THE COASTLINE OF EASTERN NEWFOUNDLAND

N.R. Catto, D.A. Scruton, and L.M.N. Ollerhead

Department of Geography
Memorial University of Newfoundland
St. John's NL A1A 1A2

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N.R. Catto[1] D. A. Scruton[2] and L.M.N. Ollerhead[2]

[1]Department of Geography
Memorial University of Newfoundland
St. John's NL A1A 1A2

[2]Science, Oceans and Environment Branch
Department of Fisheries and Oceans
P.O. Box 5667
St. John's NL A1C 5X1

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The coastline of eastern Newfoundland, including the Coast of Bays, Fortune Bay, Placentia Bay, St. Mary's Bay, Southern Shore, Conception Bay, and Trinity Bay shorelines, has influenced all previous human occupants of the region, and will continue to do so. The population concentrated in the northeast Avalon Peninsula, along southern Conception Bay, and in other areas of eastern Newfoundland places particular stress on these segments of the coast.

Prevailing winds from the southwest have a substantial influence on wave climate. Hurricanes and their associated precipitation are major elements shaping embayments along the South Coast, Burin Peninsula, Placentia Bay, and St. Mary's Bay, particularly those embayments open to the southwest. Northeast winds, particularly those associated with autumn storms, have a strong geomorphic influence along Conception Bay and Trinity Bay. Yearly variations in hurricane frequency and strength, in the occurrence and impact of northeast winds, and in the extent of seasonal ice cover, play a major role in shaping coastal morphology.

Tidal regimes are generally microtidal and semidiurnal, although mesotidal conditions exist at the heads of some embayments. The wave climate is driven by the prevalent wind systems and storm activity. The embayed nature of the coast results in reflective, moderate-to-high energy, wave-dominated shorelines in the majority of embayments. Sea level along the entire coastline of eastern Newfoundland is currently rising, at a rate between 2 mm/a and 6 mm/a. Limited evidence suggests that the rate of sea level rise has accelerated within the past 300 years, but additional confirming data is required. Rising sea level is one factor inducing coastal erosion, but anthropogenic activity and interruptions to sediment flux also are important locally. Successful management of the coastline must consider coastal erosion.

Repetitive observations between July 1989 and April 2001 have allowed detailed geomorphic mapping of the coastline. The geomorphic classification scheme considers sediment texture, coastal morphology (width and slope), and the nature of the substrate. Local circumstances, including aspect, sediment type and flux, offshore bathymetry and onshore physiography, energy levels, and anthropogenic influences combine to produce numerous distinctive coastal geomorphic assemblages. In addition, the coastline has been classified and mapped in terms of the vulnerability to coastal erosion of individual segments. The sensistivity of the shoreline to petroleum pollution has also been assessed and mapped.

Human perceptions of the coastal environment of eastern Newfoundland are changing, due to both economic changes and the arrival and influence of other groups and individuals. Traditionally, geomorphologists have not interacted extensively with social scientists, and have not considered socio-economic issues in their investigations. Mutually profitable future investigations are possible throughout Atlantic Canada, and should be encouraged.

Résumé

Catto, N. R., Scruton, D. A., and Ollerhead, L.M.N. 2003. The Coastline of Eastern Newfoundland. Can. Tech. Rept. Fish. Aquat. Sci. 2495: vii + 241 p.

Le littoral oriental de Terre-Neuve, comprenant les rivages de la région des baies, des baies Fortune, Placentia, St. Mary's, Conception, Trinity et de la côte méridionale, a influencé tous les précédents occupants humains de la région et continuera de ce faire. La population, concentrée dans la partie nord-est de la presqu'île Avalon, le long de la partie méridionale de la baie Conception et dans d'autres régions de l'est de Terre-Neuve exerce des contraintes particulières sur ces segments du littoral.

Les vents dominants de sud-ouest exercent une substantielle influence sur le régime des vagues. Les ouragans et les précipitations qui leurs sont associées constituent des éléments majeurs façonnant les indentations le long de la côte méridionale, de la péninsule Burin et des baies Placentia et St. Mary's, mais surtout les indentations ouvertes au sud-ouest. Les vents de nord-est, en particulier ceux associés aux tempêtes automnales, ont une forte incidence géomorphologique le long des baies Conception et Trinity. Les variations annuelles de la fréquence et de la puissance des ouragans, de l'occurrence et de l'incidence des vents de nord-est ainsi que de l'étendue de la couverture glaciaire saisonnière ont une influence majeure sur la géomorphologie littorale.

Les régimes tidaux sont généralement microtidaux et semi-diurnes, bien qu'il existe des conditions mésotidales au fond de certaines indentations. Le régime des vagues dépend des systèmes éoliens prédominants et de l'activité des tempêtes. Le caractère indenté de la côte engendre des rivages réfléchissants à modes modérément à très battus dominés par les vagues dans la majorité des indentations. Le long de tout le littoral oriental de Terre-Neuve le niveau de la mer s'élève actuellement à un taux de 2 à 6 mm/an. Des indications limitées témoigneraient d'une accélération de l'élévation du niveau de la mer au cours des 300 dernières années, mais des données de confirmation additionnelles sont nécessaires. L'élévation du niveau de la mer constitue l'un des facteurs contribuant à l'érosion littorale, mais l'activité anthropique et les interruptions des flux de sédiments sont également des facteurs importants par endroits. La gestion du littoral ne peut être couronnée de succès que s'il est tenu compte de l'érosion littorale.

Des observations répétées entre juillet 1989 et avril 2001 ont permis une cartographie géomorphologique détaillée du rivage. La méthode de classification géomorphologique tient compte de la texture des sédiments, de la morphologie littorale (largeur et pente) et de la nature du substrat. Des conditions locales dont l'exposition, le type et le flux de sédiments, la bathymétrie au large et la physiographie des étendues émergées, les niveaux d'énergie et les influences anthropiques se combinent pour engendrer de nombreux assemblages géomorphologiques littoraux particuliers. En outre, le rivage a été classé et cartographié en fonction de la vulnérabilité de segments individuels à l'érosion littorale. La sensibilité du rivage à la pollution par les hydrocarbures a également été évaluée et cartographiée.

Les perceptions par l'homme du milieu littoral oriental de Terre-Neuve évoluent tant en raison des changements économiques que de l'arrivée et de l'influence d'autres groupes et personnes. Les géomorphologues n'ont traditionnellement pas eu d'abondantes interactions avec les spécialistes en sciences sociales et leurs études ne prenaient pas en compte les problèmes socio-économiques. De futures recherches avantageuses pour les deux groupes sont possibles partout au Canada atlantique et devraient être encouragées.

1. Introduction

Study of the coastline forms a central focus for any understanding of eastern Newfoundland. For most of the plant and animal species, and for all the human occupants, life has revolved around the coastline and the coastal environment since deglaciation. All human cultures in eastern Newfoundland, including the first inhabitants of the Little Passage area, have had an intimate relationship with the coast.

For the Beothuk culture, the spatial and temporal fluctuations of food resources were crucial for nutrition (Pastore 1990, 1992; Rowley-Conwy 1990). Most resources, such as marine mammals, birds, fish, shellfish, and fruit-bearing vegetation, are found in the coastal zone. These marine and littoral resources could be harvested from early spring to mid-fall. The primary inland resource, caribou, would be harvested during the migration season, from mid-fall to early winter. Efforts to harvest either seals or caribou could fail if weather patterns caused shifts in migratory behaviour. Autumn gales during inshore seal migration periods would force the seals offshore. Failure to locate either the seal or caribou populations would cause hardship and place stress on Beothuk communities, forcing increased reliance on preserved stores and alternative diets based on littoral zone plants (such as blueberries). Without marine food sources the Beothuk would not have adequate nutrition. Nomadic people would have to move so as to adapt to changes in available resources.

When the development of more permanent European communities curtailed access to the coast, the Beothuk retreated into progressively smaller areas in the interior (Red Indian Lake area), increasing population density and reliance on caribou. An increasingly crowded population was being forced into a resource-poor area of steadily decreasing size (Pastore 1990, 1992). Diminished food resources and crowding increased the effects of contagious disease, in particular tuberculosis (Marshall 1981). The combined effects reduced the Beothuk population to extinction.

For Newfoundlanders of European descent, the harbours of the Avalon and Burin Peninsulas have represented economic and cultural centres since the first Basque, English, and French voyages, and the first attempt at colonization at Cupids in 1610. The deeply embayed coasts provided safe harbours for fishing vessels, with suitable onshore areas for drying and processing cod and for construction of the necessary stages, stores, and other buildings. Local fishing grounds supported inshore fisheries for cod, flatfish, herring, and crab, and capelin spawned on gravel beaches. Vessels engaged in offshore fisheries of the Grand Banks and Labrador were based in numerous ports. The historical, cultural, and economic place of the coastal zone in Newfoundland has been thoroughly documented (e.g. Rowe 1980; Handcock 1989; Pocius 1991).

Although the heritage of the fishery remains central to the culture of eastern Newfoundland, its economic importance has diminished in recent years. The collapse of the northern cod stocks led to the imposition of a moratorium on cod fishing in 1992, and restrictions continued throughout the 1990's. The shift to harvesting of previously under-utilized species, coupled with growing interest in aquaculture, has led to a new evaluation of the significance of the coastal zone. Although harvesting of marine species continues, eastern Newfoundland has increasingly turned to tourism to bolster its economy and stem out-migration.

The demise of the northern cod fishery and the shift towards tourism, combined with a growing environmental consciousness and ethos, has resulted in increased interest in the coastal zone. Realization of the damage, both actual and potential, resulting due to pollution both from marine (e.g. shipping) and terrestrial sources has also spurred interest. A further factor is the increasing utilization of coastal sites for residential and commercial construction by people not engaged in the fishery, leading to local concerns that the coastline will become inaccessible to other residents and that a valuable link with Newfoundland's heritage will be severed.

Anthropogenic influences on the physical attributes of shorelines are most evident on the northeast Avalon and in the smaller urban centres, but are apparent in all other communities. In eastern Newfoundland, anthropogenic activities resulting in modification of shorelines and coastal waters include:

- deliberate construction of breakwaters, or modification of pre-existing spits and bars. In some areas, modification of the original coastline continues to induce changes, although the original infrastructure has disappeared;
- dredging to improve navigation and access;
- construction of wharves and stages;
- construction of groynes to retard sediment erosion and beach-parallel transport;
- construction of seawalls to restrict wave erosion;
- railroad construction;
- road construction;
- construction of industrial infrastructure;
- aquaculture operations;
- commercial fishing;
- extraction of beach aggregate, either through 'official' or regulated operations, or on a casual basis;
- use of beaches for domestic purposes, such as capelin harvesting and rockweed gathering;
- angling;
- use of beaches for recreation, including ecotourism;
- regulated disposal of domestic and commercial wastes and sewage;
- unauthorized waste disposal and accidental discharges from terrestrial sources; and
- unauthorized waste disposal and accidental discharges from marine sources.

The Census of Canada indicated that the population of eastern Newfoundland exceeded 300,000 people in 1991. Anthropogenic impact is potentially much greater in the northeast Avalon Peninsula than along less densely settled or currently unoccupied shorelines, such as those of northwesterly Trinity Bay, the islands of Placentia Bay, Brunette Island, and northern Belle Bay. In some areas, anthropogenic activity has been an active force in shoreline modification for more than 100 years, precluding establishment of the 'original' character of the coast prior to disturbance. Even in the most isolated areas, however, the possibility of pollution from the offshore marine environment, the effects of anthropogenic debris transported by longshore currents, and the former activities of inshore fishers and residents of now-abandoned and resettled communities, indicate that anthropogenic influences can never be completely disregarded.

Assessment, utilization, and management of the coastal zone have been hampered by a lack of understanding of the geomorphic environment, and its response to the variations in climatic parameters ubiquitous to coastal Newfoundland. Despite its cultural and economic importance, the geomorphology of the eastern Newfoundland coastline has received relatively little attention. Understanding of the geomorphology, sedimentology, processes, and dynamics is critical to management of the coastal zone for all purposes.

This report classifies, discusses, and analyzes the shoreline of eastern Newfoundland from Red Point, west of Facheux Bay, to Cape Bonavista, including Bay d'Espoir, Hermitage Bay, Connaigre Bay, Fortune Bay, Placentia Bay, St. Mary's Bay, the Southern Shore, Conception Bay, and Trinity Bay, and offshore islands including Bell, Baccalieu, Long, Brunette, Sagona, Merasheen, Red, and Random islands. Classification is based on geomorphological and sedimentological criteria and on the physical processes and energy levels responsible for shaping the shoreline. It is hoped that this report, the latest in a series discussing eastern Newfoundland (Catto 1997, 1999; Catto *et al.* 1997, 1999a, 1999b), will contribute towards a better understanding of the eastern Newfoundland coastal zone.

