing of joint sets varies (Table 5.1) from 4 to 15 cm with inconsistency of spacing and width joint systems along the Central Sector.

Comparison of the map drawn by Alexander Liu (assisted by J. Matthews) in 2009 with observations in 2010 revealed that differential erosion of an *Ivesheadia* occurred along the inland edge of Zone F (Figure 5.2, Figure 5.8).

The 1-2 cm depth to which this fossil was eroded was the same depth of erosion observed along this surface of conjugate joint fractures. The conjugate joint width was ~ 15 cm and length was ~ 20 cm, with some oxidization and lichen growth at the planar intersections. Pebbles and cobbles were also noted near this part of the PC Site 1 surface.

Figure 5.8: Differential erosion along Central Sector, L Zone with a SDS of 242˚/90˚SW and 335˚/75˚ W.

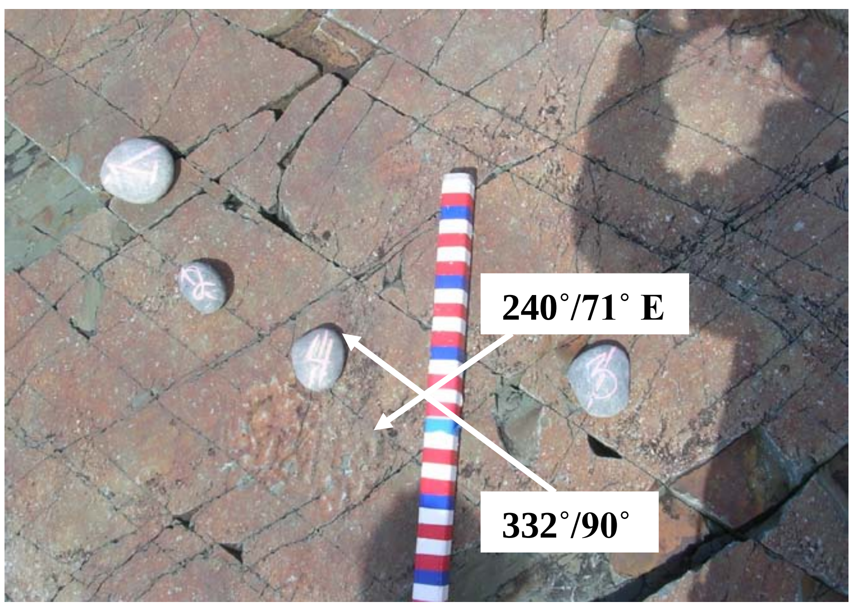

Figure 5.9: Conjugate joint system, M Sector 240˚/71˚ E and 332˚/90˚ - blue, red and white tape marks at 2 cm in width.

5.1.1.4 PC Site 1: South Sector

A highly eroded part of the bedding plane where a pool of water (presumably a mix of fresh and salt) was observed on every visit divided the Central and Southern Sectors of PC 1 IBP.

The mean attitude of the bedding plane along the South Sector is 316˚/27˚ NW. Within I Zone the most obvious structural component of this segment is the presence of two major joint sets intersecting (255˚/88˚ SW and 360˚/90˚ with a variation from 20˚ to 28˚ along the secondary set) which to forms a consistent pattern of intersecting joint fractures. For the remainder of the South Sector, variation in joint patterns was noted.

Evidence of erosion within this sector was noted. Smaller surface blocks with a thickness of 1–1.5 cm had been removed from the various surface points where conjugate joints intersect. Some of these eroded surfaces were weathered or oxidized, and others had fresh surfaces. Loose eroded blocks were most common along the inland part, interspersed with Quaternary material. Clasts along the coastal part of PC 1 IBP had highly weathered surfaces.

Conjugate joint system inland along all Zones in the South Sector of PC Site 1 intersect (Figure 5.9) with inconsistent spacing from 2 to 50 cm (Table 5.1) and more consistent width of openings at 1 to 10s of cm depending on level of erosion.

Figure 5.10: South Sector, Zone H. Three Quaternary erratics (indicated by red arrows).

The lower tephra layer that lies below PC 1 IBP is exposed within the South sector. As in the Northern sector, this layer was saturated and viscous within its exposed edges. The tephra layer below PC 1 LBP is eroded into a notch with a depth of ~ 1 m.

The Quaternary diamicton had a thickness of ~ 2m. To the north of PC Site 1 the Quaternary sediment is aligned with a slope of 46˚ SW along the upper part, and 18.5˚ SW near the base. To the south of PC Site 1 IBP the Quaternary sediment along the upper part was 37˚ N, and 42˚ N near the base. The Quaternary diamicton was unsorted, with highly angular clast material. Erratics were also observed, some of which were large (~ 0.7 m^2). Three along the South Sector had fallen onto the inland edge of PC 1 IBP (Figure 5.10).

5.1.2 PC Site 1: Physical and Chemical Processes

Weather conditions precluded visiting the sites during the winter. High winds are prevalent along the coast of MPER, as well as freezing temperatures. In the winter of 2009, frost action was observed by Richard Thomas (Department of Environment and Conservation, Newfoundland and Labrador) at PC Site 1.

5.1.2.1 PC Site 1: North Sector

To the NE, PC 1 IBP is exposed adjacent to the pebble-cobble-boulder beach. The North Sector of PC Site 1 is exposed to erosion by beach material and wave impact. Pebbles and cobbles were observed on the PC 1 IBP layer on a number of visits.

No fresh surface areas were noted on the upper stratigraphic layers, and there was little evidence of impact of large clasts eroded from the middle and upper stratigraphic layers above. These layers were present where the most protection from wave impact was observed. Overtopping was most prevalent in the northern part of the North Sector during the spring, summer and fall.

The fresh surfaces of the fractures within the North Sector demonstrated little oxidization or *Verricaria maura* growth. *Verrucaria maura*, a crustose lichen, grows as a thin, matte-black layer on rock surfaces. It attaches itself to the micro-pores of the rock surface. The reproductive bodies of *Verrucaria* resemble tiny black spots, especially where growth is sparse, but can also resemble the thickness and consistency of an oil stain (MarLIN, 2011). *Verrucaria* was defined as either heavily blackened with the consistency of an oil stain where observed as a thick layer, tiny black spots grouped within an mm of each other where patchy and thinner in distribution.

Where *Verrucaria* was present at PC Site 1, its distribution was noted as patchy, within fractures, or on the surfaces of eroded clasts, and was observed to have an affinity for sheltered areas, such as at the base of PC 1 IBP, as well as under large eroded clasts.

5.1.2.2 PC Site 1: Central Sector

Much of the Central Sector (Zone D and E, and to a lesser extent Zone F and G) is primarily covered by a deep crimson red (10R3/3) oxidization surface. There are areas of unoxidized pale white gley 1 4/5GY surface. Chemical erosion was prevalent due to oxidization (Figure 5.11 and Figure 5.12). Where unoxidized pale white gley 1 4/5GY was present, spalling was observed to be occurring where easily removed surficial pieces of material 1- 2 mm thick are present. The spalling gley 1 4/5GY surface area ends in alignment with the exposed lower tephra layer at the base of PC 1 LBP. The outcrop which protects ~ 10 m width of the northern part of PC 1 IBP ends along this length of coastline.

Figure 5.11: Surface weathering (oxidisation) and erosion along the Zone D and E, Central Sector, PC Site 1.

Figure 5.12: Oxidisation, Zone D and E, Central Sector PC Site 1.

Overtopping along the southern part of the Central Sector has been observed on rare occasions. Pebbles, cobbles, and boulders are abundant at the base of PC 1 IBP. Marine debris (plastic garbage bags) also was observed intercalated within the pebbles and cobbles along this segment. In addition, a number of clasts of various sizes, and with fresh surfaces have eroded onto this area of PC 1 IBP.

To the southern part of a Central Sector (Zone F and G) there is an inland part of this segment of PC 1 IBP has faulted. Oxidization within this sector is quite extensive, with dark red (10 R 3/3) and dark orange (7.5 YR 4/6) surfaces present.

5.1.2.3 PC Site 1: South Sector

According to observations by MPER employees a large clast (~ 200 kg) moved from the inland part of the north to inland south side of PC Site1. The incidence occurred between (December) 2008 (May) 2009 (Figure.5.2 and Figure 5.15). The event that forced the movement is unknown.

Figure 5.13: Photograph of ~ 200 kg clast (Zone L, South Sector) taken before the winter storm season. Upper right hand (white chalk arrow) part moved 4 – 5 metres from north to south during the winter; 2008-09 (See also Figure 5.2) (Photograph by Evan Edinger).

At the very southern edge, PC 1 IBP was exposed to wave action, and on a number of visits cobbles and pebbles covered a large part of this surface. The volume of beach material effectively infills the large notch created by the erosion of the tephra layer below PC 1 LBP (Figure 5.14, Figure 5.15).

Figure 5.14: Notch development along the tephra layer, Zone L, South Sector PC Site 1.

Figure 5.15: Cobble, pebble infill, Zones H through N, South Sector, PC Site 1.

Oxidization (Munsell 10 R 3/3) is not extensive in this sector, although it covers a large part of the bedding plane. Patches of *Verrucaria maura* are present. Plucking is evident where joints intersect. Oxidization as well as presence of *Verrucaria* along the surface of the southwest part is reduced, with surface erosion due to wave impact. PC 1 LBP is highly eroded (depositing clasts onto the PC 1 IBP) due to wave processes on its surface, and pebbles and cobbles were noted on the surface on a number of occasions.

5.1.3 PC Site 1: Human Impact

Pigeon Cove is highly visible and accessible from the road to Cape Race, and PC Site 1 sits between two attractive pebble-cobble-boulder beaches. As a result, tourists stopping to take in the view from the beach were noted on a number of visits. Although many of the tourists encountered were not aware that this segment of MPER's coast was within the restricted fossil zone area, there are other individuals who are more aware of the presence of the fossils at PC Site 1.

In August 2009, two people, without a scientific permit, entered into the MPER fossil zone. Their intention was to illegally cast the largest known *Ivesheadia* fossil at PC Site 1 using household insulation foam in a spray can. Because PC Site 1 is visible from the road, they were noted by residents and chased off the site before they could complete their task. Nonetheless, a substantial amount of insulation foam residue was left behind. Careful consideration is given to the chemical compounds in casting materials by palaeontologists, a sentiment not necessarily shared by those interested in illegal casting. Fortunately in late

September 2009, Research Casting International used a gentle solvent to remove the yellow foam residue from the *Ivesheadia* fossil (Figure 5.16).

Figure 5.16: Home insulation spray on an *Ivesheadia* fossil, Zone B, PC Site 1.

5.1.4 PC Site 2: Geological Structure

Pigeon Cove Site 2 (PC Site 2) , ~ 150 m east of PC Site 1, separated by a pebble-cobble-boulder beach. The coordinates for PC Site 2 are 46˚41’01.30’ N; 53˚15’31.33’ W. The primary bedding plane studied was apparently devoid of fossils. This site was chosen as a comparative to PC Site 1. Primary structural details are listed in Table 5.2.

PC Site 2 has a series of southwest sloping outcrops extending to the coastal edge of the bedding plane selected for the study. The bedding planes slope towards southwest the direction of incoming wave action. This site is more isolated from the adjacent pebble-cobble-boulder beach along the north side than is PC Site 1 (Figure 5.17), due to the prevalence of shore-normal sediment transport by wave action.

Figure 5.17: Red circle indicates location of PC Site 2 (south) viewed from PC Site 1 (north).

5.1.4.1 PC Site 2: Orientation, Width and Spacing of Joints

Although compartmentalized into sections while on site, the stereonet for PC Site 2 populations were plotted to include the entire bedding planes. This site lies along one limb of a fold, and the angle of wave impact was much less significant. The mean orientation of the bedding plane (PC 1 LBP) is 211˚/23˚ SW, and the joint populations are conjugate- oriented NW-SE and NE-SW (Table 5.2). In addition, N-S oriented joints are present. Width and spacing of the joints (Table 5.2) vary throughout the site, and differ from those at PC Site 1. PC Site 2 was broken up into three Sectors for observation of general characteristics, while SDS measures were taken within 14 Zones, lettered A through N (Figure 5.18, Table 5.2).

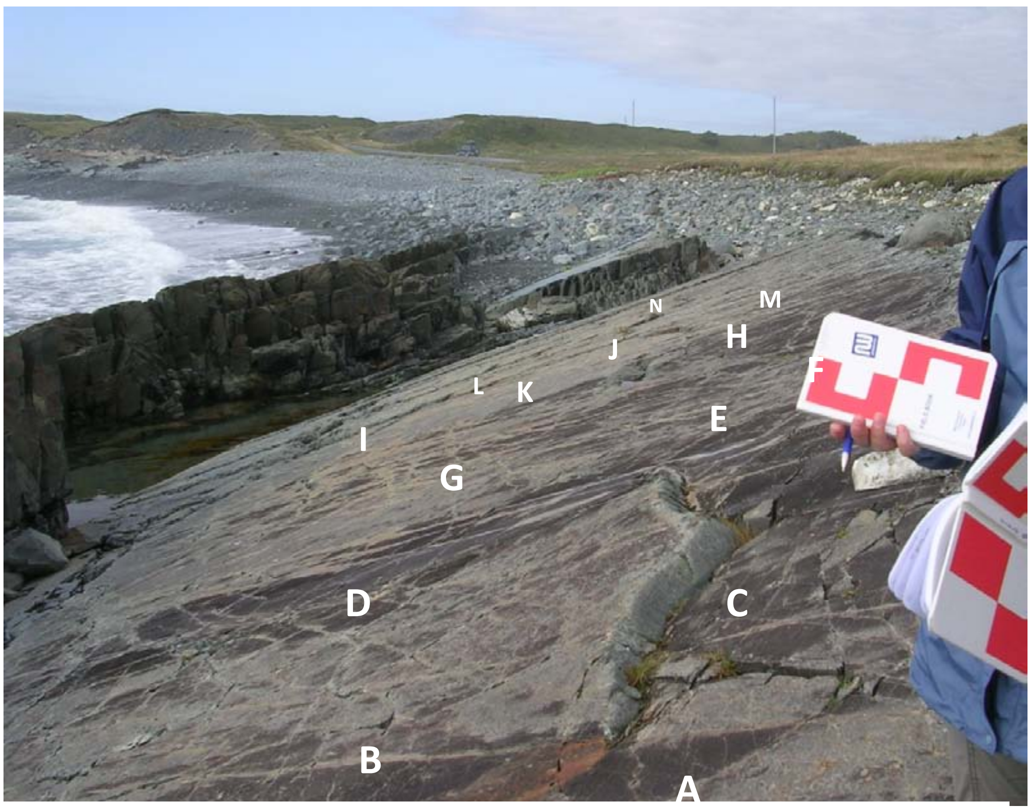

Figure 5.18: PC Site 2 facing north, demonstrating Zones and Sectors where SDS measures taken across the face of the rock.