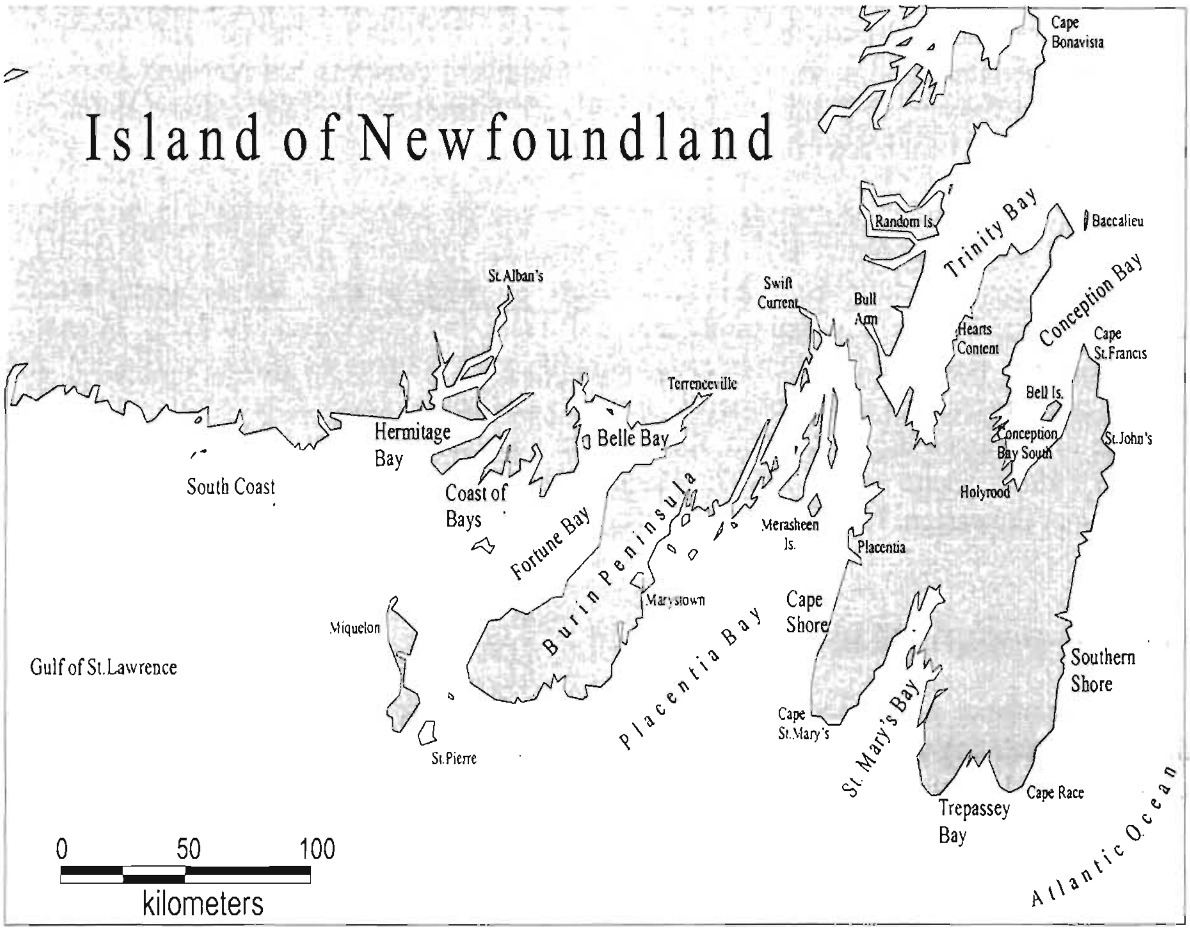
2. Climate, Oceanology, and Biota

The importance of the coastline in Newfoundland culture is illustrated not only by the wealth of terms relating to the marine environment, but also in the way that Newfoundlanders locate themselves by reference to bays, coves, and coastal features. Figure 2-1 illustrates the study region, indicating the terminology used here for subdividing the geography of the eastern Newfoundland shoreline.

2.1 Climate

The climate of Eastern Newfoundland is classified as mid-boreal (Köppen-Geiger Dfb), marked by relatively cool conditions and seasonally consistent precipitation, with humid and perhumid moisture regimes (Banfield 1981, 1993; Damman 1983; Environment Canada 1993). Newfoundland lies within the Boreal Ecoclimatic Province of Canada (Ecoregions Working Group 1989). The climate 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 of the Atlantic Ocean. Mean February sea surface temperatures are less than 0°C along the majority of the coastline. Local factors, such as topography and the prevalence of onshore and offshore breezes, create distinct mesoclimatic and microclimatic regimes in many locations (c.f. Hertzman 1997; Steyn *et al.* 1997).

Figure 2.1


Island of Newfoundland
Cape Bonavista
Random Is.
Trinity Bay
Baccalieu
Swift Current
Bull Arm
Hearts Content
Conception Bay
Cape St.Francis
St.Alban's
Terrenceville
Bell Is.
Conception Bay South
St.John's
Hermitage Bay
Belle Bay
Holyrood
South Coast
Coast of Bays
Fortune Bay
Burin Peninsula
Merasheen Is.
Placentia
Marystown
Cape Shore
Miquelon
Placentia Bay
Gulf of St.Lawrence
Southern Shore
Cape St.Mary's
St. Mary's Bay
St.Pierre
Cape Race
Trepassey Bay
Atlantic Ocean
0
50
100
kilometers

Within Newfoundland, the South Coast and Avalon climate zone (Banfield 1981; Damman 1983; McManus and Wood 1991) includes the coastal region from Cape Ray eastward to the Avalon Peninsula and the Isthmus of Avalon. The coastal zone from Sunnyside north to Cape Bonavista lies within the Northeast Coast and Central Uplands climate zone. Climate data are summarized in Table 2-1.

Table 2-1. Summary of climate parameters.

	Northeast Coast and Central Upland	South Coast and Avalon
Mean February Temperatures	-4°C to -6°C	-2°C to -8°C
Mean August Temperatures	12°C to 17°C	14°C to 16°C
Mean Annual Temperatures	4°C to 5° C	4°C to 7°C
Mean Annual Precipitation (est.)	1300 to 1500 mm	1500 to 1650 mm
Snowfall % of Precipitation	15% to 25%	10% to 25%
Freezing Precipitation hr/a	125 to 175 hr/a	50 to 175 hr/a
Prevailing Winds	SW to W	SW to W
Significant Storm Winds	Northeasterlies	SW – Hurricanes Northeasterlies

2.1.1 Northeast Coast and Central Uplands

Although interior areas within this zone, such as Gander and Grand Falls-Windsor, are the driest on the island of Newfoundland, most coastal sites are affected by onshore breezes and maritime moderation. The Labrador Current acts to cool the coastline, but the prevailing southwesterly winds blowing from the interior of Newfoundland confine the influence of the current to the region within 15 km of the coast. Winters are relatively cold. However, although cold temperatures may persist for long periods in interior valleys, the shoreline is not generally subject to lengthy periods marked by temperatures below -10°C. Summers are longer than on the Avalon Peninsula or along the South Coast, with an average of 65 high summer days and 1450 *hr*s of sunlight annually. Springs are generally short, particularly in the coastal regions. The absence of pack ice south of Cape Bonavista during most winters, however, causes spring-like conditions to begin up to 1 month earlier in the Trinity-Port Rexton region than in the Sweet Bay or Terra Nova areas along Bonavista Bay.

Mean annual air temperatures are 4°C-5°C throughout the Northeast Coast zone, with mean February air temperatures ranging from -4°C to -6°C (Banfield 1993). Typically, February is the coldest month, with mean temperatures of -5°C at Bonavista, -5°C at Sunnyside, and -6°C at Terra Nova National Park headquarters (Environment Canada 1982, 1993). August temperatures range from 17°C at sheltered sites in the interior or isolated from direct exposure to the open ocean (such as Clarenville), to 15°C at Bonavista and Sunnyside, with lower temperatures on exposed coastal sites in the eastern Bonavista Peninsula. The frost-free period varies from 140 days in inland areas below 200 m asl to less than 115 days in low-lying coastal areas. Frost boils, earth hummocks (thufur), frost-heaved block fields (felsenmeer), and weakly developed frost stone nets are present in areas which have minimal arboreal vegetation and are subject to strong winds at elevations above 250 m asl adjacent to the coastline of Trinity Bay and on the Bonavista Peninsula. All of these frost-related features are developed in localities where mean annual ground temperatures exceed +5°C (Liverman *et al.* 2000). Although formed by seasonal freezing and thawing, they are not indicative of permafrost conditions.

Precipitation estimates for Newfoundland are complicated by measurement difficulties during windy events (den Hartog and Ferguson 1975; Banfield 1993). Totals collected in precipitation gauges may represent underestimates by as much as 50%. As a result, estimates of total precipitation vary, depending upon the methods used to address the problem of wind influence. Den Hartog and Ferguson (1975) and Banfield (1993) estimate that the Northeast Coast between Cape Bonavista and Sunnyside receives between 1300 and 1500 mm of precipitation annually, increasing systematically from north to south across the axis of the Bonavista Peninsula. In contrast, Environment Canada (1982) indicated a mean annual precipitation of 985 mm for Bonavista (1951-80), compared with 1261 mm/a for Sunnyside. The difference in these figures is due, at least in part, to the stronger wind influence at Bonavista. At both locations, July is statistically the driest month, while October and November are the wettest.

Snowfall typically accounts for 15-25% of the total precipitation, with mean annual totals of 200-300 cm. Estimates of snowfall as a percentage of total precipitation, however, are similarly complicated by wind effects. Exposed coastal areas along southwestern Trinity Bay receive slightly more precipitation than interior areas and those at the heads of deep embayments, particularly where elevations exceed 200 m, but lesser proportions of snow. Annual variations are common. At Bonavista, snowfall totals increased systematically from 140 cm in 1978-79 to 318 cm in 1981-82. The mean annual total was 215 cm from 1951 to 1980 (Manning 1983). No consistent pattern of increasing or decreasing annual snowfall totals is evident.

Local topography induces variations in precipitation amounts and styles along the Trinity Bay shoreline. Freezing precipitation is ubiquitous throughout the area, but varies from a mean of 125 h/a at Sunnyside to more than 175 h/a at Port Rexton and Catalina (Banfield 1993). Freezing rain events are concentrated in the late winter months (mid-February through mid-April) and develop where warm air is underlain by air with a sub-freezing temperature. Precipitation falling from the warm air 'seeder cloud' passes through the cold air of the underlying 'feeder' cloud, causing increased condensation and ice pellet formation. Along the Bonavista Peninsula, this condition frequently results when a mass of colder air is being displaced by warmer air associated with northeasterly winds off the Atlantic Ocean. The warmer, moist air is elevated above the colder air, creating ideal conditions for freezing precipitation (Banfield 1993).

Snow cover persists for approximately 150 days in forested areas and for less than 110 days at exposed coastal sites. Snowpack depths average between 20 and 40 cm at the end of February, typically the month marked by maximum snow accumulation, but all snow may be removed by melting at any time during the winter, leaving the ground exposed (Potter 1965). Frost penetration can exceed 1 m depth in coastal locations. Active frost-related features develop in cleared areas disturbed by human activity and animal grazing (Liverman *et al.* 2000).

Winds are variable, occurring from all points of the compass, although west, southwest, and south winds are somewhat more common. At Bonavista, calm periods account for only 2%

of daylight hrs, compared with approximately 15% of the daylight hrs at interior sites (Environment Canada 1982, 1993; Banfield 1993). In January, Newfoundland typically is overlain by a system of mid-latitude air, which progresses from southwest to northeast across the island towards the Icelandic Low Pressure system. Prevailing winds are westerly, with storm tracks showing progressive deflection towards the north. In contrast, the July pattern sees mid-latitude air driven by southwesterly winds across the island, with storm (hurricane) tracks paralleling the prevailing winds. These patterns bring drier, warmer conditions to the Bonavista Peninsula. Heavier precipitation, especially during autumn and spring, is associated with northeasterly winds. These winds cause modification of the beach systems, and drive coastal brash ice ('swish') onshore during the spring months.

2.1.2 South Coast and Avalon

Within the South Coast and Avalon zone, summers are short, cool, and wet (normally, the driest and hottest month is August). Winters are moderately mild and wet. Long springs (March through June) and relatively short autumns (September through mid-October) are normal. The South Coast and Avalon zone, influenced by southwesterly winds blowing landward, is considered to be the area of Newfoundland showing the least continentality and the most marked maritime influence (Banfield 1981, 1993).

At shoreline sites, daily mean temperatures in February vary from -2.5°C to -6°C (Environment Canada 1982, 1993; Banfield 1993). Warmer temperatures are associated with the southern Burin Peninsula (St. Lawrence, Grand Bank) and the most southerly points of the Avalon Peninsula (St. Shotts, Trepassey, Cape Race). Interior areas are 1-2°C colder than adjacent coastal sites. Along Conception Bay and the open Atlantic Southern Shore, January and February mean temperatures also are slightly higher in coastal locations sheltered from northeast winds, in comparison to those exposed to the northeast.

August daily mean temperatures vary from 14°C to 16°C, with sites exposed to maritime conditions associated with southwesterly winds (St. Shotts, St. Lawrence) being cooler than sites on the northeast coast. On local scales, summer temperature values vary with aspect, with the northerly areas and those consistently exposed to onshore northeast winds being cooler. Whereas southwesterly winds have a marginal cooling effect on the South Coast, their effects vary along Conception Bay and southern Trinity Bay. Sites in these areas that are exposed to direct southwesterly winds are somewhat more variable in temperature than are sheltered areas. Freeze-thaw cycles are generally numerous from mid-December to early April, and frost events may occur at any time from early September to June. In exposed coastal headlands, several freeze-thaw cycles may occur daily during the early and late winter.

As estimated by den Hartog and Ferguson (1975) and Banfield (1993), the mean annual precipitation throughout the South Coast and Avalon zone varies from 1500 to 1650 mm. Environment Canada (1982) recorded mean annual totals (1951-80) of 1068 mm at Argentia, 1265 mm at Arnolds Cove, 1128 mm at Come-by-Chance, 1297 mm at Grand Bank, 1450 mm at St. Lawrence, 1379 mm at Cape Race, 1501 mm at Bay d'Espoir, and 1644 mm at St. Alban's. The local variations between adjacent stations, and the generally lower values recorded by

Environment Canada (1982), indicate that wind effects are significant in causing the amount of precipitation to be under-estimated.

Additional variations are due to aspect and differences in the proportion of precipitation types. Areas marked by larger proportions or amounts of snowfall also generally receive less total precipitation. Shoreline areas receive less snowfall and more freezing rain and drizzle than do interior locations, although rainfall events in coastal areas may be associated with freezing precipitation events inland. Freezing rain totals vary from less than 50 h/a on the southernmost part of the Burin Peninsula, to 100 h/a at Come-by-Chance and Cape Broyle, to more than 175 h/a at Cape St. Francis, and on the Carbonear sub-peninsula north of Hants Harbour and Northern Bay (Banfield 1993).

In coastal sites, typically 15-25% of the precipitation falls as snow (Environment Canada 1982, 1993; Manning 1983), although in exposed regions subject to onshore winds the proportion of snowfall may be less than 10%. Large annual variations are common: between 1951 and 1980, Argentia received as much as 320 cm and as little as 48 cm of snow annually. Similar variations have been observed in the past 20 years (e.g. Environment Canada 1993). On 6 April 1999, some sites on the northeast Avalon Peninsula received more than 70 cm of snow within a 24 hr period. The highest annual value, in excess of 600 cm, was recorded during the winter of 2000-01.

In the northern parts of the Avalon Peninsula, snow cover persists for approximately 135-150 days in wooded areas, and for 100-110 days in exposed barrens or logged terrain (Potter 1965). Snow is removed rapidly from exposed coastal zones. The mean annual duration of snow cover decreases southward. The low summer temperatures and abundant precipitation combine to produce a perhumid moisture regime and an excess of soil moisture, keeping soils saturated throughout most of the year.

Fog is common along the Placentia Bay, St. Mary's Bay, and Fortune Bay shores. Argentia, the foggiest weather station in Canada, averages 206 days/a with at least 1 hr of fog (Environment Canada 1993). Fog is less ubiquitous on the Conception Bay and Trinity Bay coasts than along the south-facing and open Atlantic shorelines. Around Conception Bay, the prevalence of fog is greatest in those areas most influenced by southwest winds. North of Harbour Main, fog is less common and is often confined to the deep southwest-trending embayments (such as Bay de Grave and Harbour Grace).

Ice foot development is commonly a major factor in the geomorphic development of the Conception Bay shoreline north of Spaniards Bay, and along the Trinity Bay shoreline. Formation of an ice foot largely precludes winter erosion of beach sediments. The southerly extent of persistent ice foot development coincides with the position of the -0.5°C February SST isotherm (US Naval Oceanographic Office 1967; Markham 1980; Cote 1989; McManus and Wood 1991), confining the phenomenon to the northern and central parts of the shoreline surrounding the Avalon Peninsula. Ice foot development does occur on beaches in southern Conception Bay in some winters, but it is less extensive, pervasive, and persistent. Adhering ice, however, is common along all beaches, which are not anthropogenically, disturbed. Offshore pack ice persists from February to April, and icebergs are present along the coastline throughout the spring and early summer.

Formation of the ice foot begins in late December during most winters, and several beaches commonly retain an ice foot until late March (especially to the north of Western Bay). During the winters of 1995-96 and 1998-99, ice foot development was severely restricted, and none developed along the Conception Bay coastline during the El Niño-influenced winter of 1997-98. Erosion was greatly accentuated during all three winters. Between 1989-90 and 1998-99, Trinity Bay beaches north of Hant's Harbour showed ice foot development in all years with the exception of the winter of 1997-98.

Ice foot development is less common along Placentia Bay than along Trinity and Conception Bays. The winters between 1988 and 1994 were marked by formation of landfast ice along all sediment beaches south of Point Verde, notably at Big Barasway. In contrast, ice foot development did not occur during the milder winters of 1995 and 1996, or during the earlier 1980's. The El Niño year of 1997-98 was marked by warmer water in the embayments of the Cape Shore, no ice foot development, and decreased precipitation (resulting in decreased stream flows). Coastal erosion was accentuated as a result, and Placentia Bay beaches have generally become steeper and coarser. The absence of hurricane activity during the summer of 1997 resulted in gradual modification of the beach systems, in contrast to the punctuated erosive events resulting from major hurricanes between 1991 and 1995 (particularly 'Bob', 'Felix', 'Luis', and 'Opal'). Hurricane activity increased in 1998, 1999 ('Floyd', 'Greta-Harvey', 'Irene') and in 2000 ('Michael') from the lull of 1997, but storm events in general did not impact the Avalon coastline as severely as in 1995, and their effects were less areally extensive or cumulatively pervasive. Individual beaches and coves, however, were affected by the storms of 1999 and 2000.

Wind patterns vary seasonally, and local topographical effects are extremely significant in many embayments. Westerly and southwesterly winds are more prevalent throughout the year (Banfield 1981, 1993; Environment Canada 1982, 1993), although winds may originate from any point of the compass at any time of the year. The southwesterly winds generally bring warm, moist air to the region from the warmer ocean surface waters south of the Burin Peninsula.

Along the open shorelines of the South Coast, Placentia Bay, and St. Mary's Bay, the extensive fetch allows the southwesterly winds to be effective agents driving the evolution of coastal geomorphology. Strong southwesterly winds are associated with many of the major storms and hurricanes during the summer and autumn, which generally pass over the region from southwest to northeast (Banfield 1993). During 1994, 1996, 1998, 1999, and 2000, hurricane activity was moderate, and shore development followed the modal pattern of the previous years (1981-93). In 1995, the enhanced frequency of hurricanes caused southwesterly wind activity to be particularly effective in modifying the coast. In contrast, the absence of hurricanes from eastern Newfoundland in the summer of 1997 (for the first year since 1961) resulted in limited modification of the beach systems by strong southwesterly winds, allowing swell activity to assume a more significant role. Wind patterns show some seasonal variation, with easterly and southwesterly winds alternating during the summer, and southwesterlies dominating during the winter. Northeasterly winds, which are responsible for much of the storm modification of beaches along Conception and Trinity Bays and the open Atlantic Southern Shore, are generally ineffective agents of shoreline modification in these areas. Diurnal onshore and offshore winds are common in most embayments.

In the southern parts of Conception Bay and Trinity Bay, and in the St. John's region, the combination of low topography inland to the southwest (Salmonier Basin area) and the long open fetch of the Placentia Bay shore south of Placentia allow the southwesterly winds and the associated precipitation to influence coastal development. In contrast, along the northern part of the Conception Bay/Trinity Bay shoreline, the combination of the reduced fetch of northern Placentia Bay and higher topography along the spine of the Carbonear sub-peninsula, particularly in the Heart's Content Barrens area, reduces the effectiveness of southwesterly winds. In this area, the dominant winds responsible for storm modification of shorelines are the northeasterlies, associated with the autumn gales. Strong northeasterly gales in late September-early October 1992 modified many beaches along the northern part of the Conception Bay coastline, and further modification resulted from the somewhat weaker (but substantial) storms of autumn 1994. Northeasterly winds are also effective agents of shoreline modification in the southern part of Conception Bay. Northwest winds are occasionally significant along the Conception Bay South and northwestern Bell Island shores, and influence beaches along northeastern Trinity Bay. In southern Conception Bay, southeast winds have their greatest influence north of Broad Cove, in areas where fetch is not restricted by Bell Island.

The open Atlantic Southern Shore is influenced by winds from all directions. The greatest geomorphic changes are associated with strong northeasterly winds, such as the major events of 1966, 1992, and 1994. However, southeasterly winds also cause modification to this shoreline, in contrast to their relatively limited significance elsewhere. Strong southwesterly hurricane winds frequently generate a northeast counter-flow at sea level, resulting in high waves and beach modification. This effect was notable during hurricane 'Opal' (1995), but was less pronounced during other hurricanes ('Bob', 'Luis'). Northwesterly winds have little influence on the geomorphology of the Atlantic Southern Shore.

Thus, the impact of 'extreme' storm events varies greatly with aspect and location. The most significant hurricanes in this region during the period 1989-99 were 'Bob' (1991), 'Luis' (1995), 'Opal' (1995), 'Hornets' (1996), 'Irene' (1999), and 'Michael' (2000). Hurricanes and other storms that have significantly influenced the geomorphology of the eastern coastline of Newfoundland from July 1989-April 2001 are listed in Table 2-2.

Table 2-2. Significant storm events July 1989-February 2000 mentioned in text.

Year	Storm	Areas Most Affected
1989	Hugo	Cape Shore, Burin Peninsula
1991	Bob	Cape Shore, South Coast, Trepassey B.
1991	Hallowe'en Storm	South Coast, Cape Shore, Conception B.
1992	October Northeaster	Conception B., Trinity B., Southern Shore
1993	"Storm of the Century"	limited effects
1994	October Northeaster	Conception B., Trinity B., Southern Shore
1995	Felix	South Coast, Cape Shore, St. Mary's B.
1995	Luis	St. Mary's B., South Coast
1995	Opal	St. Mary's B.,Trepassey B., South Coast
1995	Saros	South Coast, St. Mary's Bay
1996	Hortense	South Coast
1999	April Storm	Conception Bay
1999	Floyd	Conception Bay, Cape Shore
1999	Gert-Harvey	southern Cape Shore
1999	Irene	southern Cape Shore, Burin Peninsula
2000	January 21-23	Burin Peninsula, South Coast
2000	Michael	Burin Peninsula, Cape Shore

The effects of 'Bob' in general were greatest along the eastern Placentia Bay coastline; moderate along the exposed South Coast, St. Mary's Bay, and at Holyrood Pond and Trepassey; lesser along western Placentia Bay, southeastern Fortune Bay, and the Southern Shore; and minor in Trinity Bay and Conception Bay. 'Luis' effectively modified the coastlines of St. Mary's Bay, Holyrood Pond, and the exposed South Coast, and had moderate effects in southeastern Fortune Bay, but had only minor effects along Placentia Bay and the Southern Shore. Some shorelines which were altered by 'Luis' had been previously destabilized by hurricane 'Felix'. Hurricane 'Opal' had its major effects on shorelines which had undergone modification by 'Luis' (and locally by 'Felix' as well), and also caused some modification of Southern Shore beaches. Along Placentia Bay, 'Opal' had little influence on the western margin, and its effects along the eastern shore were confined to isolated localities (such as Point Verde and Southern Harbour). At most sites along Placentia Bay, 'Luis' and 'Opal' were unsuccessful at modifying the higher-elevation sediments remaining from 'Bob'. 'Hortense' had its greatest effect along the South Coast, particularly east of Northeast Arm, but was less effective in modifying Avalon Peninsula and southern Burin Peninsula beaches along Placentia Bay. 'Hortense' had a limited effect on Holyrood Pond and Trepassey, very minor effects on most St. Mary's Bay shores and those along the Southern Shore, and no discernable effect on most Conception Bay and Trinity Bay beaches. 'Irene' affected several sites along the Cape Shore and Burin Peninsula, and the terrestrial rainfall associated with this storm resulted in erosion of some coastal bluffs. 'Michael' affected beaches along the southern Cape Shore and the southern Burin Peninsula.

Strong southerly winds associated with late autumn and winter storms also are effective agents at modifying coastlines, if they arrive prior to the formation of pack or landfast ice.

During the period 1989-January 2000, the strongest of these events were the Halloween Storm (October 1991), the 'Storm of the Century' (March 1993), and the 'Saros' event (December 1995). Other events, marked by less severe winds but single-day record snowfall (69 cm in St. John's) and rainfall (70 mm) occurred during April 1999. All of these events impacted the coastline of eastern Newfoundland, but the presence of pack and brash ice at sea, and snow-covered, frozen sediments on land limited their effectiveness. As a result, these storms are much less critical in the genesis of the landscape than is the case in Nova Scotia (Taylor *et al.* 1997) and along the US eastern seaboard. The 1991 Halloween Storm, as the earliest in the season, had the greatest effect, particularly in those areas where beaches had previously been destabilized by Hurricane 'Bob'. The Halloween Storm also generated northeast countering winds at sea level, which modified shorelines along the Southern Shore and locally in Conception and Trinity Bays. In contrast, both the 'Saros' and 'Storm of the Century' events were ineffectual modifiers of the coastal geomorphology along most shorelines, although both caused damage to coastal vegetation and structures. The South Coast and parts of St. Mary's Bay were most affected by the 'Saros' event, whereas the 'Storm of the Century' left no significant geomorphic imprint.

The storm of January 21-23, 2000, had a significant impact on the South Coast of Newfoundland, especially along the southern shore of the Burin Peninsula. Lamaline, Allan's Island, and other localities experienced waves in excess of 4 m height above mean sea level, resulting in erosion of beach sediments and damage to homes and infrastructure. The effect of this storm surge, driven by southwesterly winds, was greatest at localities open to the southwest. In contrast, effects were minimal along the northeast coast of Newfoundland and along the Southern Shore, although one wharf in Tors Cove initially damaged during the hurricanes of autumn 1999 suffered further damage.