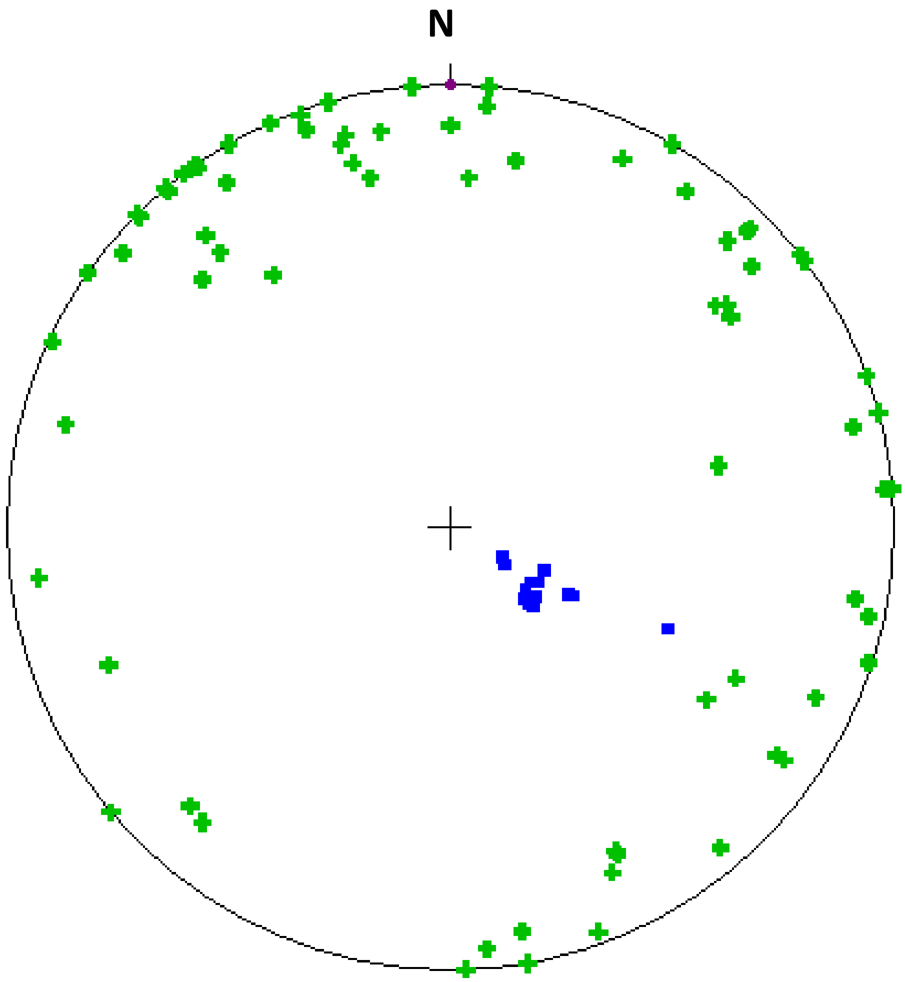

Figure 5.19: Pole-to-plane stereonet of joint sets measured at PC Site 2. The data below indicate the joint systems measured as well as their mean principal orientation.

PC Site 2 Bedding Plane (blue squares)
No. of Data = 14
Mean Principal Orientation = 215/21W
Mean Resultant dir'n = 21-305

PC Site 2 Joints (green cross)
No. of Data = 78
Mean Principal Orientation = 63/89S
Mean Resultant dir'n = 66-191

PC 2 BP	Bedding Plane	Primary Joint Set	Opening Width (mm)	Spacing (cm)	Secondary Joint Set	Opening Width (mm)	Spacing (cm)
South Sector							
Zone A	225˚/19˚ SW	319˚/79˚ W	1	5 - 25	225˚/90˚	1	5 - 25
Zone B	205˚/19˚ SW	321˚/69˚ S	1	1 - 25	273˚/68˚ W	1	~ 30
Zone C	210˚/25˚ SW	345˚/70˚ W	1	5 - 8	257˚/70˚ SW	1	10
Zone D	212˚/19˚ SW	320˚/90˚	1	25 – 70	254˚/79˚ E	1 – 5	15 - 30
Zone E	210˚/11˚ SW	313˚/75˚ SE	1 - 2	2 - 70	255˚/81˚ E	1	7 - 10
Zone F	205˚/45˚ SW	260˚/82˚ W	1	15 - 20	310˚/76˚ NE	1	3 - 20
Central Sector							
Zone G	215˚/12˚ SW	230˚/89˚ E	1 - 5	1 - 8	323˚/68˚ W	1 – 10	15 - 40
Zone H	209˚/25˚ SW	270˚/90˚	1 - 5	25 – 40	340˚/90˚	1	30 - 40
Zone I	214˚/18˚ SW	315˚/85˚ SE	30 – 100	10 – 60	268˚/90˚	1	3 - 20
Zone J	220˚/18˚ SW	205˚/80˚ N	1 -3	10 - 25	230˚/90˚	1	1 - 3
North Sector							
Zone K	219˚/20˚ SW	314˚/79˚ W	1	10 - 30	295˚/81˚ W	2 – 5	8 - 30
Zone L	238˚/20˚ SW	315˚/84˚ W	2 – 100	15 - 200	275˚/85˚ SW	1 – 5	15 - 30
Zone M	228˚/20˚ SW	315˚/84˚ W	1	10 - 100	246˚/90˚	1	2 - 5

Table 5.2: Primary and Secondary joint sets, as well as spacing and width of sets along PC Site 2 bedding plane.

Two bedding planes were considered, with the primary bedding plane under observation termed PC 2 BP, and the upper surface to west (coast) termed PC 2 UBP (Figure 5.21). PC 2 UBP extended along the western length of the PC 2 BP with a height above PC 2 BP being 2.5 m, and a SDS of 198˚/27˚ W.

The total perimeter of PC 2 BP is ~ 70 m^2: 7.10 m along the north side, 29.70 m along the coast, 4.6 m to the south, and 29.20 m along the inland part. Overall, PC Site 2 is much less complex than PC Site 1 with respect to structural geology and erosional features.

Directly to the east of PC 2 BP is a layer of Quaternary diamicton forming a bluff ~ 2-3 m in height and with a slope inclination of 46˚ N. The diamicton was composed of unsorted materials with boulder, cobble and pebble size erratics, some of which had directly fallen on to the PC 2 BP surface. Some angular materials were observed, although fewer than at PC Site 1.

Eighty-one joint sets were measured, and the exposure was divided into South, Central and North Sectors, which were subsequently divided into Zones. With regards to joint systems and erosion, the bedding plane surfaces at PC Site 2 were much more homogeneous than PC Site 1. The fracture surfaces within PC 2 BP and PC 2 UBP were well weathered, and no loose clasts were observed.

5.1.4.2 PC Site 2: South Sector

The primary joint sets within the South Sector maintained a mean orientation of 320˚ with dips varying from 69˚ to 90˚. Zone C (345˚/70˚), Zone E (313˚/75˚ SE) and Zone F (260˚/82˚ W) are the exceptions.

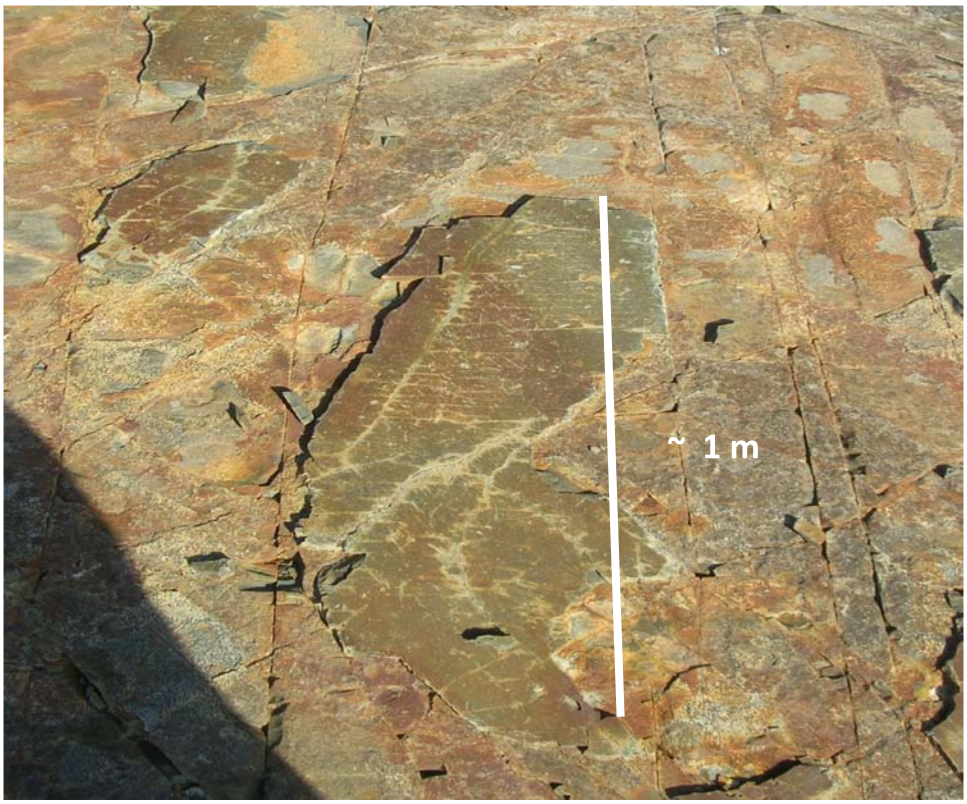

Figure 5.20: Spalling and plucking, South Sector, Zone B, PC Site 2.

Spalling and plucking to depths of 0.5-1 cm was also present within the South Sector (Figure 5.20). To the north part of this Sector, a well-weathered fault approximately 3 m in length is oriented south-north with a vertical displacement of ~ 15 cm. Rockweed was observed along the exposed vertical opening along the fault. Eroded material and Quaternary material were also present along the coastal edge of this South Sector. Water (presumably a mixture of fresh and salt) and algae was observed at the base of PC 2 BP on each visit. The surface of the bedding plane was eroded smooth.

Many large blocks eroded from PC 2 UBP have fallen onto PC 2 BP. A few rounded pebbles and cobbles were dispersed along the base (coast) of the South Sector. However, it is not known whether these rocks came from the beach or the Quaternary material above. Marine debris was noted along the base of PC 2 BP as well.

5.1.4.3 PC Site 2: Central Sector

The Central Sector which included Zones G through J was the most eroded part of PC Site 2. The mean attitude of this bedding plane is 214˚/18˚ SW. A large eroded gap was present within the Central Sector (Zone I). The primary joint set was ~ 3 m in length with an orientation of 315˚/85˚ SE with two other joint sets intersecting (orientation of 268˚/90˚ S and 340˚/90˚ S) which contributed to the extension of the eroded pocket (Figure 5.22). The narrowest points along the eroded pocket were ~ 0.3 m with the widest parts being ~ 1 m. Normal to the coastal edge, the pocket effectively widened allowing for greater wave impact onto PC 2 UBP, thus, complimenting the extensive plucking observed within Zone I. However, the surface was also highly weathered, with no fresh clasts, and rockweed was prevalent within the extension joints of the large fracture both in the inland and coastal parts.

Figure 5.21: Erosion along the Zone I, Central Sector, PC Site 2 with intersecting SDS 315˚/85˚ SE, 268˚/90˚ S and 340˚/90˚ S with 1.5 m.

Figure 5.22: PC Site 2, Central Sector, and west of Zone I, coastal outcrop erosion with an SDS of 198˚/27˚ W.

5.1.4.4 PC Site 2: North Sector

In association with the extensive fractures within the North Sector, much of the exposed PC 2 BP showed consistent patterns of joint system alignment and erosion. However, within Zone K some triangular plucking was observed (Figure 5.23). The primary joint set was 314˚/79˚ W with a few cm spacing. Complementary joint sets included orientations of: 295˚/81˚ W, 355˚/88˚ NW, and 235˚/89˚ E. .

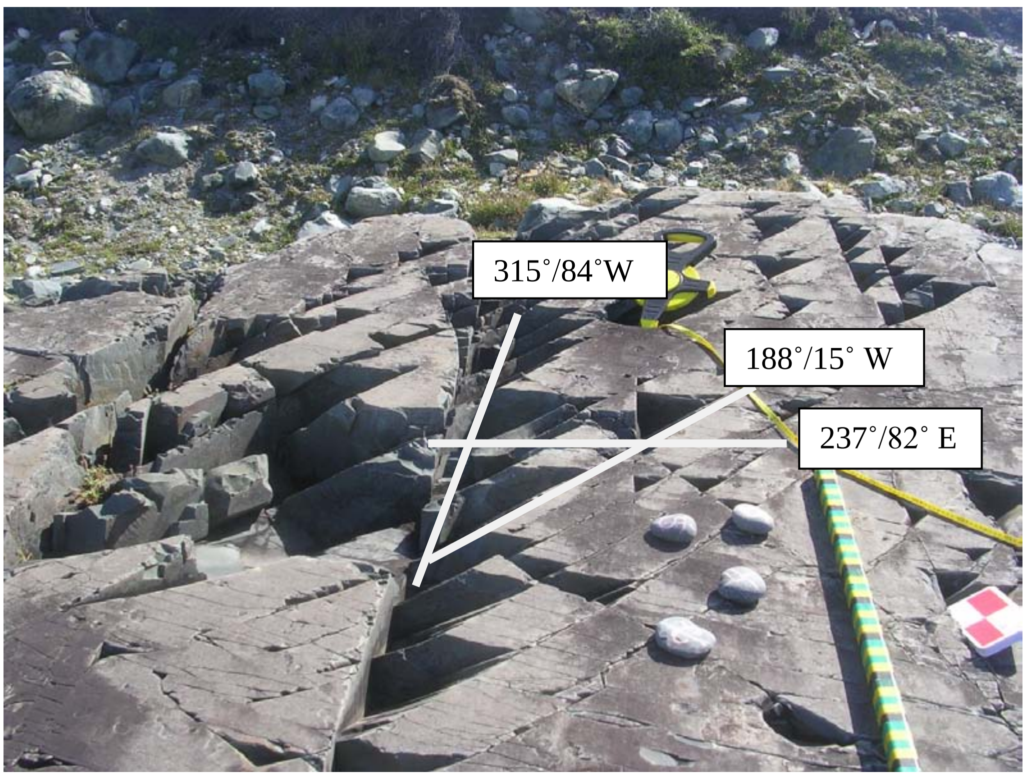

Figure 5.23: Plucking with joint set measures, K Zone, North Sector, PC Site 2.