Northeasterly winds have the greatest influence on the coastlines of Trinity and Conception Bays. As a result, the events which most severely impact on these regions are not the hurricanes (unless they generate strong northeasterly counterwinds), but the autumn North Atlantic storms. Particularly severe events occurred in 1966 and 1992, with a less severe occurrence in 1994. These storms also resulted in extensive modification of most Southern Shore beaches. Northeasterly winds associated with the April 1999 event had a minor influence on beaches along the Southern Shore and in southern Conception Bay.

2.2 Climate Change

Current discussion concerning climate change is based on differences of scientific opinion concerning both the significance and magnitude of the numerical changes recorded in temperature and precipitation statistics, as well as on the 'global' nature of the change, and the appropriateness of applying records from one region to another. Unfortunately, the meteorological statistics are limited in their usefulness by the relatively short time that they represent. The longest accurate numerical temperature records, from Europe and New England, span the period since Fahrenheit's thermometer was refined to be sufficiently reliable, less than 200 years. In most areas of western North America, accurate temperature records encompass 150 years at most; in arctic Canada, reliable observations date from World War II. Climate, by definition, involves long term averages. If climate change is to be recognized, it is necessary to look beyond the numerical records. This necessitates the study of 'proxy data' -- biological (e.g. pollen, plant remains) and physical (e.g. landforms, soils) signatures that result from climate conditions, and hence can be considered as 'proxies' for past climates.

In the countries surrounding the North Atlantic Ocean, abundant proxy data exists for the last 1000 years. This recorded data, along with the impressions of contemporary writers, allows reconstruction of the climate patterns. The results show that much regional variability existed, even over very short distances. Modern weather events, such as the hurricanes and storms discussed above, produce equally diverse responses and effects. When results are compared across the expense of Western Europe and mid-latitude North America, however, a pattern of consistent climate change on a continental scale emerges.

In general, the period from ca. 700 to *ca.* 1300 a.d. was marked by relatively warm conditions (in most regions, slightly less warm than those at the end of the 20th century). This interval is referred to as the "Little Climatic Optimum" or the "Mediaeval Warming" (Bray 1980; Wigley *et al.* 1981; Rampino *et al.* 1987; Driver and Chapman 1996). Following this, temperatures cooled, resulting in glacial advances in alpine areas (Luckman 1993; Grove 1988). This event, referred to as the "Neoglacial" or "Little Ice Age", persisted until the mid-19th century. In the interior of North America, the Neoglacial was followed by a cycle of climate warming, which is currently in progress.

2.2.1 Little Climatic Optimum

The dates of the Little Climatic Optimum are not identical throughout the northern North Atlantic region. In most areas of Western Europe bordering the ocean, the event lasted from *ca.* 700 to *ca.* 1300. Areas further to the east (Denmark, Poland, and Hungary) appear to have been slower to warm and cool, with 'delays' of about 100 years in Denmark and slightly longer in central Europe (Lamb 1995).

The magnitude of the event also varied throughout the Northern Hemisphere. Ice core data from Kalaallit Nunaat indicate temperature rises of 1° to 2°C. The expansion of vineyards in Europe, with cultivation at elevations up to 200 m higher in 1300 than in 700 along the foothills of the Alps in France and Germany, suggests mean temperature rises locally up to 4°C. More significantly, the frost periods and precipitation totals would have been lower, allowing the grapes to ripen (Ladurie 1971; Bray 1980; Lamb 1995).

The climate during the Norse occupation of northernmost Newfoundland, as indicated by palynological data, was slightly milder than at present (Hennigsmoen 1977, 1985; Mott 1975; Davis 1980, 1984, 1985; Davis *et al.* 1987; Macpherson *in* Liverman and Batterson 1995). Red currants flourished in the area. The palynological record shows no sign of human impact during the Norse occupation, suggesting that this was a short-lived event not marked by extensive modification of the land. This picture is compatible with the saga record.

2.2.2 Neoglacial

The colder (locally wetter) period following the Little Climatic Optimum is referred to as the Neoglacial. Along the margins of the northern North Atlantic, mean temperatures were 1°C to 3°C cooler than those during the mediaeval optimum. Precipitation also increased at many coastal sites. In Iceland, Scotland, Ireland, and Norway, the reduction in the growing season, the enhanced frost, and the diminished sunlight led to a reduction in agricultural activity, particularly grain farming (Ladurie 1971; Grove 1988; Lamb 1995). In many of these areas, as in coastal Newfoundland, it was the excess precipitation, the diminished sunlight (decreasing evapotranspiration potential), and the saturated ground that limited or precluded agriculture, rather than lowered temperatures.

Changes in agricultural productivity affected areas adjacent to the North Atlantic. The settlement of eastern North America by Europeans, beginning in earnest *ca.* 1600, was driven in part by poor economic conditions in Europe (Lamb 1995). Until the Industrial Revolution, economic conditions throughout most of Europe meant agricultural conditions. Most communities that were not agricultural in nature were dependent on the fishery, forestry, trapping, and other climate-controlled activities; only the few mining communities were somewhat immune.

Fish populations also responded to the changes in climate. Cod, which require water temperatures above 2°C, moved progressively southwards as the Neoglacial intensified. The concentration of stocks off the Newfoundland coast in response to colder water conditions allowed the establishment of the strong fisheries of the 1700's and 1800's. Another factor encouraging growth of cod stocks was the migration of capelin, which prefer cooler waters. Capelin stocks would have been concentrated in the somewhat contracted region extending from the 2°C isotherm southwards to the northern fringes of the Gulf Stream.

The record of the Neoglacial in interior North America indicates that the most severe climate occurred in the early 1800's (Harington 1992; Lamb 1995). In eastern North America, the climatic 'minimum' encompassed the decade of 1810-20. During these years, major rivers and lakes remained frozen throughout the winter (8 months for Lake Superior, 4 months for the St. Lawrence), and pack ice was extensive (more than twice as persistent as today in the Strait of Belle Isle). Crop failures were common throughout New England and Atlantic Canada. Many communities, including several in Newfoundland, were temporarily abandoned.

Although climatic conditions were sub-par throughout the decade, 1816 stands out as the worst year (Harington 1992). Throughout New England and the Maritimes, 1816 is referred to as "the year without a summer" (Strommel and Strommel 1983). The overall temperature during the year was only 0.9°C colder than the 50-year mean, but July temperatures averaged 3-7°C colder than the mean values. Snow remained on the ground throughout the summer in northern New Brunswick and in Cape Breton. Frosts occurred in late May, early June, early July, and August throughout Atlantic Canada. The year had seen the total destruction of the corn crop in the Maritimes, almost total elimination of hay and fodder growth, and large losses in wheat and rye; much of the grain produced had been harvested in desperation before it was fully mature. Losses in the freshwater fish populations also occurred, as water temperatures dropped below critical levels for survival and reproduction of salmon, smelt, eels, and other species.

The effects were felt in Newfoundland as well, although statistically 1818 was the coldest year of the decade in the Avalon Peninsula. Total crop failures were recorded in many coastal communities. At several communities, disputes erupted over the distribution of food in storage

(Prowse 1895; Rowe 1980). Collapses in freshwater fish stocks were apparent. Although the marine stocks appear to have suffered little long-term change, local shortages were evident as inshore fisheries suffered.

The anomalous conditions were triggered by an eruption of volcano Tambora, in Indonesia, on 11 April 1815 (Siguardsson and Carey 1992). This event, the single largest volcanic eruption documented in historic times, sent an estimated 120 km^3 of debris into the atmosphere as volcanic ash -- about 140 times that contributed by Mount St. Helens in 1980, and about 60 times the cumulative contribution of Mount Pinatubo, between 1992 and 1995. Tambora may have been the largest single volcanic eruption on Earth in over 6,000 years (Chester 1993; Scarth 1994). The tephra and sulphur compounds sent aloft by Tambora blocked incoming solar insolation, lowering temperatures in the atmosphere. In the Northern Hemisphere, Tambora's effects were evident in some areas, such as Zurich (Strommel and Strommel 1983; Harington 1992), whereas adjacent areas, such as Vienna, Vilnius, and Kobenhavn, remained unaffected. Japan suffered no effects, with summer 1816 being slightly warmer than normal (*see* Harington 1992). Along the northern North Atlantic, however, the combination of an anomalously cold decade and the immense volcanic eruption were responsible for what ensued.

The lack of a uniform 'global' influence of volcano Tambora suggests that climate change in one region may not directly mirror that in other areas. Although in general terms the Neoglacial can be recognized throughout the Northern Hemisphere, its effects, severity, and chronology are not identical and synchronous in all localities (Bergthórsson 1985; Grove 1988; Mooney *et al.* 1993; Lamb 1995). The reason for the two-year 'lag' between Maritime Canada's non-summer of 1816 and the coldest summer of 1818 on the Avalon Peninsula is not firmly established at present. Whereas the most severe Neoglacial conditions are associated with the decade 1810-1820 in eastern North America, in the western part of the continent the 'height' of the Neoglacial occurred later, *ca.* 1840-45.

2.2.3 Recent Changes

These variations within an overall cycle of climate suggest that similar variations would be evident on a regional basis within the last 150 years. Thus, discussion of 'global change' can only be based on a statistical average or mode on a global scale, and cannot be used to imply that climates at all localities will change to the same magnitude. Individual areas may oppose 'global' trends, becoming colder while the world as a whole warms, or showing different temporal responses to the same stimuli.

The capacity of humans to influence climate, primarily by increasing temperature and/or precipitation, has been abundantly demonstrated on a local scale in urban centres. The degree of change, however, differs with industrial activity, automobile usage, and local topography and weather patterns. The existence of variations over small areas suggests that variations are to be expected over wider regions.

The overall pattern in North America since 1845 indicates that the climate has become warmer. In the Rocky Mountains, glacial recession and dendrochronological records indicate that glaciers today are less areally extensive than they were 9,000 years ago (Luckman 1993). The maximum extent of most Rocky Mountain glaciers was achieved *ca.* 1845, at the height of the Neoglacial, and thus they have retreated more within the past 150 years than they had advanced in the previous 9,000 years. These data indicate that climate warming and drying have occurred in this region. Similar conclusions have been drawn from proxy data obtained from lacustrine sites in the Western Canadian Prairies, and are also indicated by the numerical data available from the past *ca.* 120 years (Stewart and Cadou 1981; Williams *et al.* 1988; Goos 1989). In Canada as a whole, Environment Canada statistics indicate that 4 of the 5 warmest years on record (i.e. since *ca.* 1800) have occurred within the last decade (1990-99).

Although recent climate warming is reasonably well established for interior North America, the picture is not the same for Europe. European locations with long numerical records (more than 200 years) show considerable variation in the warmest decade noted at each (Morgan and Pocklington 1996). Although data from Berlin, Vienna, and København suggest that climate warming reached a high in the 1980's, the 1940's were the warmest decade on record in Basel and Geneva, and the 1930's were warmest in Stockholm and Trondheim. Many interior stations (e.g. Budapest, Munich, Paris, and St. Petersburg) recorded their warmest decades in the latter part of the eighteenth century, within the overall 'Neoglacial' episode (Morgan and Pocklington 1996). Although the absolute reliability of early numerical thermometer measurements can be questioned, the general prevalence of a warm climate episode in central Europe during the late eighteenth century is well established. At these sites, climate warming has occurred in recent decades, but has not reached the pre-Industrial maxima.

In Atlantic Canada, numerical data records indicate that the pattern of temperature change does not follow the general trend for interior North America (Drinkwater *et al.* 1992; Narayanan *et al.* 1995; Pocklington *et al.* 1994, 1998; Canavan 1996; Lewis 1996; Abraham *et al.* 1997). A warming trend in the 1880's was followed by climate cooling from 1895 to the mid-1920's. Gradual warming occurred from the mid-1920's to the mid-1950's, reaching a peak in the latter 1940's at many stations. Cooling then resumed until the mid-1970's, followed by a warming event lasting less than a decade. From the early 1980's until the latter 1990's, general cooling has resumed in Atlantic Canada, with lesser warming events in 1980-82 (in part associated with El Niño influences) and 1987-88 (Drinkwater *et al.* 1992). An overall cooling of 0.7°C has occurred in Atlantic Canada from 1948-95 (Lewis 1996). Although summers are marginally warmer (+0.5°C mean), autumns are cooler (-0.8°C mean) and winters substantially colder (-2.2°C mean). Daily minimum temperatures show a slight increase (0.3°C), but daily maximums have decreased more (0.8°C). Precipitation has increased in Atlantic Canada since 1948 (Lewis 1996). Pocklington and Morgan (1996) indicate that the general temperature decrease in Atlantic Canada is mirrored by European North Atlantic stations. Proxy data, such as durations of river ice cover in Nova Scotia and Newfoundland (Clair *et al.* 1996), and landfast sea ice cover and pack ice extent from Cape Bonavista to St. John's (Narayanan *et al.* 1995) also reflect these climate changes.