5.1.5 PC Site 2: Physical and Chemical Processes along South, Central, and North Sector

Although pebbles and cobbles were noted along the base of PC 2 BP, no overtopping was observed on any of the visits from 2009 to 2011. Marine debris (e.g. plastic bottles) was noted, but individual pieces remained for most of the two years during observations, and no new debris was noted.

Oxidization was observed throughout the length of all Sectors but was most apparent in the South Sector. The colour of oxidized surfaces ranged from 7.5YR 4/6 to 5YR 4/6.

Verrucaria maura was observed in thin patches throughout the surface and was noted to be denser and covering more surface area along the coastal edge of PC 2 BP.

5.1.6 PC Site 2: Human Impact

No human impact was observed along PC Site 2 bedding plane. However, PC Site 2 does flank the same pebble, cobble, boulder beach with PC Site 1 which was observed on a number of occasions to be an attractive spot for visitors to stop.

5.1.7 Synopsis of Pigeon Cove Sites

The differences that were observed between PC Site 1 and PC Site 2 from 2009 to 2011 are related to Ediacaran sedimentation, Ediacaran and Palaeozoic tectonics, and Quaternary processes. Four of the most evident differences that were observed between these sites were: 1) the distribution of fossils; 2) the structural geology; 3) the stratigraphy, including the presence of weak tephra layers, overlying Ediacaran beds, and the flanking bluff of Quaternary diamecton; and 4) the angle of wave impact and influence of beach materials.

The published research of Liu et al. (2010) has resulted in increased recognition of the scientific value of PC 1. The resultant publicity for PC Site 1 fossils suggests that it may become more vulnerable to unpermitted visitation.

The lithological assemblage along PC Site 1 is also more exposed to physical processes, such as wave impact. PC 1 IBP (mean of 324˚) is oriented NW, whereas PC 2 BP (mean of 216˚) is oriented SW. Due to headland protection as well as its flanking position to the shore-normal dominated beach, PC 2 BP was not exposed to significant wave impact. Many of the joint sets along the PC Site 2 surface were also not as open and eroded as those at PC Site 1.

PC Site 1 had a series of very prominent open sets of joint systems throughout the whole of the surface area, but it was scoured (possibly by pebbles, cobbles and scree) along the South Sector where surface weathering from wave impact was more prevalent. The orientation of the bedding plane as well as its variation in inclination is indicative of the fold at PC Site 1.

Although the lithology is similar at PC Site 1 and PC Site 2, presence of tephra layers, coupled at all four sites, its fragile nature coupled with the occurrence of a more prominent fold, makes PC Site 1 more vulnerable to erosion. The inclination of the fold at points along the surface, with the weaker tephra layer as an underpinning foundation, is the catalyst for tensional joints and fractures that widen and lengthen when exposed to physical processes over time. The propagation of old or new fractures along the exposed PC 1 IBP is further emphasized to ave energy, falling, toppling, and wave-thrown clasts.

5.2 Mistaken Point (MP Sites 3 and 4)

Mistaken Point Sites 3 and 4 are accessible from two points of entry along the graded road from PCS to Cape Race. The first path accessible from the road to Cape Race is called the Berry Picker trail (46˚38’54.80” N; 53˚10’10.68”W), and requires hiking east of Watern Cove for 30 to 35 minutes to Mistaken Point. The second path is further along the road to Cape Race, and is used more frequently, including daily guided tours (46˚38’29.72” N; 53˚08’26.31”W).

The guided tour trail extends west of Watern Cove along the coast to the Mistaken Point fossil beds (Figure 5.24). Which path is used depends on time of year and weather, and the ease which visitors may cross Watern Cove. Berry Picker trail is considered the alternative route, and is commonly used by researchers, and less commonly used by the general public.

Temperatures in the months of January, February, and March may go below freezing, and winds are intense. The prevailing wind at Mistaken Point varies seasonally. During the summer months, the wind comes from the southwest, and in the winter northwest winds hit MPER’s coast. Due to the presence of cliffs and steep bathymetry, waves impact with high energy.

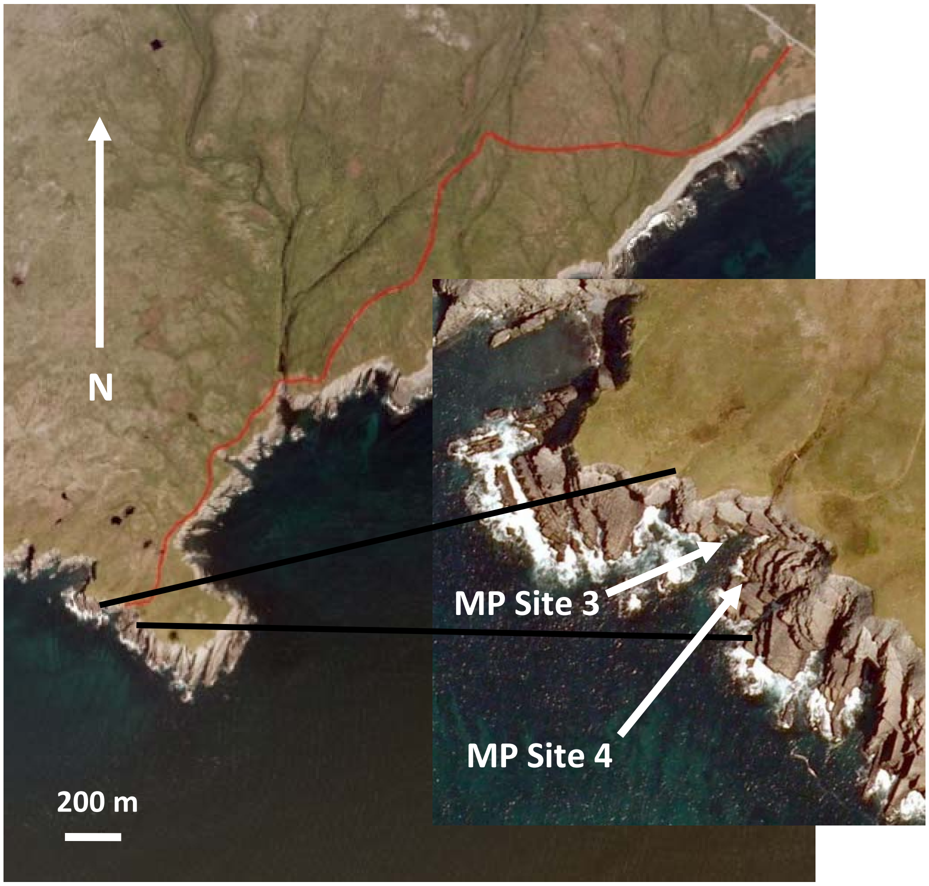

Figure 5.24: Air photograph of Mistaken Point. Mistaken Point guided trail indicated by red line.

MP Site 3 and MP Site 4 are separated by less than 100 m. The coastline of MP Site 3 is along the southern edge, and MP Site 4 faces west. Aside from sharing very similar geological structure, both sites have bedding planes of greyish green siliceous sandstone (greywacke, mud-, and siltstones, representing multiple turbidites (Benus, 1988; Gardner and Hiscott, 1988; King, 1988). In addition to the greywacke, two other layers of weaker under- and over-lying pyroclastic material were present. A ~ 35 cm layer of tuff is interbedded at the base of the rock walls at MP Site 3 and 4, composed largely or entirely of pyroclastic debris, containing a maximum of 25% non-pyroclastic minerals. Although somewhat eroded, the tuff at the MP Sites receded minimally relative to the other rock units, and so was observed to have little impact on the progress of erosion at the site.

The second layer, a millimetre- to 0.5 centimetre- thick pyroclastic tephra laminae, is present on the exposed fossil bed and is responsible for moulding the Ediacaran fossils. Aside from being responsible for the moulding of the Ediacaran organisms, the pyroclastic layer acts as a protective layer over fossils which may be unveiled at a later time.

Above the tuff and bedrock strata layers there is a 2 – 3 m thick diamicton layer that covers the inland part of Mistaken Point's coast. The slope of the diamicton face varies from approximately 23.5˚ S to 36˚S. The unconsolidated material included both organic as well as inorganic components, with angular to sub-angular clasts. Some sections were observed to have moved downwards (flow) from the top of the Quaternary layer to its base, - where the D and E surfaces were located.

5.2.1 MP Site 3: Geological Structure

MP Site 3 E and D surfaces have the most distinct fossil assemblage along MPER's coastline. Each surface was measured to be ~ 130 m^2, covered with a densely sown Ediacaran assemblage. Due to this spectacular assemblage as well as their accessibility, these bedding planes are most frequently visited by researchers and the general public. Therefore, they receive the greatest amount of human impact of all four sites. Both surfaces within MP Site 3 slope inland (SE) with a mean dip of 14˚ and visually share similar features with respect to geological structure and erosion.

Figure 5.25: View of MP Site 3 and coastline to the west and diamicton layers lying above it. Photograph taken from the east MP Site 4 shows bisection of large scale dominant joint sets (213˚/64˚ W and 320˚/68˚ SE).

5.2.2 MP Site 3: Orientation, Width and Spacing of Joints

The measures for MP Site 3 and 4 were plotted on stereonets and divided into coastal and inland populations for comparison of the possible effects of wave impact. The two sites which stand at different heights from sea level were then further analyzed for any differences in joint orientation as well as distribution. The bedding planes at MP Site 3 had a mean orientation of 14˚ SE with a gentle slope inland. Although both surfaces share the same basic structure, the joint population along the D surfaces varies somewhat. D surface joint populations show a greater number of intersecting conjugate joint patterns than does the E surface, and are more prevalent along the coastal section of the surface under analysis. Zones with primary and secondary joint measures were based on visible prominence (width, and spacing of joints) as well as the bisecting joint set relation to one another. Zones were divided into A through to F.

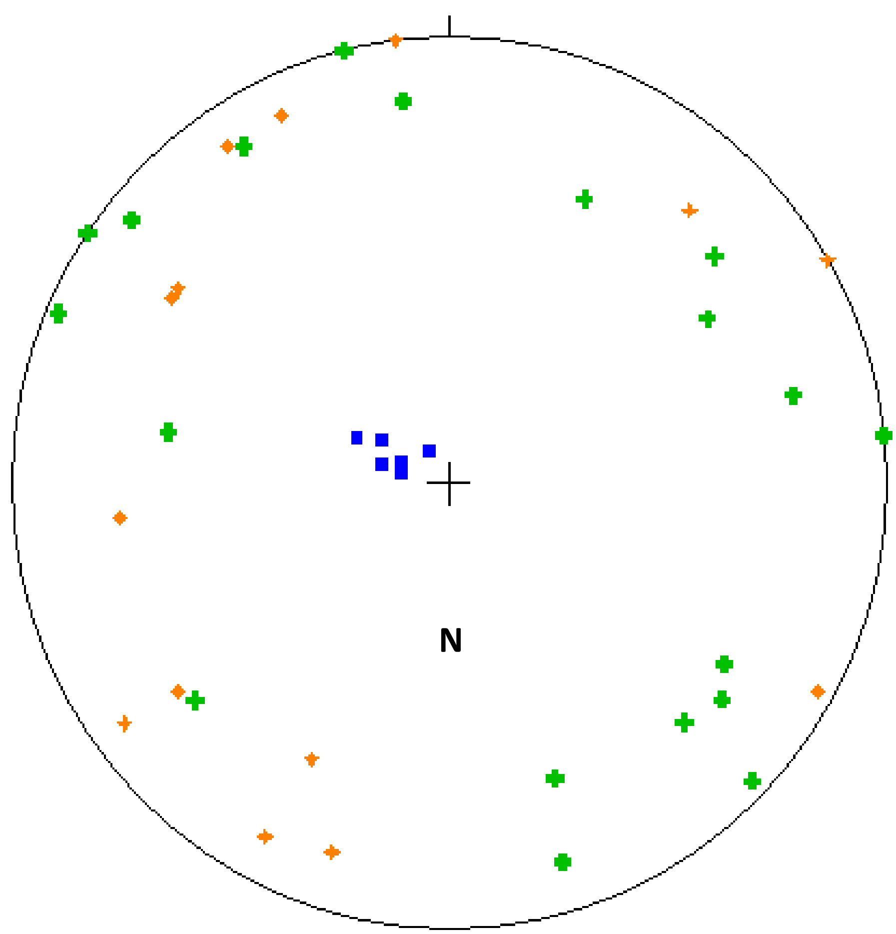

Figure 5.26: Pole-to-plane stereonet of joint sets measured at the D surface, MP Site 3. The data below indicate the joint systems measured as well as their mean principal orientation.