The differences between the pattern of temperature changes recorded in the northern North Atlantic and those of interior North America have been linked to the relative importance of aerosols and acidic precipitation derived from upwind interior North America over the Atlantic coastal region (Lewis 1996, Morgan and Pocklington 1996). The strength of the North Atlantic Oscillation (NAO) in recent years, resulting from the enhanced pressure differential between the

Icelandic Low and the Azores High, is also positively correlated with negative temperature anomalies in Labrador and western Kalaallit Nunaat (Topliss 1996). Strong NAO conditions result in severe northwesterly winds, large wind stresses on the ocean surface, low sea surface temperatures (especially in winter), and extended areas and durations of pack ice and brash ice (Drinkwater 1996, Prinsenberg *et al.* 1996). These effects would be most pronounced in the winter months, when the majority of the temperature change has been recorded.

The effect on climate change on storm frequency and magnitude in the North Atlantic is also a subject of contention. Although some researchers have argued that climate warming will result in increased storm frequency and magnitude, others have argued for the opposite effect. Studies of modern hurricane frequency in the North Atlantic reveal no linkage to postulated patterns of overall ('hemispheric' or 'global') climate warming (Goldenberg *et al.* 1996). Although warmer conditions in the Main Development Region (MDR) located between North Africa and the Caribbean at 10-20°N latitude would be expected to increase the number of hurricanes spawned, there is no firm connection between climate conditions in the MDR and those elsewhere.

Goldenberg *et al.* (1996) noted a lull in hurricane activity between 1970 and 1987, a period which includes both a cooling event (*ca.* 1955-*ca.* 1975) and a warming event (*ca.* 1975-*ca.* 1984) in Atlantic Canada (Pocklington and Morgan 1996). The period 1944-69 was marked by higher than mean hurricane activity in the North Atlantic, with 'net tropical cyclone' (NTC) indices >100%, and five 'hyperactive' hurricane years (1950, 1955, 1961, 1964, and 1969). Between 1961 and 1969, as the climate of Atlantic Canada slowly cooled, there were 5 'hyperactive' years (NTC ~150%) and two very quiet years (NTC ~50% in 1962 and 1968). Similar lack of correlation marked subsequent years: the lull between 1970 and 1994 (NTC of 75%, and no hyperactive years) encompasses both cooling and warming events. The decade 1975-84, generally marked by warming in Atlantic Canada, also saw three quiet (NTC ~50%) hurricane years (1977, 1982, 1983), and only two years with NTC values greater than the statistical mean of 100% (1980, 1981). The years 1995 and 1996 were hyperactive (NTC of 231% and 198%, respectively), while 1997 was marked by no hurricanes in Atlantic Canada, and 1998 and 1999 saw a return to more 'normal' conditions.

In the short term, overall hurricane frequency in the North Atlantic cannot be correlated with temperature variations in Atlantic Canada. This suggests that although conditions in the MDR may be more or less suitable for hurricane development, the suitability is not directly linked to a 'global' temperature pattern. The effectiveness of any particular hurricane as a geomorphic agent does not depend on the overall NTC index. Goldenberg *et al.* (1996) noted that Hurricane 'Andrew', the single most destructive hurricane in US history in dollar value terms, occurred during 1992, a below-average NTC year. In eastern Newfoundland, Hurricane 'Bob' occurred in 1991, also within the general 1991-94 hurricane lull period. Several closely spaced hurricanes, however, as were 'Felix', 'Luis', and 'Opal' in the 1995 season, may reflect an overall hyperactive year. In 1999, the arrival of 'Floyd', followed shortly by the almost simultaneous landfall of 'Gert' and 'Harvey', and then by 'Irene', is suggestive of hyperactive conditions. However, these storms proved in general to be less effective in causing storm surges or modifications to coastal geomorphology than were the 1995 events. 'Michael' (2000) produced storm surges along some Cape Shore and Burin beaches, but in most areas the areal extent and resulting modification of the shoreline were less than the effects produced by the storms of 1995, or by 'Irene' in 1999.

Hurricane frequency and temperature variations represent only two aspects of climate and climate change. Overall assessments of previous climate fluctuations were based on longer-term averages of changes, based primarily on proxy data (as for the Little Climatic Optimum and the Neoglacial). Human perceptions of climate change are biased by short-term weather events (such as hurricanes, ice storms, or the non-summer of 1816). Any single short-term record is not a valid indicator of regional climate. Although global linkages between climate phenomena, such as El Niño, are well documented, the specific regional effects may be highly variable. In addition, local topography and human activity will produce different microclimate responses to similar conditions.

Thus, although overall climate warming is influencing many areas of the Northern Hemisphere, parts of Atlantic Canada are not enjoying these effects. Eastern Newfoundland in particular does not show significant evidence of climate warming on a local or regional scale, although sea levels will change in response to global climate variations. Although no statistically significant long-term warming is evident on the Avalon Peninsula, climate variability and change are occurring in Atlantic Canada at present, as they have in the past. The region's climate is influenced by global climate patterns, but the climates of any two regions of Earth are not changing in the same fashion. Climate change is a reality in eastern Newfoundland, but marked climate warming is not.

2.3 Ocean Currents

Surface currents in the northern North Atlantic are driven by the combination of prevailing winds and pressure gradients on the surface (Duxbury and Duxbury 1991; Narayanan 1994; Beer 1996; Kearns 1996). The net result is to establish a gyre system, involving clockwise rotation in the latitudes south of 60°N. The major current associated with this gyre system is the Gulf Stream, carrying 55 million m^3/s of water along the North American seaboard. It is further strengthened by the surface pressure gradient, which slopes northeastward from the Caribbean and southern Sargasso Sea (3×10^{-5} $kg\text{-}m^2/s^2$) to the Barents Sea (1.5×10^{-5} $kg\text{-}m^2/s^2$). Mean sea level is thus slightly higher (by " 0.5 m) in the Caribbean than it is in the Barents Sea. The Gulf Stream typically has widths of 50-75 km, and a peak velocity of 15 km/hr. August mean surface temperatures in the Gulf Stream vary from 18°C off Cape Cod, Massachusetts, to 16°C off Bantry Bay. February temperatures vary from 10°C to 8.5°C (Pyle 1962; U.S. Oceanographic Office 1967; Duxbury and Duxbury 1991). Surface salinity in the Gulf Stream usually approximates 35 ppt throughout its length.

The Gulf Stream flows along the coastline of the southeastern United States, past Florida, Georgia, and South Carolina. At Cape Hatteras, North Carolina, the Gulf Stream is deflected seaward, and follows the continental shelf/continental slope break to the Grand Banks. The warming effect of the Gulf Stream on the land is thus lessened north of Cape Hatteras. Along the South Coast of Newfoundland and Placentia Bay, the westerlies blow warm, moist air from the Gulf Stream coast, warming these shorelines.

Anthropogenic and natural debris is especially evident along the Cape Shore and open South Coast (Catto *et al.* 1997; Catto 1997). On these beaches, natural debris derived from shorelines south of Cape Hatteras, such as fragments of cypress wood (*Taxodium distichum*) and pumice, indicates that shore-parallel currents have been partially fed by the Gulf Stream. Such debris is very rarely encountered north of Cape Verde in Placentia Bay, and is not encountered east of St. Shotts. Although pumice from Icelandic sources has been reported along arctic Canadian shorelines (Blake 1970), the absence of volcanic detritus from the shores of Conception Bay and the Atlantic coastline of the Avalon Peninsula indicates that the pumice was transported northwards by the Gulf Stream.

Cold currents flow southwestward from the Barents Sea along the Greenland coast. The East Greenland Current brings cold water along the coast through Denmark Strait between Iceland and Greenland. This water circulates along the Greenland coast to Cape Farewell, and then flows northwestward along the Greenland coast as the west Greenland Current. Augmented by cold, fresh water from the glaciers, the flow returns southward along the Labrador coast as the Labrador Current (U.S. Oceanographic Office 1967; Farmer 1981; Duxbury and Duxbury 1991). The Labrador Current brings approximately 6 million m3 /s of water southwards at a velocity of 1-3 km/hr, cooling Labrador and northeastern Newfoundland. A low pressure surface zone exists in Baffin Bay and Davis Strait, forcing the Labrador Current to flow 'uphill' towards the Gulf Stream. Although the difference in sea level between Nain and St. John's is less than 5 cm, this gradient is sufficient to reduce the volume and velocity of the Labrador Current. Weak northward flow of the Labrador Current marks the area north of Iqaliut during some seasons.

Nearshore currents around eastern Newfoundland generally follow a counter-clockwise circulation pattern, driven by the Labrador Current. As the Labrador Current and Gulf Stream interact, the Labrador Current is deflected landward (north), as the Gulf Stream is deflected to the south. On medium (major embayment) and local (small embayment) scales, considerable variation exists. Headlands and offshore islands, which induce cornering winds and deflect currents, are responsible for generating many localized effects. Discharge of fresh water from streams also causes variations in current flow.

Open beach areas are influenced by shore-parallel and shore-normal transport. Alternating shore-parallel and shore-normal transport is common, due to shifts in wind direction and strength and in surf and swell action, and resultant changes in shore-normal motion and edge wave activity. In the majority of embayments, onshore-offshore sediment movement essentially normal to the beach dominates. Along all beaches and in many coves, current patterns shift in response to changes of wind direction and to storms. Conditions thus vary diurnally, seasonally, and annually.

2.4 Tides

Most segments of Earth's coastline, including eastern Newfoundland, are subject to two high tides and two low tides during each 24 hr rotation of the Earth. This pattern of tidal activity is referred to as semi-diurnal. Along eastern Newfoundland's shore, the semi-diurnal tide progresses southwestward, requiring approximately 2 hrs to travel from Cape Bonavista to

Facheux Bay. Once the tide enters a restricted embayment, such as Bay d'Espoir, its progression is slowed as the water begins to interact frictionally with the bay floor and the coastline.

Tidal ranges are classified as microtidal (0-2 m), mesotidal (2-4 m), and macrotidal (>4 m) (Hayes 1967). Along the eastern Newfoundland coast, microtidal conditions are present throughout the length of the shoreline (Canadian Hydrographic Service 1991a, 1991b), with the exceptions of minor mesotidal areas at the heads of shallow embayments (such as at Come-by-Chance).

The coastline of eastern Newfoundland is not suited for the development of most types of tidally-influenced geomorphic features. Tidal regimes here are microtidal and low mesotidal, and tides are insignificant compared to waves in shaping almost all segments of the shore. The development of many tidal flats and associated salt-water marshes elsewhere is related to slowly rising sea level (Allen 1990; Plater *et al.* 1999).

2.5 Waves and Wave Climate

Along the east coast of Newfoundland, wave activity is partially or totally responsible for shaping the majority of the coastal landforms. Although bedrock features are largely the products of pre-existing geology and climatically-induced frost weathering, wave action accounts for the majority of sedimentary landforms and contributes substantially to coastal erosion of unconsolidated cliffs.

Wave energy is controlled by the fetch, the expanse of open water unobstructed by land (or islands) across which winds blow (Komen 1994). Prolonged periods of wind activity are necessary to overcome the frictional losses of energy between atmosphere and ocean, and to overcome the inertia of the water, in order to set the waves in motion. A wind blowing at 5.1 m/s (10 nautical miles per hr, or 10 knots) can theoretically produce waves 2.2 m high with a velocity of 8.6 m/s, but the wind velocity must be maintained for at least 11 hrs and the fetch must be at least 129 km (Anikouchine and Sternberg 1981; Duxbury and Duxbury 1991; Massel 1996). For gale-force winds at 40 knots to produce waves of 25.8 m height and 28 m/s velocity, they must operate constantly for 69 hrs over a minimum fetch of 2590 km. As waves of this height have been recorded by ship's captains off the coast of Newfoundland, these theoretical conditions can be met, but they are relatively rare. In most cases, the heights and wave velocities actually produced are far less than the theoretical maxima, although still impressive to coastal observers.

In deep water, the wave velocity is a function of the period of the wave. The velocity of one of these clapotis waves (m/s) is equal to the period(s) multiplied by 1.56. This relationship holds as long as the wave does not interact with the bottom. In most circumstances, if the wavelength (distance between successive wave crests) is less than 50% of the water depth, the wave will not frictionally interact with the bottom. The orbital motion of water within the wave will continue unhindered by friction or compression, and the wave will exhibit clapotis behaviour.

As the wave enters shallower water, it 'feels the bottom' when the depth shallows to 50% of the wavelength. The orbital motion within the wave is disrupted, and frictional interaction with the substrate slows the base of the wave. The crest continues to move forward, resulting in the development of a curl of water as the surface moves faster than the base. When fully developed, the 'tube' of semi-compressed air beneath the forming breaker produces the 'tubular' conditions beloved by surfers. Eventually, the wave crest and the centre of mass of the wave move so far ahead of the base that the breaker is unable to sustain its position, and it collapses ('breaks') under the influence of gravity. The breakpoint occurs where the water depth is between 5% and 10% of the initial clapotis wavelength. Once the wave is broken, it may dissipate all of its energy, or smaller wavelets may reform and head shoreward, only to break in shallower waves.

The release of the energy of the compressed air 'tube' is the major factor in wave-induced erosion, much more so than the impact of the water itself. The air pressure beneath the breaker may exceed 4 times the value of atmospheric pressure (3000 mm Hg or 400 kiloPascals). In contrast, the water itself exerts a pressure only slightly greater than atmospheric. The amount of coastal erosion is thus conditioned by the shape and volume of the air pocket, in addition to the properties of the material.