Bedding Plane (blue square)
No. of Data = 6
Mean Principal Orientation = 26/12E
Mean Resultant dir'n = 12-116

Inland Joints (orange stars)
No. of Data = 14
Mean Principal Orientation = 308/79N
Mean Resultant dir'n = 48-100

Coastal Joints (green cross)
No. of Data = 19
Mean Principal Orientation = 223/84W
Mean Resultant dir'n = 31-228

N

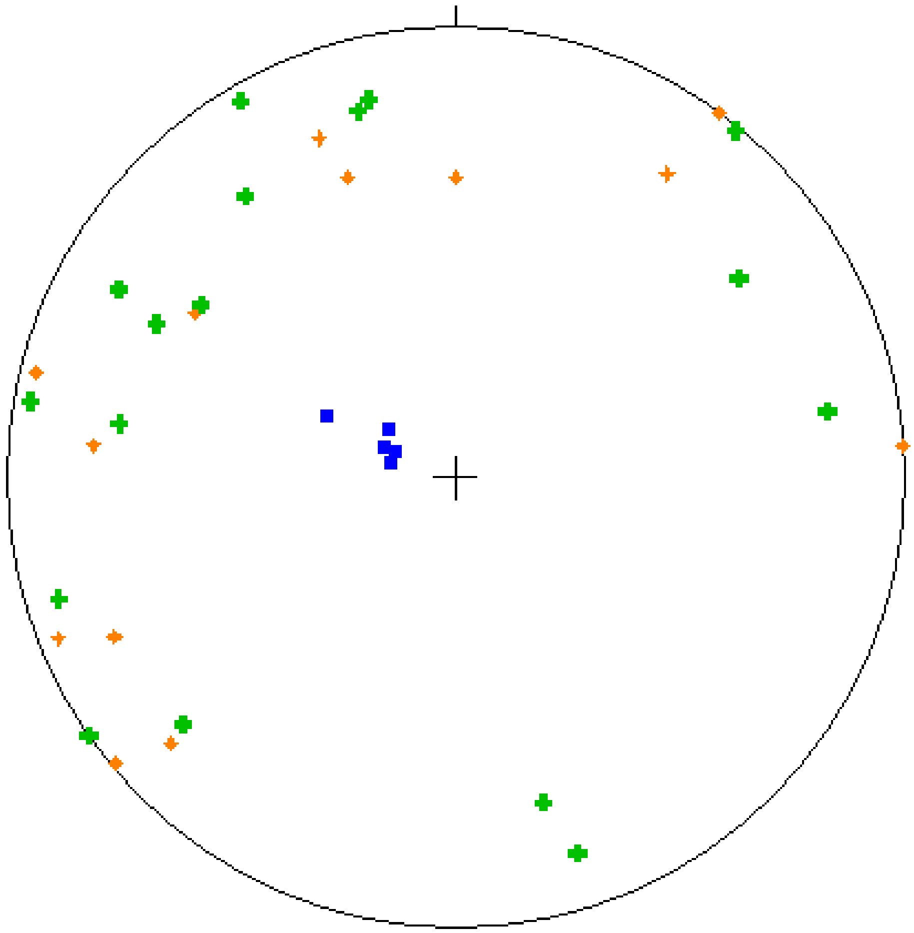

Figure 5.27: Pole-to-plane stereonet of joint sets measured at the E surface, MP Site 3. The data below indicate the joint systems measured as well as their mean principal orientation.

Bedding Plane (blue square)
No. of Data = 5
Mean Principal Orientation = 24/16E
Mean Resultant dir'n = 16-114

Inland Joints (orange star)
No. of Data = 13
Mean Principal Orientation = 336/84E
Mean Resultant dir'n = 58-123

Coastal Joints (green cross)
No. of Data = 17
Mean Principal Orientation = 28/78E
Mean Resultant dir'n = 54-122

Table 5.3: Primary and Secondary joint sets along MP Site 3, D Surface.

MP Site 3, 'D' Surface	**Bedding Plane**	**Primary Joint Set**	**Width (mm)**	**Spacing (cm)**	**Secondary Joint Set**	**Width (mm)**	**Spacing (cm)**
Zone A (SW Coast)	195°/13° SE	213°/64° W	1 - 40	12	250°/60° W S	1 – 20	3 - 16
Zone B	236°/07° SE	320°/68° SE	20 – 100	700	263°/75° W	1 – 50	65 - 140
Zone C	192°/09°SE	218°/68° SW	20 - 100	2 - 24	253°/78° N	3 - 9	17 - 30
Zone D	203°/10°SE	324°/81° SE	2 – 20	1	263°/90°	1	1 - 5
Zone E	205°/19° SE	215°/65° NE	1 - 50	30 - 150	297°/59° E	1 – 15	2 - 6
Zone F (W Inland)	212°/15° SE	312°/71° W	5 - 40	700	245°/80° SW	1	2 - 6

MP Site 3, 'E' Surface	**Bedding Plane**	**Primary Joint Set**	**Width (mm)**	**Spacing (cm)**	**Secondary Joint Set**	**Width (mm)**	**Spacing (cm)**
Zone A (SW Coast)	215°/15° SE	325°/90°	1	1 – 3 - 5	233°/67° E	1 - 10	25
Zone B	203°/14° SE	214°/58° NE	1 – 400	55	245°/74° N	1 – 20	8 - 25
Zone C	192°/12° SE	350°/73° S	1	6 - 12	255°/73° E	1 - 20	5 - 12
Zone D	205°/26° SE	317°/76° SE	20 – 15	50 - 100	248°/70° E	20 - 150	20 - 40
Zone F (W	203°/12° SE	320°/89°	1	0.5 - 7	270°/56° E	1 -5	6 - 12

Table 5.4: Primary and Secondary joint sets along MP Site 3, E Surface.

5.2.2.1 MP Site 3: D surface

The D surface has an area of ~ 130 m^2. The perimeter of the D surface includes 14 m along the coast and 33 m along the inland parts of the surface.

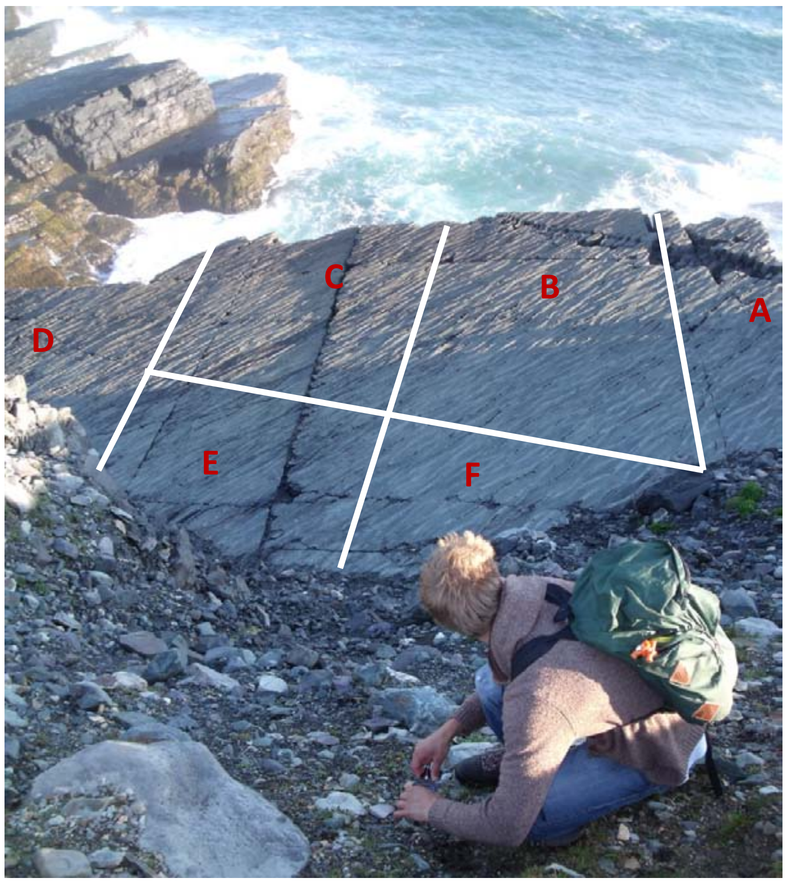

Figure 5.28: Zones A through F of joint sets measured along the D surface, MP Site 3 facing SW. Photograph taken from top of Quaternary layer (Field Assistant William Ferguson).

Although six joint sets were observed along the D surface, the most prominent bisecting joint system was observed to have a mean strike of 213˚/64˚ W (normal to coastline) and a second set with an SDS of 320˚/68˚ SE (Figure 5.29).

Figure 5.29: Eroding pocket with bisecting joint sets; 213˚/64˚ W (normal to coastline) and 320˚/68˚ SE. 1.5 m long stick is orientated S-N.

The westernmost joint of the first set (213˚/64˚ W), adjacent to the entrance onto the D surface, had an exposed length of ~ 3 m and was bordered by Quaternary material. The second joint within this set is ~ 4 m to the east, with a displacement of 1-2 cm. Within this joint was a large amount of rockweed. Plucking along the fracture was noted in association with parallel micro-fractures. These two joints flanked an eroded pocket along the southwest coastal edge of the D surface (Figure 5.29). An additional fracture between these joints borders the coastal edge and eroded pocket, extending 3-4 m inland. A third joint within the same system is located ~ 2 m to the east and had an exposed length of 8.6 m from coast to inland. A fourth joint near the easternmost edge of the bedding plane had an exposed length of 4.6 m and a width of ~ 1-1.5 cm.

The second joint system was oriented 320˚/68˚ SE (length of coastline), trending normal to the first system. Joints extended across the W - E length of the surface. Spacing varied from 2-9 m. Fracture opening widths were ~ 0.5-1 cm. The southernmost joint was 1-2 m inland, and intersected the eroded pocket in the southwestern edge. Within the same system and approximately 2 m northward, another fracture ran parallel with this system, extending 10 m inland from the eastern (lowest point) edge. The joints on the northernmost part of the D surface were spaced within 2 m, parallel to the flanking rock wall to the north and extending beneath diamicton material. The two joints had a high degree of plucking, as well as rockweed infilling open fractures, especially where they intersected the first system.

The southwestern edge (of Zones A, B, C, and D) is the highest point (~ 9 m from sea level) on MP Site 3 D surface, and lies directly south of the trail entrance onto the fossil surface (Table 5.6). This segment of bedding plane is extensively eroded, marked by the presence of loose blocks along its coastal edge. A eroded pocket was ~ 1 m from the edge. Irregular in shape, the dimensions of the pocket were 1.5-2 m west/east, and 2-3 m south/north. The eroded pocket was flanked by the intersection of the large D surface fractures. A measure of 236˚/07˚ SE for Zone B is significantly different from Zones, A, C and D. The reason for this is that the measure was taken along a dip of a crenulation rather than across the plane of the D surface.

The second distinguishing feature observed over the entire D surface was the presence of parallel micro-fractures. The parallel micro-fractures, observed at the apex of small folds (crenulations), are parallel features caused by compressive stress. With a SE-NW (250˚-70˚) orientation, the dip direction of the D surface parallel micro-fractures is 65˚ to 76˚. Lengths ranged from 100 to 150 cm. Their spacing was 30 to 40 cm, with width openings of 2 to 10 mm, greater where the parallel micro-fractures intersected major fractures, joints or the coastal edge.

A third common structural feature on the D surface was the presence of crenulations. The crenulations had a trough to crest distance of roughly ~ 1-2 cm, spaced at ~ 5-10 cm with an orientation of ~ 240˚.

Aside from the intersecting joint systems, there were two additional sets of small parallel micro-fractures fractures along the southeast edge of the eroded pocket. Both of which had a 343˚/78˚ SE. The fracture sets were irregular, and the main fracture line was hard to perceive due to normally-aligned extension cracks associated with the crenulation peaks that intersected the fractures.

The eastern edge of the D surface is the lowest point relative (~ 6 m) to sea level (Table 5.6). Zone D had a highly weathered surface that extended roughly 10 m inland (NE). In addition, the scoured smoothed, rounded surfaces as a result of continuous wave impact, erosion within the joint intersections resulted in diamond-shaped plucking. Two joint systems contribute to this erosional pattern, oriented at 334˚/81˚ SE and 218˚/68˚ E. The primary systems of 334˚/81˚ SE joint set had a minimum of 6 joints and extended 2 to 6 m inland. Their spacing was ~ 2.5 cm with fracture width of ~ 1 cm. Rounded and angular pebbles were present in the joint openings.

The rock wall to the north of D bedding planes had a series of wide set joint systems with eastward-leaning blocks.

5.2.2.2 MP Site 3: E Surface

The E surface at MP Site 3 has a perimeter of ~ 52 m with the inland length covering 31 m while the coastal part has a length of ~ 21 m. Zones were designated separately along the coastal edge and inland to compare the observed changes (joint widening, increased plucking) due to impact from physical processes (coastal) as well as gravitational displacement (inland).

Aside from the primary set in Zone C the primary and secondary joint sets along the E surface are similar to those on the D surface. The shared characteristics includes a bedding plane attitude of with strike of 203˚ and a mean dip of 16˚ SE that intersected with a consistent series of crenulated parallel micro-fractures (Figure 5.30).

Observed in all Zones, the parallel micro-fractures had a width of roughly ~ 1-2 cm, spaced at ~ 5-10 cm on the E surface. The parallel micro-fractures shared a similar orientation of 240˚. The intersection of these primary and secondary joint sets contributed to the loose clasts discovered along the surface, especially on the along the coastal edge.

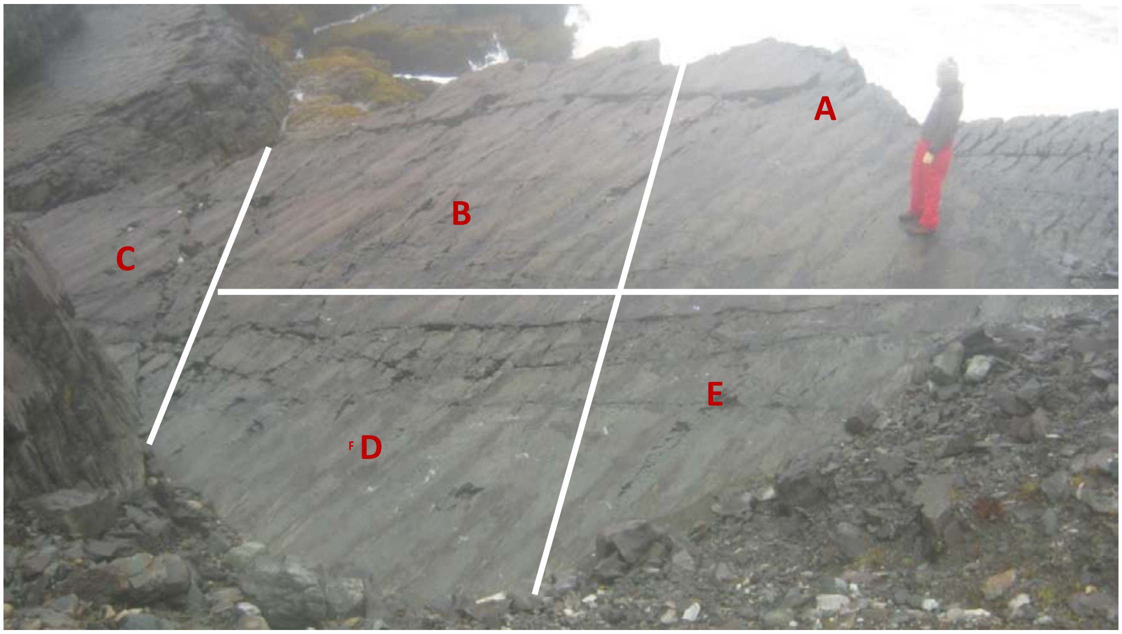

Figure 5.30: View of E Surface, MP Site 3 from Quaternary bluff above.