Coastlines affected by waves are classified in three ways. The angle of attack of the waves, and the resultant direction of sediment movement, can be specified as either shore-parallel, shore-normal (at approximately 90° to the shore), or shore-oblique.

Wave action can generate a net current parallel to the shore (longshore current), or can result in sediment motion normal or oblique to the shore in the form of incoming swash or outgoing backwash. Landforms that are created by longshore current motion, also termed 'longshore drift', are described as drift-aligned. Barrier islands, such as those formed along the Gulf of St. Lawrence coastlines of New Brunswick and Prince Edward Island, are classic examples of drift-aligned features. Other coastlines are dominated by swash-backwash motion, producing features which extend seaward (cuspate spits, tombolos) or indicate that waves move sediment normal to the shore (cusps and overwash fans). Such coastlines are referred to as swash-aligned. The majority of the eastern Newfoundland coastline is dominated by swash-aligned systems. Individual segments of shoreline may have both swash- and drift-aligned parts, or may evolve from swash- to drift-aligned systems (or vice versa) over time (e.g. Forbes *et al.* 1995).

The third classification scheme involves assessment of the fate of the incoming wave energy (Kemp 1960; Wright *et al.* 1979; Bryant 1982). If the offshore bathymetry is very shallow, or gently sloping, the incoming waves will 'feel bottom' and break far from the shore. This will result in their energy being dissipated across the surf zone, away from the shoreline. Such coasts are termed 'dissipative' (Wright *et al.* 1979). Although many dissipative coasts are characterized by relatively low energy levels (e.g. Kouchibouguac, NB), others are marked by higher energy conditions (e.g. Portland Creek, NF).

Alternatively, if the offshore bathymetry slopes steeply, waves will be able to reach the vicinity of the shore before breaking. If the shoreline is a vertical cliff, the waves will strike it in an unbroken state. Under these circumstances, the waves will retain most of their energy until the instant of breaking, and substantial amounts of wave energy will be available to be returned to the sea as backwash (unless the wave completely surmounts the beach to create an overwash fan in the lagoon behind it). As well, the incoming wave will rise above mean sea level, creating a potential energy gradient and gravitational effect that will add impetus to the outgoing backwash. As a result, a substantial proportion of the incoming energy will be reflected seaward (Baquerizo *et al.* 1998). These coastlines are termed 'reflective' (Wright *et al.* 1979). Reflective coastlines are generally (though not always) associated with deep embayments and high-energy situations. The shorelines of Conception Bay north of Holyrood, Fortune Bay west of Terrenceville, and Bonavista Bay are good examples of areas with predominantly reflective systems.

The strength of the incoming waves, and hence their velocities, wavelengths, and locations where they break, depend upon the direction of wind and the fetch. Consequently, coastlines which are periodically influenced by waves of differing characteristics (e.g. by different wind strengths and directions) may alternate between reflective and dissipative behaviour. These coastlines are referred to as 'transitional'. Under some circumstances, a shoreline may alternate between dissipative and reflective behaviour over the course of a single tidal cycle, with the transition being driven by changes in the slope (e.g. Forbes *et al.* 1995). Southeast of St. Mary's Bay, Holyrood Pond barachoix, extending southeastwards to Peter's River, exhibits reflective, transitional, and dissipative conditions at different times in response to differing wave regimes (Nichols, in preparation). Along the shoreline of eastern Newfoundland, however, the microtidal conditions generally preclude shifts in dissipative/reflective status.

Off the open Atlantic shoreline, modal significant deep water wave heights throughout the year are 7-8 m (Neu 1982). The 10-year significant wave height is estimated at 11 m, and the 100-year height is approximately 15 m. These values, however, represent modal conditions, and individual waves exceed these heights. Waves up to 30 m high have been recorded by ships off the Newfoundland coast (Swail 1996). Anomalous individual storm waves result in distortions of the 'average' height calculated for significant waves; conversely, the significant wave models have a tendency to underpredict extreme storm wave heights (Cardone and Swail 1995; Cardone *et al.* 1995). There is no clear trend suggesting either increased heights of storm waves, or increased wind speed off the Newfoundland coast (Swail 1996), in contrast to increased storminess suggested for the eastern Atlantic (Bacon and Carter 1991). Data from the Scotian Shelf and the Labrador Sea can be interpreted to suggest either unchanged or slightly decreased storminess within the past 40 years (Swail 1996). The existence of anomalously large waves throughout the century has been documented (e.g. WASA 1995; Resio *et al.* 1995), without a clearly recognizable change in frequency of occurrence.

Off the eastern Newfoundland coastline, modal wave periods fall between 6 and 8 seconds. Longer-period waves, *ca.* 12-14 seconds, are associated with decaying ocean swells along the South Coast and the exposed southern margins of the Burin and Avalon Peninsulas (Forbes 1984).

All wave parameters undergo substantial changes as the waves 'feel bottom' and approach the shoreline. Consequently, wave heights and periods measured adjacent to the shorelines, and those which are responsible for modifying shoreline geomorphology, may differ substantially from these offshore values.

2.6 Terrestrial Vegetation

Newfoundland has remained isolated from the Canadian mainland throughout the last interglacial-glacial-interglacial cycle, and there is no evidence that the island had a land connection to Labrador at any time during the Quaternary. This, combined with the sometimes harsh nature of the coastal climates, has limited the spread of plant species and severely curtailed animal migration to the island (Macpherson 1981; Mednis 1981). Terrestrial vegetation influences coastal geomorphology by stabilizing unconsolidated sediments and altering the effectiveness of frost wedging and related weathering processes.

Throughout the sheltered parts of the coastal region, where vegetation is not exposed to strong onshore winds, terrestrial vegetation assemblages are dominated by coniferous boreal forests (Ryan 1978; Damman 1976, 1983; Woodrow and Heringa 1987). The major species are black spruce (*Picea mariana;* the provincial tree of Newfoundland and Labrador) and balsam fir (*Abies balsamea*). On drier, coarser soils, larch (*Larix laricina*), *Juniperus communis* (common juniper), and *Juniperus horizontalis* (trailing juniper) are important constituents, with larches forming nearly homogeneous stands and junipers preferring open, sometimes unstable terrain. Coastal regions that have a limited degree of exposure may support white spruce (*Picea glauca*), locally with krummholz or tuckamore habit, as do areas that are less exposed and have less wetland terrain.

Deciduous trees are rare in most areas. White birch (*Betula papyrifera*), balsam poplar (*Populus balsamifera*), trembling aspen *(Populus tremuloides*), green alder (*Alnus viridis crispa*), chuckley-pear (*Amelanchier spp.*), and dogberry *(Sorbus decora*) occur in most forested areas. Sheltered zones support red maple (*Acer rubrum*). Broadleafed species common to Nova Scotia, such as sugar maple (*Acer saccharum*), northern red oak (*Quercus rubra*), and beech (*Fagus grandifolia*) are not native to Newfoundland, due in part to their inability to tolerate multiple freeze-thaw cycles and freezing rain. In conjunction with climate and native fauna, this area is assigned to the Oceanic Mid-Boreal ecoclimatic region (Damman 1983; Ecoregions Working Group 1989).

Anthropogenic fire and logging has resulted in the local replacement of the boreal forest by dwarf shrub heath, with *Kalmia angustifolia* (sheep laurel), *Kalmia polifolia* (bog laurel), and *Rhododendron lapponicum* (Lapland Rosebay). In recent years, particularly since the imposition of the Northern Cod Moratorium in 1992, woodcutting for domestic purposes has substantially reduced the extent of forests in coastal areas (Catto 1997). Denudation in the interior areas has substantially changed the hydrologic regime, greatly affecting the quantity and timing of freshwater and sediment influx to the coastal region. Additional forest losses due to fire and insect predation have also resulted in increased sediment supply to the coastal areas.

Plateaux, and plains in exposed locations overlooking the shore, are dominated by ericaceous vegetation, including *Empetrum nigrum* (crowberry), *Vaccinium vitis-idaea* (partridgeberry), *Arctostaphylos uva-ursi* (bearberry), *Vaccinium boreale* (dwarf bilberry), *Ledum groenlandicum* (Labrador Tea), and *Rubus chamaemorus* (bakeapple) (Ryan 1978, Thannheiser 1984). Other common plants are *Juniperus communis, Kalmia angustifolia, Kalmia polifolia*, and *Rhaecomitrium* (feather moss) and other mosses. Vegetation cover in these areas, although low-lying, is generally continuous where undisturbed.

2.7 Terrestrial Fauna

Of Newfoundland's fourteen indigenous terrestrial mammal species, only the pine marten (*Martes americana*) is confined to the densest interior forests (Soper 1964; Snow 1996). The herbivores, particularly caribou (*Rangifer tarandus caribou*) utilized the food resources of the littoral areas (Bergurud 1971). Concentrations of deciduous tree species such as trembling aspen (*Populus tremuloides*) and green alder (*Alnus viridis crispa*) in sheltered river valley habitats provided favourable environments for the Newfoundland beaver (*Castor canadensis caecator*), the Meadow Vole (*Microtus pennsylvanicus terraenovae)*, and the Newfoundland muskrat (*Ondrata zibethicus obscurus*). Herbivore species which are more confined to interior woodland areas, such as moose (*Alces alces*), varying (or snowshoe) hare (*Lepus americanus*), common shrew (*Sorex cinereus*), chipmunk (*Tamias striatus*), Red squirrel (*Tamiasciurus hudsonicus*), red-backed vole (*Clethrionomys gapperi*), and Bank vole *(Clethrionomys glareolus*), have only been recently introduced (deliberately in 1878 and 1904, in the case of moose, (Shortis 1919; Pimlott 1953) to the island.

Although the Newfoundland black bear (*Ursus americanus hamiltonii*) has only recently (*ca.* 1993) expanded its range to the western and central Avalon Peninsula, the other predatory species such as lynx (*Lynx canadensis subsolanus*), red fox (*Vulpes vulpes deletrix*), river otter (*Lutra canadensis degener*), ermine (*Mustela erminea*), and, prior to *ca.* 1920, Newfoundland wolf (*Canis lupus beothucus*) inhabited littoral regions (Maunder 1982). The crossing of the Isthmus of Avalon by the black bears may indicate that relatively milder climatic conditions have prevailed since 1990.

Large seabird colonies, featuring various assemblages of gannets (*Morus bassanus*), puffins (*Fratercula arctica*), cormorants (*Phalacrocorax*), razorbill auk *(Alca torda*), thick-billed murre (*Uria lomvia*) and turr or common murre (*Uria aalge*), are present at Cape St. Mary's and other steeply cliffed sites (Godfrey 1986). Eider ducks (*Somateria mollissima*) have also been introduced locally (Reed 1986). Seabird numbers have declined recently, due to pollution (particularly marine-based petroleum spills and discharges), local over-hunting, and a scarcity of capelin and other prey fish. Osprey (*Pandion haliateus*), snowy owl (*Nyctea scandiaca*), and bald eagle (*Haliaetus leucocephalus*) frequent the Avalon and Burin Peninsulas, although most nest on Long and Merasheen Islands in Placentia Bay. Raptors are also found along the South Coast and Bonavista Peninsula.

2.8 Biological Shoreline Units

Catto and Hooper (1999) presented a classification scheme for biological shoreline units of the Placentia Bay region, based primarily upon key indicator species. Their third-order biological subdivisions can be applied to the eastern Newfoundland coastline, and are briefly discussed here.

Saltmarsh shores are high intertidal areas dominated by vascular vegetation, especially *Carex* (sedge). Additional key genera include *Plantago, Triglochin, Glaux, Festuca, Arenaria,* and *Potentilla.* Directly above the spring high tide level, riparian vegetation dominates, particularly *Myrica gale* (sweet gale) and *Juncus balticus.* Grasses, including *Arenaria* and *Festuca*, other vascular plants such as *Iris, Potentilla spp., Glaux,* and *Triglochin*, diatoms, and cyanobacteria, occupy the high tide zones. Marine assemblages occur between the high water spring tidal and the neap tidal zones, with abundant *Festuca* and other low grasses, blue-green algae (cyanobacteria), diatoms, green algae, and brown algae. Plantain (*Plantago maritima.*), dwarf seaside buttercup, and *Potentilla* are other important members of this zone. Below the neap tide line, saltmarsh vegetation is less abundant due to shifting sediments and moving ice.

Eelgrass *(Zostera)* assemblages are found in sandy, relatively sheltered lowshore locations. *Zostera* is not as tolerant to freshwater influxes as is saltmarsh vegetation, although the two assemblages frequently overlap. Eelgrass beds are important feeding and resting areas for salmon, trout, eels, and other fish. At Swift Current (Placentia Bay), *Zostera marina* forms meadows from near the low tide level to about 3 metres depth. The sand surrounding the plant roots harbours a wide range of burrowing invertebrates, especially the softshell clam *Mya arenaria*, the lugworm *Arenicola marina*, and the sand shrimp *Crangon septimspinosus.* The leaves form an anchorage for numerous seaweeds including *Polysiphonia harveyi, Rhodophysema georgii,* and *Myrionema sp.* Hydroids, bryozoans, and serpulids are among a number of animals which have also attached themselves.

Fucus anceps surf zone shores are typical of extremely exposed bedrock shores subject to essentially continuous surf and pervasive fog. Vertical zonation of marine plants and animals characterizes the rock faces well above the tidal zone. Pack ice can damage these communities by damping wave energy, so that the raised communities do not receive the sea spray that they require. Additional key taxa include *Pilinia, Porphyra linearis, Audouinella purpurea,* and *Sphacelaria nana.* Kelps, especially *Alaria* and *Laminaria digitala*, are locally present.