The pattern of erosion along their coastal edges including the vertical walls to sea level also was very similar to that on the D surface. The southwestern edge of the E surface is the highest point of this surface (~ 10 m from sea level) (Table 5.6). Observed within Zone A is enhanced erosion similar to the one observed on the D surface. This feature formed a crack extending to a maximum depth of 0.5 m, roughly 2 m in length (W-E), and 25 cm in width. Several extension fractures oriented approximately NE extend from the fracture. Some plucking has occurred, but the surfaces that remain are well-weathered with consistent oxidization especially in areas where *Verrucaria* was not present. This was more prevalent along the coastal part.

Along the inland part of the E surface 3 - 6 m long joint setsoriented E-W ran the length of the surface from its lowest eastern point to the westernmost edge. Aside from the intersecting parellel micro-fractures sets, a third set of fractures running NNW-SSE ran along the eastern part of the E surface intersected this dominant system. The surface along the easternmost edge of the E surface was highly scoured by wave action.

Movement due to satuaration and gravity was observed within the Quaternary diamicton bluff flanking the northwest side of the E surface, both within the flow itself and onto the E surface as well. The slope was 30˚S near the bluff's upper edge and 36˚S near the base on the west side. Further to the north (adjacent to rock wall) the inclination for the upper part was 27˚S and for the lower was 23.5 ˚S.

Figure 5.31: Coastal edge, MP Site 3, E Surface, with cobbles to mark joint sets within Zone A.

__5.2.3 MP Site 3: Physical and Chemical Processes along D and E Surfaces__

A number of rock toppling and wave overwashing events have been observed on the D surface (Table 5.3). In August 2009, a rock-fall occurred east of the entrance to the E surface (Figure 5.32). Although this event did not result in the loss of fossils, it could have posed a threat to visitors.

Figure 5.32: Flexural toppling (indicated by red arrows), MP Site 3, D Surface, Zone D and E. Standing in photograph is Field Assistant, Ryan Gibson with rock fall to his left.

A large block with an estimated mass of 500 kg toppled into the ocean between December 2009 and April 2010, from the southeastern edge of the D surface, Zone B, an event that resulted in the loss of a number of Ediacaran fossils (Figure 5.33 and 5.34).

Figure 5.33: Large loose clast at the SW edge of D surface, Zone B MP Site 3. summer 2009.

Figure 5.34: Large loose clast at SW edge of D surface, Zone B, MP Site 3, removed winter 2010.

Movement due to satuartaion and gravity was observed within the Quaternary diamicton bluff flanking the northwest side of the D surface. The slope was 40.5˚ SSW near the bluff edge and 42.5˚ near the base on the east side, and to the north (adjacent to rock wall) the slope for the upper part was 33˚ SW and for the lower was 29.5˚ SW. The slope of the Quaternary material above the rock wall was 21.5˚ SW.

Following Hurricane Igor in 2010, a large part of the colluvium was observed to have been removed from the base and center of the rock wall (Figure 5.35). Water discharge (spring) was noted within the area where the material was removed. In 2011 the eroded area was again infilled with colluvium from the flow directly east of the rock wall (Figure 5.36). Along the northwest section of the rock wall, more displaced Quaternary debris was noted in 2011 than in previous years.

Figure 5.35: Quaternary debris at base of rock wall (April, 2010), Zone E, D surface, MP Site 3.

Figure 5.36: Quaternary debris removed from base of rock wall (October, 2010), Zone E, D surface, MP Site 3 post-Hurricane Igor (Field Assistant Matthew Philbrick).

Wave overwashing has been observed on both D and E surfaces at MP Site 3. The amount of overwashing received along these surfaces generally depended on their height from water level. Waves can reach the base of the steps from D to E surfaces, as noted by their repeated removal post storm events.

Surfaces	**Heights in m**
E to D	~ 2.5
D (west) to sea level	~ 8.80
D (east) to sea level	~ 5.80
E (west) to sea level	~ 9.90
E (east) to sea level	~ 8.30

Table 5.6: MP Site 3, bedding plane surface height from water line.

Along the surface at MP Site 3, the *Verrucaria* was observed as thin and spotty with a distribution in depressions (e.g. within crenulations).

Although a number of natural incidences of erosion have been noted all along MPERs coastline, the majority have been observed at MP Site 3, D and E surfaces. This is both due to the impact of physical processes and therefore active erosion, and also due to the popularity of the site and the presence of people to witness these incidences. It is therefore difficult to determine if MP 3 is more susceptible to erosion in comparison to other adjacent, less frequently-observed sites.

Date	Type of Event	Winds	Area Affected	Damage	Source
March 11, 2009	4 m movement by wave action of 204 kg clast		Zone L, PC Site 1 – Pizza Disc Bed		Richard Thomas
Winter 2009 - 2010	Rock Fall		Zone D, MP Site 3, D surface		Sheridan, Chris Kennedy for first observation, Ryan Gibson for 2nd
Aug. 23 and 24, 2009 Hurricane Bill	Over washing		MP Site 4, D and E surfaces		Julie Cappleman
Aug. 11, 2009	Rock fall		MP Site 3, D surface		Discovered by MPER Interpreters. Documented by Richard Thomas and Brandon Ward
June 15, 2010	Over washing		MP Site 3, D and E surfaces		Richard Thomas
Aug. 2010, Post-Hurricane Danielle	Over washing		MP Site 3, E and D surfaces		Richard Thomas
Aug. 29, 2010	Loose clast – rock toppling into ocean		Zone B, MP Site 3, E surface, east of Alex's work coastal edge		Sheridan Thompson
Sept. 20, 2010 Post-Hurricane Igor	Removal of Quaternary debris		Zone E, inland wall on MP Site 3 D surface		Emily Mitchell
March 8, 2011	Storm damage		PC Site 1 – Pizza Disc Bed		Richard Thomas
Sept. 15, 2011 Post-Hurricane Katia	Storm damage		PC Site 1 – Pizza Disc Bed	Tephra layer severely eroded in places	Richard Thomas
Oct. 6 and 7, 2011		118km/hr SW wind at Cape Race on Oct 6th	MP Site 3 D and E surfaces and gravel slopes above	Oct 6th: Large waves and high winds. Oct 7th: Rocks and gravel on both surfaces, "rock stairs" to E surface destroyed by wave action, Turf edges (sods) hanging further down slope of bank	Edwina Ward
Oct. 13, 2011 Post-hurricane Ophelia	Storm damage		PC Site 1– Pizza Disc Bed	Major storm-related damage	Richard Thomas

Table 5.7: Major events affecting MPER sites.

Two features noted only on the E surfaceare: 1) a greater degree of oxidization covered the surface area; and 2) pyroclasts were present within the depressions of the crenulations. Significant oxidization along the E surface was noted, with a deep red colour that only was diminished in the presence of thick patches of *Verrucaria* lichen. The pyroclastic material had flecks of lighter coloured feldspar (1 mm in diameter) which made it easier to discern from the blackness of the *Verrucaria.* Pyroclast were prevalent on the E surface, with an uneven and patchy distribution (maximum thickness ~ 2 mm) that was primarily confined to the depressions of the crenulations. *Xanthoria sp.* was noted in very small amounts along the rockwall of the E surface.

5.2.4 MP Site 3: Human Impact along D and E Surfaces

The removal of two rock cores was noted on the D surface: one to the west of the entrance on the D surface and one to the northeast of the entrance to the E surface. These cores were extracted for the purpose of geochronology.

Visitors to the D surface were noted on a number of occasions, including tourists and researchers. Since 2007, the increased popularity of the Reserve has meant increased impact due to the presence of camera crews (e.g. 2009 and 2011), as well as the implementation of a large casting project over the E surface in the autumn of 2009. Although the E surface is considered the surface that has the most distinctive and prominent fossils, it can only be accessed via the D surface. Therefore, any increased attention to the E surface inevitably results in increased impact to the D surface.

Relative to the fossils on the D surface, the E surface fossils had more prominent relief. Therefore, in addition to receiving the greatest amount of foot traffic of all four sites, it is also the site to receive the greatest amount of researcher attention. Forms of human impact that affect the rate of erosion along the E surface include: increased foot traffic due to increased visitations, individual casting, a large casting project, and removal of fossils from the bedding plane.

5.2.4.1 MP Site 3: Human Impact - Permitted and unpermitted visitation

Aside from observing the bedding plane surfaces on which the fossils lie, as well as the Quaternary bluff above them, observations were also made of the hiking trail leading to the Mistaken Point fossil site (Table 5.8). Although it is difficult to determine a projection into the future concerning the number of visitors that may use this trail, it is clear that since the PCS visitors centre's opening in 2007 individual and group uses of the trail have increased.

Statistics for Mistaken Point Guided Tour					
	2007	2008	2009	2010	2011
May	12	19	9	32	41
June	7	97	70	66	130
July	70	105	237	195	249
August	75	128	234	250	261
September	129	132	192	190	147
October	10	19	47	43	18
Total	**303**	**500**	**789**	**776**	**846**

Table 5.8: Visitation statistics for MPER guided tour from 2007 to 2012.

Although PCS residents are permitted by the Park Manager by permit to be within the reserve for grazing of livestock and in-season picking of berries, visitation to the fossil site was the most frequently observed use of the reserve grounds.

For much of the hike, the trail is quite flat, with some surface lowering exposing Quaternary erratics. As well, undercutting of nearby bluff edges was noted. In some areas along the trail, especially near the Point, the trail was located within ~3-4 m of the cliff line with an undercut that extended ~ 1-2 m.

In addition, although no motorized vehicles, all-terrain vehicles (ATVs), snowmobiles, bicycles, or horses are permitted within the reserve, ATV tracks were found periodically with the reserve boundaries. Off road bicyclists were also noted on several occasions.

5.2.4.2 MP Site 3: Human Impact - Individual Casts

Before the mould for individual casts is created, the surface of the fossil is cleaned. Two cleansers have been used: chlorine bleach and biodegradable camp soap. In the past, latex residue has also been left behind as an end product of individual casts. As well, if the compound formulation and processing of casting are improper, damage to the fossil surface can result. At MP Site 3, although no casting residue was observed on the surface, there were a number of lightened areas where casting material had removed the natural materials such as pyroclasts and *Verrucaria* lichen.

During the large casting project in September 2009, any residue from the casting was effectively removed. However, other effects were noted as a result. Bluff material flanking the E surface had been disturbed and excavated by the crew of Research Casting International.

Extraction of fossils from MP Site 3 took two forms. Prior to MPER's enstatement as a Ecological Reserve, museums such as the Royal Ontario Museum (ROM) legally removed fossils from the E surface during the 1970s (David Rudkin, ROM, personal communication) (Figure 5.37). In addition, some holdfasts of *Charniodiscus spp.* were removed, presumably by hammer (Figure 5.38). However, the shattered holdfasts that were observed are at the base of the disturbed Quaternary material, a source of granite erratic boulders.

Figure 5.37: Zone D, MP Site 3, E surface with fossil cut-out and diamicton flow in back ground (Field Assistant William Ferguson).

Figure 5.38: *Charniodiscus* fossils with chipped hold fasts, Zone D, MP Site 3, E

5.2.5 MP Site 4: Geological Structure

Although the structural geology of the D and E surfaces at MP Site 4 is similar to that at MP Site 3, differences were noted. The greatest length of the exposed bedding planes at MP Site 4 is aligned east to west. Of the four sites, MP Site 4, D and E surfaces are the least accessible. The site is off limits to visitors, unless a scientific permit has been obtained, and it is a steep (30˚ - 40˚) hike to reach the surfaces. However, because MP Site 4 shares the same diversity and abundance of fossils as MP Site 3, it is frequented by researchers. Unlike the other three sites, MP Site 4 is many metres below the Quaternary material above it, and is much less affected by this loose eroding debris.

Figure 5.39: MP Site 4, taken from MP Site 3, demonstrating the similar geological structure between the two sites.

Both surfaces within MP Site 4 slope inland with a NE attitude. D surface has a mean SDS 204˚/13˚ SE, and E surface has an SDS of 224˚/15 SE. Crenulation and parallel micro-fractures orientation on both surfaces are similar to those observed at MP Site 3 (Figure 5.40). Both had a mean orientation of 253̊ indicate dip. The parallel micro-fractures at this site had a greater width (6-8 cm) near the southwestern part of the site, which contributed to erosion where intersected by the single major joint set. Plucking was apparent, although the surfaces were well weathered and no loose blocks were visible.

Figure 5.40: Parallel micro-fractures secondary joint sets measured along both MP Site 3 and 4. Emery stick orientated north – south.

5.2.5.1 MP Site 4: Orientation, Width and Spacing of Joints along D and E Surfaces

Both D and E surfaces at MP Site 4 has a series of conjugate joint systems trending (NE-SW) and (NW-SE). However, the coastal area of the E surface has much more prevalent NE-SW jointing.

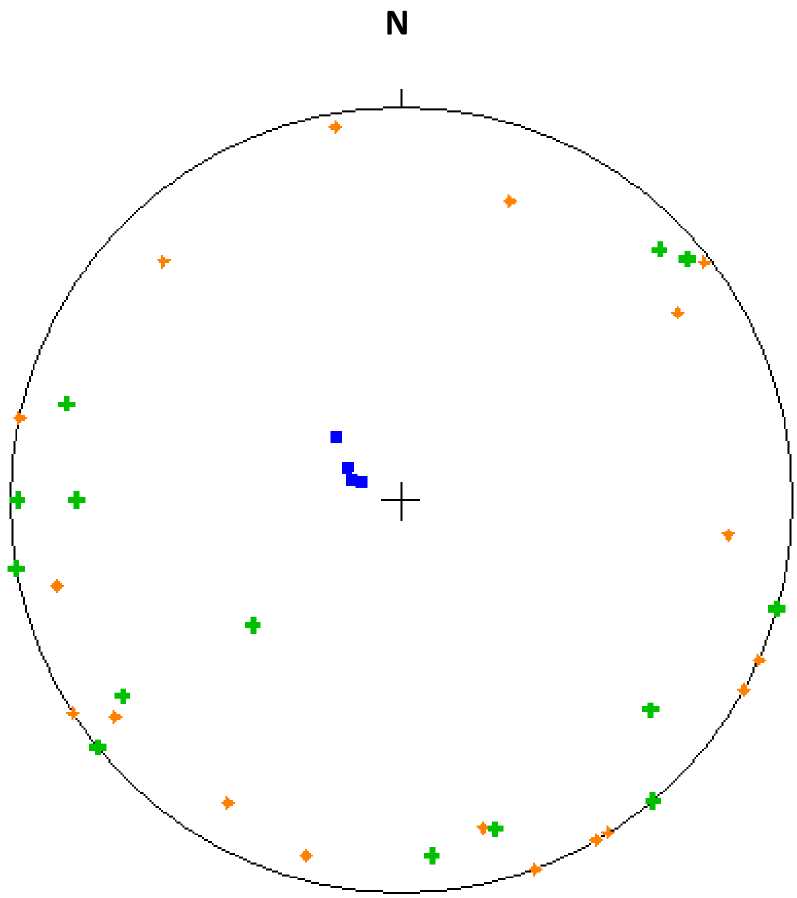

Figure 5.41: Pole-to-plane stereonet of joint sets measured at the D surface of MP Site 4. The data below indicate the joint systems measured as well as their mean principal orientation.

Bedding Plane (blue squares)
No. of Data = 5
Mean Principal Orientation = 32/13E
Mean Resultant dir'n = 13-122

Inland Joints (orange stars)
No. of Data = 18
Mean Principal Orientation = 250/90N
Mean Resultant dir'n = 61-344

Coastal Joints (green cross)
No. of Data = 14
Mean Principal Orientation = 351/84E
Mean Resultant dir'n =59-026

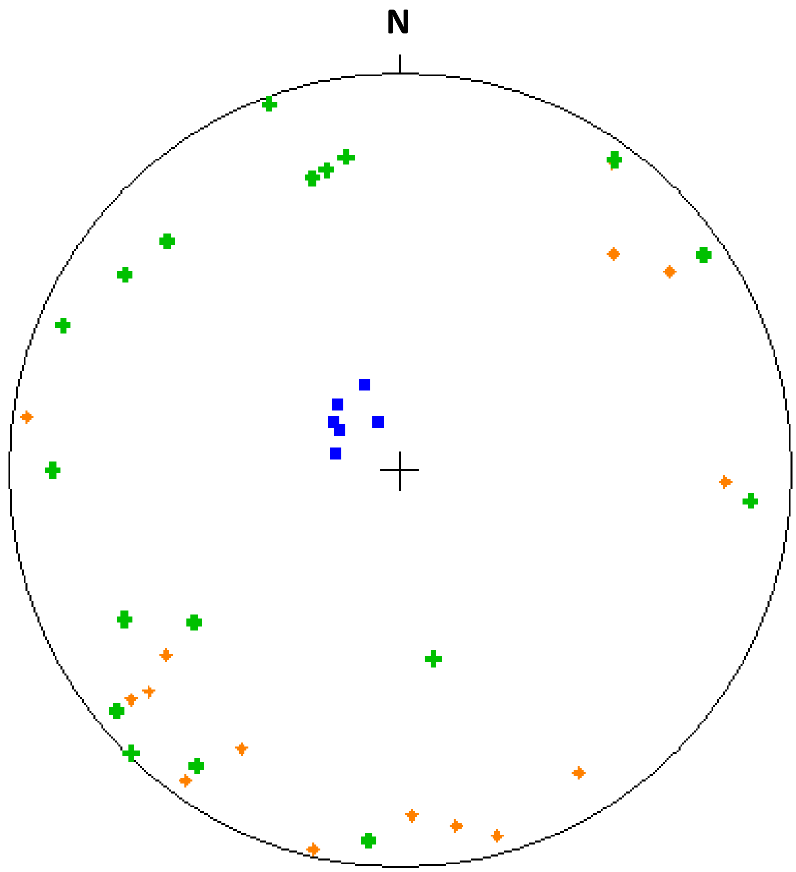

Figure 5.42: Pole-to-plane stereonet of joint sets measured at the E surface of MP Site 4. The data below indicate the joint systems measured as well as their mean principal orientation.

Bedding Plane (blue squares)
No. of Data = 6
Mean Principal Orientation = 44/15E
Mean Resultant dir'n = 15-134

Inland Joints (orange stars)
No. of Data = 15
Mean Principal Orientation = 302/85N
Mean Resultant dir'n = 62-005

Coastal Joints (green cross)
No. of Data = 18
Mean Principal Orientation = 303/86N
Mean Resultant dir'n = 52-108

MP Site 4, 'D' Surface	Bedding Plane	Primary Joint Set	Width (mm)	Spacing (cm)	Secondary Joint Set	Width (mm)	Spacing (cm)
Zone A	201˚/11˚ SE	327˚/90˚	2 – 3	10 - 25	260˚/86˚ E	1 – 10	15 - 20
Zone B	224˚/19˚ SE	323˚/81˚ SE	1 – 20	2 - 12	250˚/90˚ NW	1	2 - 10
Zone C	210˚/13˚ SE	322˚/88˚ SW	1	2 - 8	240˚/90˚ NW	1	1
Zone D	212˚/13˚ SE	326˚/74˚ W	1 – 20	1 - 5	256˚/75˚ NE	1	5 - 15
Zone E	205˚/09˚ SE	320˚/85˚ NW	1 – 20	1 - 5	230˚/90˚ W	1 – 2	3 - 6
Zone F	196˚/17˚ SE	165˚/80˚ W	2 – 10	10 - 30	350˚/90˚	1 – 80	1 - 8
Zone G	186˚/14˚ SE	180˚/72˚ S	1	1 - 6	254˚/76˚ W	2 – 8	10 - 30

Table 5.9: Primary and Secondary joints, MP Site 4, D Surface.

MP Site 4, 'E' Surface	Bedding Plane	Primary Joint Set	Width (mm)	Spacing (cm)	Secondary Joint Set	Width (mm)	Spacing (cm)
Zone A	194˚/14˚ SE	319˚/74˚ N	15 - 60	100 - 900	255˚/85˚ N	10 - 30	1 -5
Zone B	247˚/19˚ S	323˚/81˚ SE	1 – 25	60 - 100	239˚/78˚ N	1 – 15	20 - 40
Zone C	213˚/15˚ SE	320˚/79˚ SE	1 – 2	2 – 9.5	261˚/80 W	1 – 3	1.5 - 10
Zone D	225˚/17˚ SE	320˚/84˚ NE	20 – 250	60	250˚/88˚ SW	1 – 40	10 - 30
Zone E	226˚/19˚ SE	332˚/69˚ N	1 – 20	3 - 12	260˚/69˚ SW	10 – 70	8 - 15
Zone F	244˚/11˚ SE	324˚/55˚ E	1 – 10	3 - 9	260˚/40˚ N	5 – 30	30 -35

Table 5.10: Primary and Secondary joints, MP Site 4, E Surface.

5.2.6.1 MP Site 4: D Surface

With an area that is 115 $m^{2,}$ the perimeter of the D surface is ~ 53 m with roughly 26.2 m along the coast and 28.3 m along the inland margins of the surface.

The D surface at MP Site 4 had only one major joint system. A dominant joint system had a SDS of ~ 320˚/85˚ N with joint sets that ranged from 0.5 to 2 m spacing in some parts, and 4 to 9 m in others. The width of the joint openings was ~ 15 to 60 mm. This set included nine joints that extended across the length of the surface, normal to the coastal edge. One of the joints indicate zones was faulted with a displacement of ~ 3 cm. There were a number of smaller, and variable joint systems (in terms of width and spacing) that intersected this large scale system.. Although open joint sets were observed, loose blocks were not observed along the rock wall located to the east of the surface. At the base of the wall was a receding layer of tephra ~ 35 cm thick. Some pebbles and cobbles were lodged into the base of the rock wall.

Large clasts have been removed from the southwest part of the D surface. However, although not blackened to the degree of an oil slick, *Verrucaria* lichen along these eroded surfaces indicates that these blocks were not removed recently.

Overall, the whole of the surface was much more abraded by wave action than any of the other MPER surfaces observed. As well, the slope along the leading coastal edge of this surface was convex rather than having a sharp 90˚ angle, as observed along the other three MP Site coastlines.

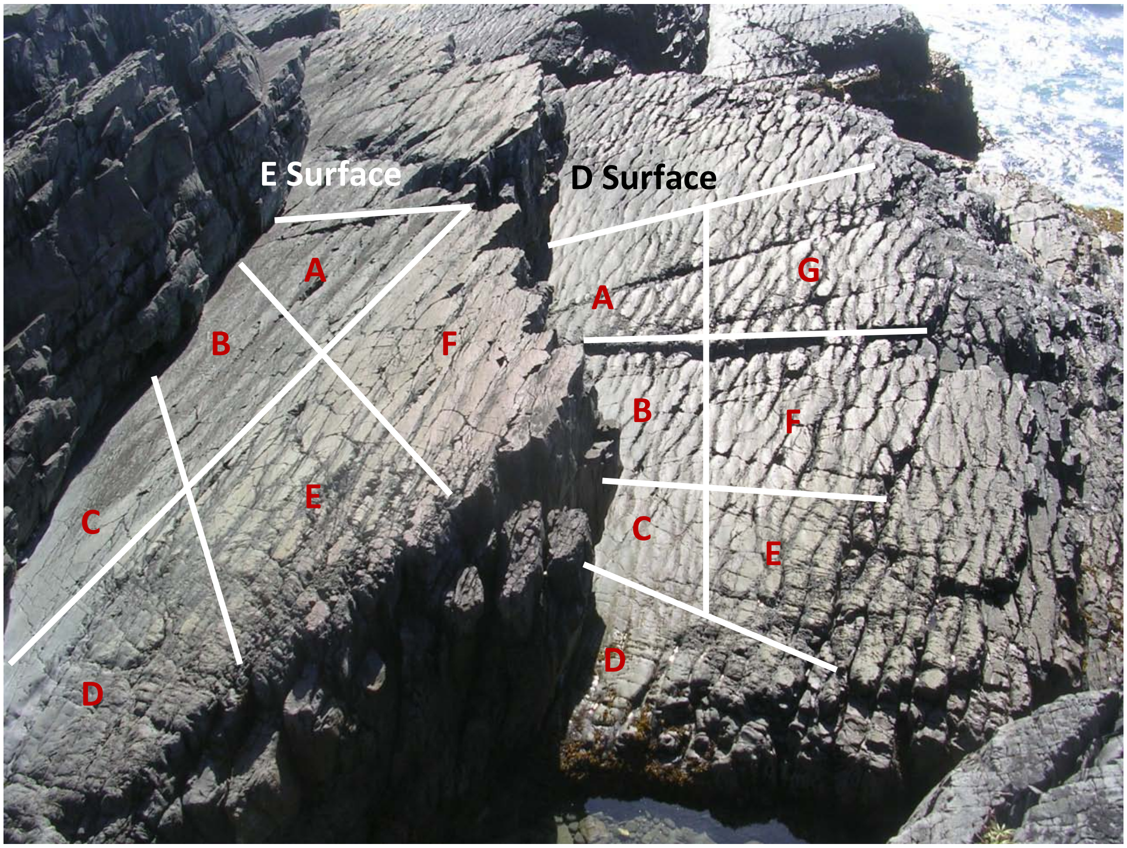

Figure 5.43: D and E surface at MP Site 4, with zones where geometrical measures were taken.

5.2.6.2 MP Site 4: E Surface

The structure along the E surface is very similar to that of the D surface. The dominant set with nine major fractures and some faulting shares the same SDS (319˚/74˚ N) as the D surface. The parallel micro-fractures along the E surface share the same orientation and spacing as those on the D surface, but the crenulations had a lesser depth from trough to wave, indicating. Width of the parallel micro-fractures increases where they intersect dominant joint sets.

The coastal edge of the E surface drops at a 90˚ angle to the D surface. E surface was visibly less weathered by possible scour observed than the D surface.

5.2.7 MP Site 4: Physical and Chemical Processes along D and E Surfaces

MP Site 4 receives direct impact, and is much closer to sea level than MP Site 3. As a result, overtopping has been noted along the surfaces of MP Site 4, and both the D and E surfaces have been entirely engulfed by waves on a number of occasions, notably during Hurricane Bill (2009).

Surfaces	**Heights in m**
Top of rock wall to E surface (south)	~ 4.60
Top of rock wall to E surface (north)	~ 3.33
E to D surface (south)	~ 2.55
E to D surface (north)	~ 2.55

Table 5.11: MP Site 4, heights of bedding plane to water line.

Erosion was observed on the southwestern corner of both the D and E surfaces. However, along the D surface this erosion extended to a depth of ~ 30 cm, over an area of 4 m^2. The eroded areas were bounded by parallel micro-fractures intersecting joint systems.

The entirety of the D surface at MP Site 4 was abraded quite extensively by salt water. The lowest point of the surface along the northeast edge lies within the intertidal zone. This is also the part of the D surface that had the greatest distribution of algae.

Verrucaria maura lichen had a consistent distribution over the D surface, but was thicker in the depression areas of the crenulations. *Verrucaria* was not present at the lowest northeastern edge where the greatest amount of scouring occurred. Along the southwestern edge, *Verrucaria* is quite heavily blackened along the surfaces where surface erosion has occurred.

The presence of pyroclasts along this surface was observed, but was not conspicuous. *Verrucaria* was quite thick (black) and extensive along this surface, and the pyroclasts were extensively eroded and weathered. On the E surface, overtopping as well as wave impact caused by long fetch winds and storm activity were observed along this surface on a number of occasions, especially during the autumn months.

Verrucaria was observed to be less extensive along the E surface, mostly forming patches. *Verrucaria* was thickest within the depression of the crenulations as well as along the base of the rock wall. Areas of higher relief (e.g. northwest and southwest coastal segments) generally had less *Verrucaria* on the surface. It was on these areas that oxidization was present. Similar to the D surface, *Verrucaria* was also thick along the eroded (lower relief) surfaces on the southwestern edge. Although some of the northeastern part of the E surface was scoured clean, the lichen remained in the fine fissures.

Xanthoria sp. was noted in very small amounts along the rock wall and near the outer edge of the E surface.