Seabird-dominated shores are typified by green to yellow-orange rock faces, the result of nitrogen-loving algae and lichens which thrive in the seabird excrement (guano). Key genera include *Rosenvingiella, Prasiola, Xanthoria, Calothrix,* and numerous associated Cyanobacteria and insects. Bird excrement contains high levels of nitrogen and phosphorus compounds, which are toxic to many organisms. Other organisms are not only resistant, but are able to use these chemicals as growth-promoting fertilizers. The colour of the cliffs at the seabird sanctuary at Cape St. Mary is due mainly to the green algae (*Rosenvingiella polyrhiza, Rhizoclonium*, and *Prasiola*) and lichens (*Xanthoria).*

Ascophyllum rockweed shores are dominated by extensive carpets of yellow-brown fucoid seaweeds growing on bedrock and stable boulder substrata. These beds require several years of biological succession to develop, with *Ascophyllum* outliving its competitors and dominating by suppressing their recruitment with its shading canopy. They cannot mature on shores which are regularly scoured by severe storms or marine ice. Additional key organisms include *Chondrus, Chorda, Hildenbrandia, Phymatolithon lenormandii, Phymatolithon laevigatum, Fabricia sabella, Dynamena, Littorina obtusata, L. littorea, Flustrellidra,* and *Polysiphonia lanosa.* The inner Ragged Islands area is the best example in all of Newfoundland, with hundreds of hectares of bright yellow shore covered by dense beds of *Ascophyllum.* The lower limit of this zone was determined by competition with *Laminaria longicruris*, but this latter species has been dragged out by scallop fishermen, and has not yet recovered from this devastation.

Capelin spawning beaches are associated with wave-dominated, exposed fine gravel shorelines. Although these areas can appear biologically barren, they are marked by microscopic algae and invertebrates. The food webs developed in these environments are supported by stranded seaweeds and animal remains, which are consumed either directly or *via* microbial decay pathways. In the early summer, capelin eggs and dead capelin form the main food supply. Numerous animals immigrate to capelin beaches to feed during the spawning and incubation season in June. The biological assemblage of capelin beaches has been poorly studied to date, but it is known to include *Navicula* and other motile diatoms, nematodes, burrowing crustaceans, insects, and fungi.

Temporary intertidal communities form on rounded boulders that are stable in calm weather, but are unstable under storm conditions. Pocket beaches backed by steep cliffs often develop a biota of rapidly growing, ephemeral seaweeds and invertebrates that are removed as the boulders roll during storms. During calmer periods these substrata are colonized by a range of fast-growing, opportunistic seaweeds and animals. Species present depend upon chance, the magnitude of the last scour, the duration since the last scour, and the season of the year. At any particular time, diversity is low, with a very few species dominating. Typical taxa include *Pilayella, Ulothrix, Chordafilum, Ectocarpus*, harpacticoid copepods, and amphipods.

Barachois estuaries are marked by the development of dark tannin-coloured fresh water at the surface and higher salinity waters below. When the sediment bar has been built high by waves and river flow is relatively low, the lagoon is almost totally fresh water, with runoff permeating through the bar. Severe river flooding can breach the bar, leaving a passage for seawater to enter the lagoon on the flood tides. The barachois estuaries are biologically stressful sites, with low biological diversity and low productivity, although many shelter sea-run trout or salmon. Plant growth is dominated by black coloured blue-green algae (cyanobacteria) and small numbers of a few green algae species.

Vertical biological zones cover sheltered bedrock vertical cliff faces. Horizontal bands of lichens, seaweeds, and invertebrates form well-defined zones, most prominent along glaciated fjord walls which are protected from surf and pack ice. Typical inhabitants include *Hildenbrandia, Lichina,* and *Mytilus*. The lack of wave action eliminates most of the variation in species distribution observed at more exposed *Fucus anceps* locations. The upper intertidal zone is marked by the lower limit of terrestrial crustose lichens and the appearance of marine lichens, especially *Verrucaria*. *Littorina saxatilis* is abundant in minor crevices. Above the midwater level is a barnacle zone dominated by *Semibalanus (Balanus) balanoides*, locally including patches of the highshore seaweed *Fucus spiralis*. Most of the mid- to lowshore is occupied by *Ascophyllum nodosum*. Lower on the shore, where space has been opened by herbivores or minor ice scour, are found other *Fucus* species and shorter lived plants such as *Sphaerotrichia*.

Rockweed platform exposed shores have an irregular rocky substrate which usually includes frequently developed tidepools. *Fucus edentalus, F. vesiculosis, Chondrus*, and other seaweeds are most abundant in protected microhabitats, while the most convex (most exposed) microhabitat is more barren with some lichens and *Littorina saxatilis*. The pools are dominated by *Chondrus, Fucus distichus*, and crustose seaweeds. The lower portion of the shore supports *Alaria, Laminaria, Palaria*, and *Devaleraea*.

Periwinkle (*Littorina littorea)* shores are somewhat similar to the rockweed platform shores with respect to the abundance of intertidal fuccoids and Irish moss, but the substrata can include boulders, cobbles, and fine gravel. The diversity of both plants and animals is lower and the low shore kelps are absent, being replaced by crusts and summer ephemeral beds of *Chordaria, Scytosiphon, Dictyosiphon, Pilayella*, and *Ectocarpus*. The differences in the low shore assemblages are caused by the depredations of herbivorous sea urchins and periwinkles, which are controlled or precluded by waves in more exposed locations. The remaining species are crustose organisms such as *Ralfsia*, barnacles, and lichens resistant to grazing. Between the rocks are numerous nestling animals, especially polychaetes, nemerteans, *Gammarus spp.*, oligochaetes, and nematodes. Where sediments are suitable, lugworms and soft shell clams are present.

3. Physiography, Bedrock, and Structural Geology

3.1 Physiography

Eastern Newfoundland represents the most easterly area of North America. The physiography of the terrain is primarily the result of its geological history prior to Quaternary glaciation, with recent processes serving to modify the landscape. The configurations of the embayments and uplands are the product of tectonic events, beginning in the latter part of the Proterozoic Eon of Precambrian time.

Physiographically, southeastern Newfoundland, including the Avalon, Burin, Bonavista, and Connaigre Peninsulas, has been classified within the Atlantic Uplands of Newfoundland (Bostock 1970), within the broader division of the Appalachian Mountains and Plateaux (Bostock 1970; Graf 1987). The interior terrain can be generally described to consist of low, rolling uplands in the interior areas, with maximum relief of less than 300 m. The highest summits are located within 20 km of the coastline in most areas, and no location on the Avalon Peninsula is more than 30 km from the shore. Coastal cliffs locally exceed 70 m in height, particularly along the southern Cape Shore and Southern Shore, along Paradise Sound, and surrounding the deep fjords of the South Coast. Although southeastern Newfoundland is considered to have limited relief, the presence of steep coastal cliffs locally isolates the shoreline from the interior.

Offshore bathymetry exceeds terrestrial relief in many areas. The deepest waters in Hermitage Bay (in excess of 230 m), Conception Bay (in excess of 280 m), Placentia Bay (in excess of 300 m), Fortune Bay (in excess of 430 m), and Trinity Bay (in excess of 580 m) are associated with northeast-southwest trending structural depressions. In contrast, St. Mary's Bay is relatively shallow, with a maximum depth of 210 m and a modal depth within the embayment of 120 m south of Great Colinet Island. Although depths shallower than 100 m are found offshore at the mouth of St. Mary's Bay (65 m) and up to 50 km south of the Burin Peninsula, the depths are sufficiently great to preclude interference with all but the longest wavelength open marine waves. Offshore areas shallower than 100 m depth include the St. Pierre, Green, Whale, and Grand Banks. Both offshore and onshore within the overall Atlantic Uplands physiographic division, however, there are significant differences in terrain related to rock type, faulting and folding, and to a lesser extent Quaternary history.

3.1 Regional Geology and Structural Geomorphology

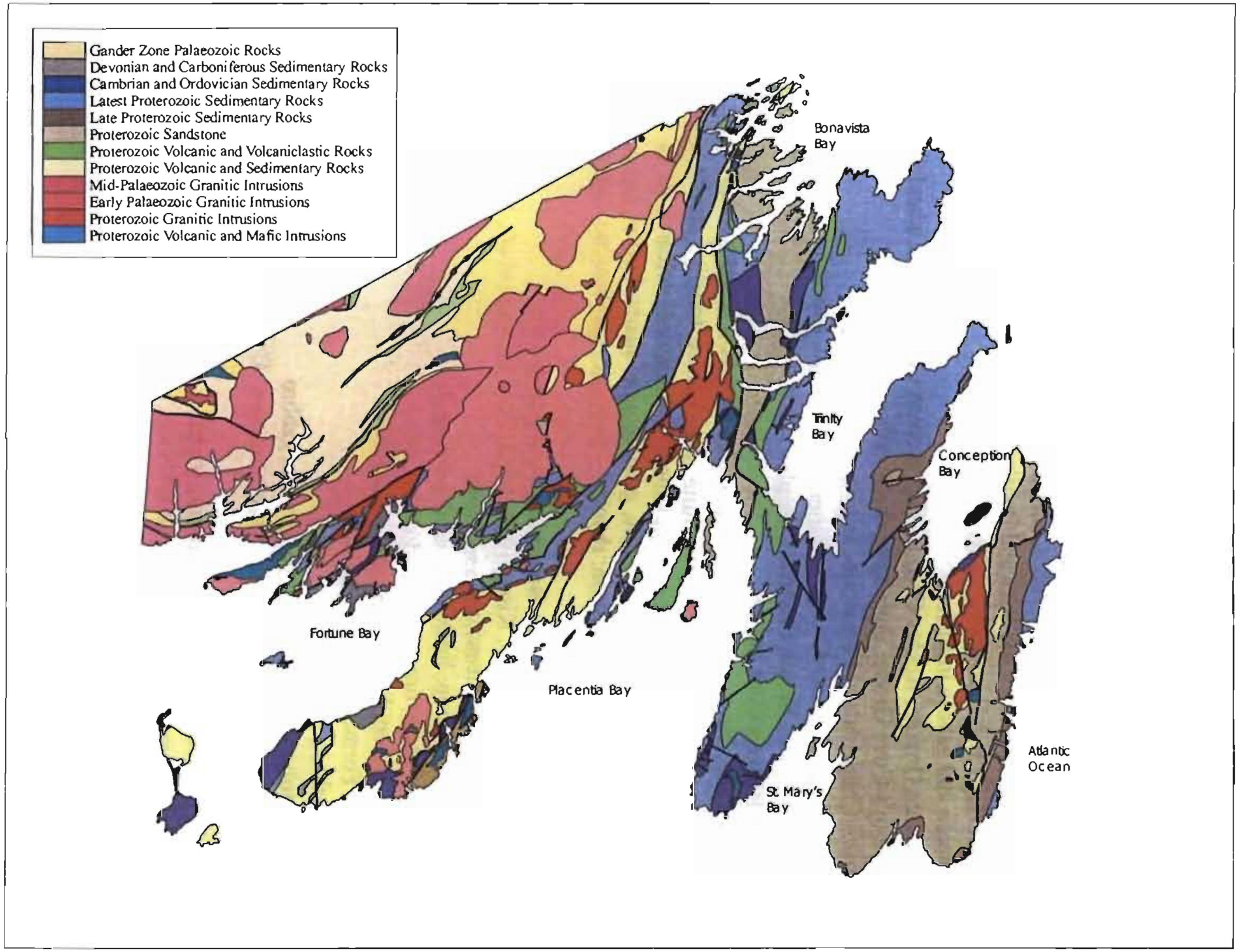
Analysis of the tectonic history of Newfoundland has demonstrated that the island is divided geologically into a number of zones: Humber (or Western) Zone; Dunnage and Gander Zones, combined by some authors into a single Central Zone; and Avalon (or Eastern) (Williams *et al.* 1988; Hodych and King 1989; Colman-Sadd *et al.* 1990; Batterson and Liverman 1995). The westernmost part of the study region, west of Hermitage Bay, is within the Central Geological Zone. The remainder of the terrain is included within the Avalon (Eastern) Zone. Along the shoreline of Bonavista Bay, the division between the Central and Avalon Zones is marked by the Dover Fault.

Geological units are arranged by stratigraphic position and chronologic age. The table of bedrock units within the study region is presented as Table 3-1, and a generalized geological map of the region is illustrated in Figure 3-1.

3.1.1 Central Zone

The Central Zone extends from Hermitage Bay westwards to Cape Ray along the South Coast. The division between the Avalon and Central Zones in the Hermitage Bay area is marked by a major fault system, involving several faults trending northeast-southwest. The Hermitage Fault parallels the southern shoreline of Hermitage Bay, extending from offshore of Pass Island north of Fox Island, and northeast along the axis of the bay. The deepest soundings in the bay, in excess of 230 m between Furby's Cove (south shore) and Green Point (north shore), are associated with the fault. The fault extends further to the northeast along the axis of Hermitage Bay to Low Point, and trends northeast inland to Big Blue Hill Pond. The Dragon Bay Fault parallels the Hermitage Fault to the north, extending along Dragon Bay across Facheux Bay to Bay d'Espoir and northeast along the valley now occupied by Little River.