5.2.8 MP Site 4: Human Impact along D and E Surfaces

In the summer of 2010, a visiting international palaeontologist scrubbed a latex material into the E rock surface with a toothbrush in the belief that this would provide better adherence. The layer of latex penetrated the rock surface so effectively that after peeling the entire mould off after curing, the undercoat remained behind. This was unintended as the palaeontologist stated that this process had worked well in Central England with similar surface conditions. Nonetheless, although latex solvent was used to remove the majority of the latex material, specks of residue could still be observed in autumn 2011. As well, there was a minimum of five patches where the latex had removed all surface material including both *Verrucaria* and pyroclastics. Aside from the possible damage to fossils from casting, there were three fossil extractions from the E surface near the inland rock wall. Two core drill holes were noted along the rock wall east of the D surface.

Figure 5.44: Removal of *Verrucaria* lichen due to individual casting (legal) in Zone A, E Surface, MP Site 4.

5.2.9 Synopsis Mistaken Point Sites

The differences that were observed between MP Site 3 and MP Site 4 from 2009 to 2011 are related to Ediacaran sedimentation, Ediacaran and Palaeozoic tectonics, and Quaternary processes. Adjacent Quaternary bluff material was also present, but the resultant effects on each site were observed to be negligible during the period of investigation.

The coastline of MP Site 3 faces south, and MP Site 4 faces west. Both sites have two bedding plane surfaces (D and E) dipping inland with a mean orientation of ~ 15˚ trending southeast. Structural geology at each site is quite similar with consistent conjugate joint systems throughout each of the surfaces. The primary set trend SW-NE, and the secondary is an intersecting set with the parallel micro-fractures, with an E/W orientation. The greatest amount of joint plucking, widening, and depth was observed in the southwest corners of the D and E surfaces at both MP Site 3 and MP Site 4. Differences noted between the sites include the type and relative rates of erosion.

Loose clasts (cobble to boulder), orthogonal in shape, were noted along the edges of MP Site 3. One in particular, wedged in the SW corner of the D surface and ~ 200 kg, was removed by wave action in the winter of 2010 – 2011. A number of fossils resided on its surface. Random loose clasts were noted along both the D and E surfaces of MP Site 3, popped up out of their original placement, either lying loosely within or near their original position. No such loose clasts were observed at MP Site 4.

Along the D and E surfaces of both MP Sites, the SW corner is also visibly eroded, with its lowest exposed point of each surface thoroughly abraded by wave impact.

At MP Site 4, although plucking and block removal from the SW coastal part of each of the D and E surfaces had been visibly eroded, there were no loose clasts, and much thick *Verrucaria* covered the surfaces where clasts had been previously.

The wave impact at this site is quite powerful along both coastlines, especially along the SW corners. On a number of occasions, waves were observed to completely engulf MP Site 4 (especially under high tide, storm surge conditions), whereas overwashing and/or wave splash was noted at both low and high points of MP Site 3 surfaces, suggesting that MP Site 4 is much more exposed to wave impact. Overwashing was powerful enough that on a few occasions unconsolidated material on the D surface of MP Site 3 (used to construct the stair to E surface) had been removed entirely. MP Site 4 is much closer to sea level, implying that any loose clasts that might have been there have been removed by waves or gravity.

Quaternary material was present to the west of the D and E surface at MP Site 3. Little movement of this material was noted on E surface. However, following extreme storm conditions (e.g. Hurricane Igor, 2010) flow of this diamicton on to MP Site 3, D surface, was noted. Although a previous flow along the E surface was excavated in 2009, very little movement has been noted since.

Because of the diverse and abundant fossil assemblage at the MP Sites, the bedding planes are most frequently visited by researchers and the general public. However, MP Site 3, due to its accessibility, experiences a much greater frequency of visitors than MP Site 4, and receives the greatest amount of human impact of all four sites. Human impact comes in the form of foot traffic, and has also been evident in casting projects, and extraction of fossils.

Previous casting by researchers was observed on all of MP Site 3 and MP Site 4. In some cases, the removal of casting material also removed *Verrucaria* and/or pyroclasts from the surface of the rock. As well, since the most prominent populations of fossils are known to be on the E surface, extraction of fossils by diamond saw was noted. Fine fissures and cracks were noted to be aerially projecting from the pockets where fossils had been removed. Partial removal of three *Charniodiscus* holdfasts on MP Site 3, E surface was also evident. It is unclear as to the cause: however, it believed to be a product of human vandalism. However, as these three fossils were near a Quaternary flow, it is possible that debris of harder material may have fallen, shattering the raised relief of the holdfasts.

6. Discussion and Interpretation

The dominant factors influencing erosion along MPERs coastline are inherent geological features (including rock type and structure), climate-related factors (wave impact, intensity and frequency of storms, frost action), gravitational displacement due to overlying and underlying layers of weaker material, and human impact. The structural geology of the bedrock along MPERs coastline will remain unchanged in the foreseeable future. Changes in environmental controls and forcing factors such as relative sea-level and climate factors can be both qualitatively and quantitatively assessed into the coming years. At present, of the factors involved, human activity may be the most easily managed or controlled component with respect to erosion along MPERs coastline. It is also the component that has the greatest potential to increase in the foreseeable future, due to MPER's increasing popularity.

6.1 Structural Geology

The primary factors that control the strength of bedrock are structure and texture, mineral composition, bedding, jointing and anisotropy (directionally dependent properties), water content, and state of stress (Agustinus, 1992). The structure observed at each of the MPER sites is dominated by a number of joint sets which have orientations corresponding to the regional structural geology (Williams and King, 1979). Many joint sets are extension fractures formed normal to a direction of least stress, under tensile conditions. The systems along MPER are conjugate sets that enclose an angle of ~ 60°. The bedrock is primarily argillite, siltstone, and sandstone, except where patches of volcanic tephra are present.

6.1.1 Structural Geology: PC Site1 and PC Site 2

Both bedding planes at the PC sites dip seaward. Although conjugate fractures were present at both PC Site 1 and PC Site 2, the fracture widths and depths at PC Site 2 were much less than those at PC Site 1 (Table 5.1). Overall, the structural complexity with respect to folding and joints was much less at PC Site 2 than that at PC Site 1. Along the inland part of PC 1 IBP, joints are open and propagate vertically through the beds, whereas along much of PC Site 2, fractures are generally shallow, surface features with maximum depth of 1 mm. The primary joint sets at PC Site 1 are aligned complementary to the orientation of the fold, aligned with NW-SE attitudes in the North Sector, changing to W-E in the South Sector (Table 5.1).

6.1.2 Structural Geology: MP Site 3 and MP Site 4

MP Site 3 and MP Site 4 share the same structural geology. Both MP Sites have parallel micro-fractures that trend SW and propagate inland. The micro-fractures are coupled with a normally-oriented joint set, contributing to intense erosion near the coastal edges (c.f. Hall *et al.* 2008).

The dominant regional pattern structured along MPER's coastline includes joint systems oriented at 033˚- 213˚ and 124˚- 304˚ (Williams and King, 1979). However, the parallel micro-fracture set (due to compressional fracturing along the folded crenulations), had an orientation of 160̊ - 340˚ (Figure 5.32). Although air photographs of the site indicated significant erosion to the bedding planes due to wave impact along the exposed primary (033˚-

213˚) and secondary (124˚- 304˚) joint sets, field observations from 2009 to 2011 indicated that rock toppling was initiated along the parallel micro-fracture set (160˚- 340˚) (c.f. Scheidegger, 2001) measured at MP Site 3 and MP Site 4. This pattern is especially prevalent in the SW corners of both sites, suggesting greater rates of erosion. Similar effects of erosion resulting from intersecting joint systems were observed by Wolters and Müller (2008).

The Pigeon Cove and Mistaken Point sites are subject to surface brittle fracturing due to the impact of wave-thrown clasts and displaced glacial erratics (Figure 5.3, 5.10). Observations made at PC Site 1 and MP Site 3 indicate that fracture openings enhanced by hydraulically thrown materials were a major factor responsible for overall erosion at these sites.

6.2 Physical Processes

6.2.1 Wave Impact: PC Site 1 and PC Site 2

Wave activity at the Pigeon Cove sites is directed from the SW, normal to the shoreline. With the exception of PC Site 1's North Sector, wave impact along PC Site 1 is intense. The South Sector, devoid of outcrop protection, is subject to direct wave impact as well as hydraulically thrown materials. This resulted in the widening of joint systems (from ~ 1 to ~ 10 mm). The missing protective stratigraphic layer along this sector is the result of long-term erosion (c.f. Sunamura, 1992; Larson *et al.* 2000).

Indirect wave impact observed along the North Sector was the result of wave refraction brought about by the presence of the northern headlands. Impacts of wave-transported clasts contributed to erosion of the PC 1 LBP. Incoming wave impact from both the north and south sectors of PC Site 1 also erodes clasts from the upper bedding planes, which fall onto the PC 1 IBP. Fallen and/or broken material may cause abrasion (Trenhaile, 1987) on the bedding planes where wave energy is high and persistent. However, where overlying material is thick enough, the *Ivesheadia* layer below may be protected (Sunamara, 1976) from the direct wave impact for years to come.

Although Pigeon Cove is dominantly reflective, some of the wave energy is expended before reaching the shoreline. Offshore of Mistaken Point, the steeply sloping bathymetry produces consistently reflective conditions, marked by high wave energy impact on the cliffs (Galvin, 1968).

6.2.2 Wave Impact: MP Site 3 and MP Site 4

Although no loose clasts or fresh surfaces were observed along the seaward edge of MP Site 4, a number of loose clasts, rock fall and toppling, and debris removal were observed at MP Site 3. Gravitational movements may be initiated by wave action which affected the movement of both consolidated and unconsolidated material. Pneumatic wave action commonly contributes to the removal of pebble size clasts (Wolters and Müller, 2008), as was observed from both D and E surfaces at MP Site 3. Removal of debris from the base of the wall of the D surface occurred regularly as well. Storm-induced groundwater discharge to the surface is responsible for saturation of sediment and physical removal of fine materials. The resultant void is regularly infilled by debris flow material originating from the west of the rock wall. Overwashing regularly reached the NE corners of both the D and E surfaces at MP Site

3. Wave impact was powerful enough to entirely remove the clasts used to make the stairs from D to E surfaces.

At MP Site 3, evidence of substantial removal via plucking was visible along its NE sector. The effect of wave impact received at MP Sites is, however, tempered by the height above sea level and inherent structure. For several years, tourist usage of MP Site 3 has been permitted due to its accessibility from the trail north of the bluff and its secure position, given its height from sea level and therefore protection from wave impact. Although both sites share the same joint system and are subjected to the same physical processes, MP Site 4 is situated closer to sea level. As a result MP Site 4 is directly and intensely engulfed by waves and storm surges. Any loose clasts are removed during these high energy wave conditions.

During 2009 to 2011, the tropical storms to impact MPERs coastline included: Hurricane Bill (August, 2009), Hurricane Danny (August, 2010), Hurricane Igor (September, 2010), Hurricane Katia (September, 2011), and Hurricane Ophelia (October, 2011). Storm events generally resulted in overtopping at all sites, movement of clasts at PC Site 1, and movement of debris from the base of the rock wall at MP Site 3, D surface.

6.2.3 Gravitational Displacement: PC Site 1

The presence of constant wave impact also saturates the rock units. The upper tephra layers are softened into a viscous state, contributing to notch development which compromises the stability of PC 1 LBP. This eroded void will lead to the eventual collapse of PC 1 LBP (Hampton, 2002; Wolters and Müller, 2008), exposing the underlying PC 1 IBP to erosion.

The lower tephra layer is much less exposed to wave impact, and no notch development was observed.

6.2.4 Gravitational Displacement: MP Site 3 and MP Site 4

At MP Site 3, rock falls from the rock face to the northwest of the site are an issue. Due to erosion of the Quaternary layer above, excessive joint widening (1 to 5 cm), and therefore flexural toppling (bending of rock columns) onto the MP Site 3, D surface was observed. Recession of the Quaternary sediments above the rock wall contributes to the instability of the rock wall by reducing underlying support and thereby inducing gravitational failure (Hampton, 2002; Wolters and Müller, 2008).

The Quaternary diamicton is 2 to 3 metres in thickness. Although the movement of the diamicton material to the bedding plane was noted at MP Site 3, none was observed to fall from directly above. Therefore, at this time the Quaternary debris appears to pose little threat to the fossils. It is, however, subject to debris flow onto the D surface, triggered by both water saturation and frost action (Speller, 2001; White, 2002; Catto, 2011, 2012; Catto et al., 2003).

6.2.5 Frost: MPER Coastline

Aside from weakening the strength of bedding planes, the presence of conjugate joint systems provides an effective conduit for the circulation of seawater, runoff, and precipitation. Water contributes to change in a coastline not only by hydraulic force, but by frost action as well (Trenhaile and Mercan, 1984; Tharp, 1987; White, 2002; Catto, 2011).

Along Canadian Atlantic coastlines, frost contributes to the wedging of rock, leading to eventual removal of smaller and larger clasts. Along each of the sites observed at MPER, frost heave within the Quaternary bluff line contributes to the displacement of erratics from above onto fossil surfaces below. Removal of the boulders leaves voids, subjecting the overlying diamicton to further gravitational failure and contributing to the distribution of diamicton material onto the PC 1 IBP surface below.

Whether erosion by frost occurs within the softer Quaternary bluff or within the bedrock, the removal of overlying layers increases the rate of erosion of the underlying material. When bedding planes exfoliate, as in the case of PC Site 1, load is decreased (Wolters and Müller, 2008) resulting in the spalling observed near the North/Central Sectors of the PC Site 1 *Iveshedia* bedding plane.

6.2.6 Lichens: MPER Coastal Bedding Plane Surfaces

Although lichens are able to physically and chemically erode lithic substrate (Fry, 1927; Jones *et al.*, 1981; Adamo *et al*., 1993), very little research has been published that assesses the relative importance that lichen has on eroding bedrock coastlines (Stretch *et al.* 2002). *Verrucaria* lichen was helpful as an indicator in qualitatively assessing the relative rate of erosion of surfaces. Distribution of *Verrucaria* is in part a response to the environmental process impacting its existence.

Verrucaria was present at all four sites. The amount of lichen cover was observed to be inversely proportional to the level of wave impact and salt spray. *Verrucaria* was noted along most of the PC 1 IBP as well as on eroded clast surfaces. Most areas with coverage resembling the thickness of an oil stain were sheltered from wave action, within the fractures, and in notches along the base of stratigraphic layers facing inland. *Verrucaria* at MP Sites was most prevalent within the troughs of the crenulations, often interspersed with pyroclastic material, as well as along the base of rockwalls inland where lichens might be better protected from physical processes such as wave impact.

6.3 Human Impact

While human impact was noted at two of the four sites along MPER's coastline, it was also observed along the guided tour trail leading to MP Site 3. Although the fossil surfaces were the primary sites of observation, the Guided Tour trail leading visitors to the fossil site also is relevant to a discussion of human impact. Points along the trail (~ 100 m east of Berry Picker trail) are within a few metres of the cliff edge. These points show extensive undercutting (~ 1 -2 m). Undercutting near the trail may pose as a danger to visitors hiking the trail. As well, the presence of the foot path itself weakens the cohesion (damage to near-surface roots, frost heave) of the sediment along the coastline, increasing the rate of erosion (Norman, 2010).

6.3.1 Human Impact: PC Site 1

Aside from the overall aesthetic appeal of the beach area and the easy accessibility of Pigeon Cove, the increased recognition of PC Site 1 fossils (Liu *et al*., 2010) suggests that it may be more vulnerable to unpermitted visitation in the future. This may come through permitted guided tours as well as unregulated visitation on the bedding planes. Illegal fossil casting has been observed at PC Site 1.

6.3.2 Human Impact: MP Site 3

Increased visitation to MP Site 3 may also pose a threat to visitors. Rock falls have been noted during the summer months when visitation is greatest, and have been noted near the entrance from D to the E surface. The lack of a protective barrier between the surfaces being visited and the rock edge along MP Site 3 D and E surfaces is also a concern.

Although human impact differs at the sites, it contributes to increased erosion of both fossils and coastline with MPER. Erosion of the coastline and rock falls may also pose threats to humans visiting certain segments of the coastline. This was particularly noted along the D and E surfaces of MP Site 3, where greatest visitation is permitted through guided tours.

The presence of the interpretive centre as well as media recognition has contributed to an increase of visitation through guided tours at MP Site 3 from 303 (recorded) visitors in 2007 to 846 in 2011. Although there has been no documented evidence that foot traffic has resulted in erosion of fossil surfaces, the required use of "bama booties" by those visiting the fossil zone was initiated in 2007. The rate of erosion due to foot traffic was not assessed during the three-year project. However, it is suspected that the use of day shoes on the fossil surface may contribute to erosion. The harder treaded soles of hiking boots as well as the harder materials embedded into them may chip away the protective 2 mm tephra laminae overlying the fossils along the E surface. Consequently, the use of bama booties is enforced to reduce the rate of wear that would result from trail or urban footwear.

MP Site 3, D and E surfaces receive significant attention from researchers, meaning these surfaces are casted much more than the other fossil surfaces along the MPER coastline. In September 2009, an organized effort was made to cast the E surface at MP Site 3. Although this meant the presence of many individuals; motorized equipment on the surfaces as well as on the bluff above, the project was successful in that it provided paleontologists and the public with excellent representations of the fossil surface to observe and study without actually being on the fossil surfaces. No damage to the fossil surface was observed post-casting.

Individual casting, on the other hand, was not observed to be so successful. Although the protective aspect of lichen along coastlines is not well understood, and more work has been conducted concerning their erosive characteristics (Stretch *et al.* 2002), in the case of MPER *Verrucaria* lichen may possibly act as a protective cover for the fossils. *Verrucaria* essentially anchors itself into the rock surface by its thallus. During individual casting processes, with the removal of the lichen, the surface relief of rock may be removed as well. The removal of *Verrucaria* due to individual casting was noted in a number of areas throughout the Mistaken Point rock surfaces.

6.4 Summary

Ideally, to obtain reasonable quantitative rates of erosion along MPERs coastline, an analysis involving long term observations (> 60 years) would be required. Two to three seasons of observation is not an adequate time period for understanding rates of erosion along a coastline (Batterson and Liverman, 2010). Therefore, with a view to subsequent quantification of coastal erosion rates, the study conducted along MPER's coastline was primarily conducted for the purpose of collecting baseline data for future research. RTK GPS measurements were collected along MPER's coastline to benefit possible future analysis. However, during the three years of this project, the processes occurring, as well as their degree of impact at each site, provide information concerning the relative significance and rates of erosion.

The significance of erosion observed at each of the sites has been based upon the type of erosion at each site relative to that same factor or process at another site. This approach provides managers with a specific understanding of the nature of each site, without neglecting the complex set of processes and factors that contribute to the overall geomorphology of the MPER coastline, not only at present but for years to come. Consequently, over time each of those factors specifically influencing erosion at each site could change (increase or decrease) in intensity.

Inherent conjugate joint systems are present at each of the sites, increasing their vulnerability to erosion by more recent physical processes and factors. PC Site 1 is affected by wave impact along the length of the *Ivesheadia* surface as well as adjacent surfaces, but to a much greater degree along the South Sector. Seaward sloping headlands and the angle of the shoreline to wave impact mean that the bedding planes at PC Site 2 were better protected relative to those of PC Site 1.

Gravitational displacement was observed at both PC Site 1 as well as MP Site 3. Although the removal of the Quaternary materials by mechanical erosive tools such as frost action at PC Site 1 pose little threat to the *Ivesheadia* plane (PC 1 IBP) below, the notch development within the tephra layers above and below the *Ivesheadia* bedding plane does exacerbate rock toppling onto the *Ivesheadia* plane. At MP Site 3, although the tuff layer above the fossil layer does not contribute to gravitational displacement, the unconsolidated diamicton layer above the rockwall does contribute to the widening of the joint systems and subsequent rock toppling onto the Ediacaran fossil layer below.

MP Site 3 and MP Site 4 coastlines are also vulnerable to wave impact. MP Site 4, due to its lower elevation, is subject to a greater degree of wave impact. However, no loose clasts were noted along its coastal edge from 2009 to 2011. And although much higher from sea level and therefore lesser wave impact, due to the present of loose clasts, rock toppling was noted from 2009 to 2011 at MP Site 3. Bisecting conjugate joint sets coupled with wave overtopping mean that a number of fossil-bearing surfaces are at risk of toppling into the ocean.

Human presence at each of the sites varies, with much greater importance at MP Site 3 largely due to the ongoing visitation by guided tours and paleontologists. Relative to MP Site 3, the fossils at PC Site 1 have not yet been subjected to the same level of study and publication, and therefore have less public recognition. To date, there is little signage with respect to PC Site 1, and little publicity, and therefore few tourists know of its existence or significance. Nevertheless, with increased recognition of MPERs coastline, the potential consequences (foot wear, illegal removal of fossils) should be thoroughly considered for proper development of an effective plan for its conservation.

Thus, the primary factor noted to contribute to erosion at all four sites was the inherent geologic structure at the sites. Additional factors considered significant at PC Site 1 include wave impact in both direct and indirect forms. The direct form is most powerful along the South Sector of the PC 1 IBP at PC Site 1, while indirect but equally intense is the impact that results from hydraulically thrown materials, such as cobbles and pebbles. A secondary factor at PC Site 1 is frost action. A primary factor at MP Site 3 is rockfall, resulting from frost action and bluff removal. Wave impact is secondary, although powerful enough to overtop and remove already loose clasts along the outer edges.

Individual casting at PC Site 1, MP Site 3, and MP Site 4 was considered as a possible impacting factor. However, although individual casting was observed to possibly remove fossil relief, the level of fossil relief removed is so small that it was difficult to observe qualitatively and was not measured quantitatively. Foot traffic on the fossils also is believed to have impact, but the rate of removal was not measured. Nonetheless, human impact is considered as a potential factor if there is increased visitation in the future.

Site	Physical	Human
Pigeon Cove Sites	**Inherent structure** **Wave impact** **Impact of hydraulically thrown materials** **Storm frequency/intensity** **Surface abrasion by eroded clast material** **Frost action**	**Illegal casting** **Removal of fossils**
Mistaken Point Sites	**Inherent structure** **Rockfalls** **Wave impact** **Storm frequency/intensity** **Frost action** **Verrucaria lichen**	**Foot traffic** **Removal of fossils** **Illegal casting**

Table 6.1: Primary and Secondary factors and processes contributing to erosion at Pigeon Cove and Mistaken Point Sites.

7. Conclusion

The events and processes that have occurred along MPERs coastline will influence erosion in the future. Understanding the contributing factors and processes separately as well as in relation to one another has provided geomorphologists and managers a better understanding of erosion occurring at the four sites analysed along MPERs coastline.

Observations from 2009 – 2012 indicate that coastal erosion is occurring at each of the four sites under study. All four sites assessed along MPERs coastline receive wave impact, and all sites share similar rock types. However, their structural geology, intensity of wave impact, and degree of human impacts are quite different. The relative prevalence and importance of each of these factors at the sites should inform and be reflected in the strategies and level of active management exercised along MPERs coastline.

The sites of greatest interest to scientists and visitors are the sites that are proving to be most vulnerable: PC Site 1 and MP Site 3.

PC Site 1 is one of the most complex sites with respect to structural geology. It also has a number of different erosional processes occurring, such as both direct and indirect wave impact, frost heave, and oxidization. Types of erosion along the *Ivesheadia* bedding plane, especially along its North and South Sectors, include direct wave impact; hydraulically thrown beach materials propelled by wave force; and abrasion of the fossil surface by scree, especially at its northern point. In addition, due to frost heave during the winter months, large boulder erratics are falling onto the fossil surface. Gravity- induced failure and tensile fracturing (widening of already present joint systems, and fracture propagation, as well as the creation of new fractures) is occurring due to eroded underlying and overlying stratigraphic layers of weakness. Chemical weathering and erosion (oxidization) is also apparent and effectively reduces surface relief of fossils. Although there is little visitation on the surface at present, the site is easily accessed and receiving more recognition for its fossils, and is therefore under threat of increased unpermitted visitation. There is little that the Ecological Site Reserve Management can do to prevent wave impact and chemical weathering. Salvage of displaced blocks is possible: loose clasts with Ediacaran fossils have been noted along PC Site 1, and one large disaggregated block with a fossil was removed in 2009 for preservation and use in education. .

At MP Site 3, the large-scale conjugate joint system is intersected by two joint sets, one oriented NE/SW and the other N/S. Erosion due to these joint systems is ongoing and will continue. Failures along the NE/SW set intersecting with the micro-fractures oriented in a SE/NW direction are contributing to the active (observed loose blocks) erosion. Although the joint systems at MP Site 3 surfaces are the result of structural deformation, their open widths and depths, and eventual rock -toppling and –fall are due to physical processes, including the intense wave regime (including storms) that effectively remove the blocks from the coastal edge. As a result, a number of large as well as smaller clasts have been detached and fallen into the sea, carrying Ediacaran fossils. The exposed rock wall to the north of the bedding plane, due to removal of Quaternary material above, is also marked by wide, deep-set joint systems, exposed to frost action and therefore inducing rockfall onto the D surface. This poses a potential threat to visitors, especially if visitation increases.

MP Site 3 is far less accessible than PC Site 1, but is well known for its fossil assemblage. Increased visitation, even via guided tour, is a concern in that foot traffic compromises the stability of the trail leading to the fossil sites. It is believed that foot traffic contributes to fossil erosion, although this has been controlled by the use of bama booties by visitors on guided tours. Cliff undercutting poses a concern for visitor safety.

It is also clear that if casting is not done with care, the fossil surface relief will be compromised. This suggests that fossil conservation at MP Site 3 might be difficult if excessive individual casting occurs.

Thus, at PC Site 1 and MP Site 3, the following erosive mechanisms are most prevalent at present:

- Gravity induced failure by removal of overlying and underlying materials and therefore increased tensile fracturing, contributing to the widening of existing structural joint systems
- Falling Quaternary material as well as impact (especially at PC Site 1) by hydraulically thrown materials impacting the joint systems and fossil relief
- Loose clasts along PC Site 1 and the coastal edge of MP Site 3 swept away by wave action, accentuated by the seaward incline of the bedding planes
- Removal of fossils (loose clasts) during unpermitted visitation
- Danger to fossil relief as well as to visitors (rockfalls, undercutting of bluff) if visitation increases through guided tour or other forms of human presence (field trips, large scale casting projects)
- Individual casting detaching *verrucaria* lichen, believed to compromise the integrity of the fossil relief

Although the numerical rate of erosion is unknown, it is clear that MPERs coastline is eroding. At present, the physical processes far outweigh the human impact along this coastline. However, compared to other UNESCO Sites, such as Joggins, Devon/Dorset coast, and Burgess Shale, human presence at this site has been relatively low since recognition of the fossils in 1968. Control of physical factors is not an option. From a management viewpoint, control of human presence is the primary mode of conservation.

7.1 Recommendations

The following is recommended with respects to continued erosion assessment and management of MPERs coastline:

1. Rates of change at each of the sites should be observed through both qualitative and quantitative methods, for long term increases or decreases in erosion as well as any changes in the factors causing erosion:
    - Qualitative (e.g. photographs) monitoring. This includes reporting the movement and/or removal of clasts from each of the sites, either via human or physical processes.
    - Quantitative monitoring along bluff edge and along bedrock coast with the use of a RTK GPS system would be an effective method to assess the rate of seaward erosion and bluff retreat on the landward side. .
2. Although the effects of foot traffic on fossil relief were not quantitatively assessed in this study, until proper assessment can be undertaken, the reduction of foot traffic

impact by continued use of Bama-socks by visitors when entering onto each of the sites is recommended.

3. Warnings to visitors on MP Site 3 surface concerning the instability of the bluff edge, debris flows, and rock falls should be instituted.
4. Understanding the type of casting material proposed for use as well as the casting process is crucial to preserving fossil relief.

According to UNESCO Operational Guidelines (2011) MPERs coastline represents a important part of Earth's geological history and is a significant example of ongoing geological processes, however, active monitoring and management of those components that determine its geological value have only been recently implemented. It is an Ecological Reserve of interest to researchers and visitors from Canada and increasingly from around the world. Relative to other UNESCO sites of geological interest, MPER has improved its management and conservation of the coastline since 2007. Nonetheless, while processes and factors change over time, so will the morphology of MPERs coastline. It is recommended that management of those areas within the fossil zone include monitoring of those changes to maintain effective conservation of MPER.

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