Throughout the zone between these two faults, other northeast-southwest trending ruptures have created a pattern of deep embayments and narrow valleys. This area, typified by Long Island (Gaultois) and the north shore of Hermitage Bay, is marked by steep cliffs with small mixed sand-gravel pocket beaches. Embayments trending north-northwest -- south-southeast, such as Little Passage, Northwest Cove, Bonne Bay (McCallum), and North Bay, follow lesser faults developed at right angles to the primary systems during the original tectonic activity. These embayments, developed at 90° to the structural trend, tend to be shorter and have shallower bathymetry than do the main northeast-southwest systems.



Gander Zone Palaeozoic Rocks
Devonian and Carboniferous Sedimentary Rocks
Cambrian and Ordovician Sedimentary Rocks
Latest Proterozoic Sedimentary Rocks
Late Proterozoic Sedimentary Rocks
Proterozoic Sandstone
Proterozoic Volcanic and Volcaniclastic Rocks
Proterozoic Volcanic and Sedimentary Rocks
Mid-Palaeozoic Granitic Intrusions
Early Palaeozoic Granitic Intrusions
Proterozoic Granitic Intrusions
Proterozoic Volcanic and Mafic Intrusions
Bonavista Bay
Trinity Bay
Conception Bay
Fortune Bay
Placentia Bay
St Mary's Bay
Atlantic Ocean

Figure 3.1

Table 3-1. Bedrock Units of Eastern Newfoundland.

Central Zone: McCallum-Facheux Bay
(O'Brien *et al.* 1998, Blackwood 1985, Colman-Sadd *et al.* 1990)
Devonian Indian Point, Gaultois, McCallum, Northwest Brook Granites
Middle Ordovician Bay d'Espoir Group shale
Cambrian and Ordovician volcanic rocks
Early Palaeozoic Gneiss, Quartzite, Pelite
Early Palaeozoic Migmatites, Gneisses

Avalon (Eastern) Zone: Hermitage Bay-Fortune Bay
(O'Brien *et al.* 1981, O'Brien *et al.* 1998, Colman-Sadd *et al.* 1990)
Devonian and Carboniferous Cinq Isles and Pool's Cove Formations: sandstone, shale
Devonian Great Bay l'Eau Formation: volcaniclastic rocks
Devonian diabase and gabbro intrusions
Devonian Belloram Granite, Ackley Granite, Old Woman Granite, Pass Island Granite
Cambrian Young's Cove Group: limestone, shale, orthoquartzite
Early Cambrian Chapel Island Formation: sandstones, siltstone
Late Proterozoic Long Harbour Group: sedimentary, volcanic, and volcaniclastic rocks
Late Proterozoic Harbour Breton Granitic Complex
Late Proterozoic Hardy's Cove granite
Late Proterozoic Grole Intrusive Suite: gabbro, with lesser diorite and granite
Late Proterozoic Simmons Brook Intrusive Suite: granodiorite, tonalite, diorite, gabbro
Late Proterozoic Connaigre Bay Group: conglomerate, sandstone, volcanic rocks
Late Proterozoic Furby's Cove Suite: Granite, granodiorite, quartz diorite, and porphyries
Late Proterozoic Tickle Point Formation: rhyolitic, andesitic, and basaltic volcanic flows

Avalon (Eastern) Zone: Avalon & Bonavista Peninsulas
(Jenness, 1962; McCartney, 1967; King, 1988, 1990; Colman-Sadd *et al.*, 1990)
Ordovician Wabana Group: limestone, sandstone
Ordovician Bell Island Group: limestone, sandstone, shale
Cambrian Harcourt Group: limestones and shales
Cambrian Adeyton Group: limestones, shales, and slates
Cambrian Random Formation: orthoquartzite
Late Proterozoic gabbro intrusives
Late Proterozoic Holyrood Intrusive Suite: granite, gabbro
Late Proterozoic Signal Hill Group, Musgravetown Group: sedimentary, volcanic, and volcaniclastic rocks
Late Proterozoic Harbour Main Group: volcanic rocks
Late Proterozoic Conception Group, St. John's Group, and Connecting Point Group: sandstone, siltstone, argillite, conglomerate, and chert

Table 3-1. (Cont'd.).

Avalon (Eastern) Zone: Burin Peninsula & Placentia Bay Islands
(O'Brien *et al.* 1981; King, 1988, 1990; Colman-Sadd *et al.*, 1990)
Carboniferous Spanish Room Formation: limestones, shales, breccias, conglomerates
Carboniferous Terrenceville Formation: shale and sandstone
Carboniferous St. Lawrence Plutonic Suite: granitic igneous rocks
Devonian-Carboniferous Grand Beach Complex: volcanic rocks
Devonian Powder Horn diorite-gabbro complex
Devonian Red Island, Ragged Islands, Sail-the-Maid Granitic Suites
Cambrian Inlet Group, Fortune Group: shales, siltstones, and limestones
Eocambrian Bay View Formation: sandstone, siltstone, orthoquartzite
Eocambrian Grand Bank Formation: siltstones
Eocambrian Admirals Cove Formation: conglomerate, mudstone, sandstone
Late Proterozoic Swift Current granite, Cape Roger Mountain granodiorite, Anchor Drogue granodiorite, Seal Cove quartz diorite/granodiorite, Laughlin's Hill gabbro
Late Proterozoic Rock Harbour Group: volcanic rocks
Late Proterozoic Marystown Group: volcanic and sedimentary rocks
Proterozoic Love Cove Group: volcanic and sedimentary rocks
Late Proterozoic Burin Group: volcanic and sedimentary rocks
Proterozoic Corbin Head Formation: breccias, sandstones, siltstones, and argillites.

Three major rock units crop out in the zone between the Dragon Bay and Hermitage Faults. The oldest rocks are Early Palaeozoic (Silurian and older, O'Brien *et al.* 1998) migmatites and gneisses, which form a northeast-southwest trending belt cut diagonally by Little Passage north of Gaultois. Along Little Passage, resistant orthogneisses form coastal cliffs at Big Head, Gimlet Point, and between Grip Cove and Seal Nest Cove, and are also exposed on The Matchums.

Early Palaeozoic gneisses, quartzites, pelites, and other metasedimentary rocks, with associated volcanic rocks, occur south of Bay d'Espoir along the Dragon Bay Fault system. Along Little Passage, less resistant units (primarily paragneisses and amphibolites) within this metamorphic complex have been eroded to form Deer Cove, Blackfish Cove, Seal Nest Cove, Grip Cove, and Seal Cove. To the south of Big Head, ongoing erosion of these strata triggered by frost action on the cliff face, and facilitated by reworking of the talus at the base of the slope, has resulted in active block detachment and rock falls.

The youngest rock units within this zone are Devonian granites, cropping out along the north shore of Hermitage Bay (Indian Point, Gaultois, and Northwest Brook granites), along North Bay, and south of the Dragon Bay Fault system at McCallum and Facheux Bay (O'Brien *et al.* 1998). The configuration of embayments and cliff morphology is controlled by fracture patterns, exploited by frost wedging; lithological differences among the plutonic units; and post-intrusive faulting, associated with the Dragon Bay, Hermitage, and ancillary faults.

All of the granitic plutons are fractured, commonly with three systems of mutually perpendicular orthogonal joints that are readily exploited by frost wedging to form vertical cliffs. The spacing and intensity of the joint pattern, however, differ substantially among individual plutons (Blackwood 1985). At McCallum, and along southernmost Facheux Bay at Western Head, the McCallum granite is characterized by a strongly orthogonal joint system, with the principal joints striking south-southeast -- north-northwest, approximately normal to the trend of the Dragon Bay Fault. This joint pattern has resulted in a shoreline with straight SSE-NNW trending segments, linked by less regular short segments trending ENE-WSW. The mouth of Facheux Bay is a good example of this style of shoreline development. In contrast, finer-grained granodiorite and biotite granite units crop out 1 km north of Western Head. Here, the dominant joints trend NNE-SSW, and the shoreline changes orientation in consequence. The finer-grained units are more resistant to physical weathering, particularly frost action, and consequently secondary joints are not readily exploited. This produces a straighter, non-embayed shoreline than that present to the south.

The Gaultois Granite, which also crops out south of Dragon Bay, is less regularly jointed than the McCallum Granite. The Gaultois Granite is also generally coarser-grained, rendering it more susceptible to frost action. Shorelines associated with the Gaultois Granite are marked by numerous closely spaced short and extremely narrow embayments, each one initiated along an individual joint. This irregularly crenulated style of coastline is commonly associated with intensely fractured granites which have been subjected to multiple stresses, producing irregular or multiple intersecting joint patterns. This 'geos' coastline resembles those developed along similar areas of granite outcrop in Cape Breton, Georgian Bay, and the northwestern Scottish coast.

To the north and west of the Dragon Bay Fault, two rock types dominate (O'Brien *et al.* 1998). Cambrian and Ordovician volcanic rocks form the southern shoreline of Bay d'Espoir along Long Island northeastward from Butter Cove to Raymond Point. They are also exposed at Ingram Point, at Dolland Bight along the north side of the fault system, on Isle Galet, at Goblin Head and Old Harry, and south of Dennis Arm, Facheux Bay. The volcanic rocks are more resistant than the adjacent Palaeozoic sedimentary strata, and thus form local promontories defined by embayments eroded in the sedimentary rocks, or marking faults. In most localities, the volcanic rocks are bordered by the Dragon Bay Fault.

To the north of the belt of volcanic rocks, the dominant rock type is Middle Ordovician (or older) sedimentary shale of the Bay d'Espoir Group, which has been weathered and partially metamorphosed to form weakly resistant metasedimentary pelite units (Blackwood 1985). These rocks are susceptible to erosion, forming linear, narrow embayments. Dennis Arm, developed in weak graphic pelite along the west shore of Facheux Bay, is a good example. In the Bay d'Espoir area, Lampidoes Passage, Goblin Bay, and East Bay developed similarly. The metasediments form gently rolling topography, with local steep cliffs where cut by north-south trending faults (e.g. North Bay) or by northeast-southwest trending faults (e.g. north shore of Bois Island). Along Bay d'Espoir, the Palaeozoic metasediments extend north to the Head of Bay d'Espoir, and inland to Long Pond Reservoir.

3.1.2 Avalon (Eastern) Zone: Hermitage Bay-Fortune Bay

The Avalon Geological Zone encompasses all of the terrain to the east and south of the Hermitage and Dover Faults, including the Connaigre, Burin, Avalon, and Bonavista Peninsulas. Rocks exposed on land include igneous, metamorphic, and sedimentary units, and range in age from Precambrian to Devonian (O'Brien *et al.* 1981, 1998). Formation of the youngest rock units was completed *ca.* 400 million years ago, and all fault systems appear to be tectonically inactive.

In the Coast of Bays region, including Hermitage Bay, Connaigre Bay, and Harbour Breton, the Avalon Geological Zone is composed of Late Proterozoic (Precambrian) volcanic, sandstone, shale, and partly metamorphosed sedimentary rocks, varying in resistance to weathering. These strata are cut by northeast-southwest trending faults and joints, and are locally folded. The complex tectonic history has resulted in the formation of a coastline marked by numerous fjords, bays, and coves, separated by headlands forming a ragged shore.

The oldest Late Proterozoic rocks are rhyolitic, andesitic, and basaltic volcanic flows of the Tickle Point Formation (O'Brien *et al.* 1998). These volcanic units form resistant cliffs along the south shore of Hermitage Bay, particularly in the Hardy's Cove area. Plutonic intrusive rocks, including granite, granodiorite, quartz diorite, and porphyries, also crop out along the south shore of Hermitage Bay, and are classified as the Furby's Cove Suite. Both these rock units form resistant, steep, straight cliffs along the Hermitage Bay shoreline from Hermitage to Hardy's Cove. Embayments, such as Hermitage Harbour, Furby's Cove, and Olive Cove, are associated with faults trending at a variety of orientations.

The Late Proterozoic Connaigre Bay Group consists of several conglomerate and sandstone sedimentary units, along with rhyolite, basalt, volcanic breccia, and volcanic tuff, and metamorphosed sedimentary rocks. These units are found along the shores of Connaigre Bay and Deadman's Bight. Most of the area is dominated by the volcanic rocks of the Doughball Point Formation, one of the units of the Connaigre Bay Group. This shoreline is deeply indented, with the large embayments (Connaigre Bay and Deadman's Bight) and most of the smaller embayments (e.g. Great Harbour Bight) aligned northeast-southwest. Some lesser embayments, such as Partridge Cove, have developed along minor faults with varying orientations.

Northeast Arm (Harbour Breton) is flanked by Late Proterozoic granodiorite, tonalite, diorite, and gabbro of the Simmons Brook Intrusive Suite. Minor embayments along the largely straight eastern shore of Northeast Arm mark small northeast-southwest trending faults. The northern shoreline of Old Bay is also formed by erosion of these plutonic units. A major northeast-southwest trending fault marks the southern margin of the Simmons Brook Intrusive Suite from northern Little Bay northeast through Old Bay, to the heads of North and East Bay. Resistant cliffs at Bay du Nord are associated with this fault.

The Late Proterozoic Grole Intrusive Suite is dominated by gabbro, with lesser diorite and granite. This unit crops out along most of the south coast of Hermitage Bay south of Hermitage, including Pass Island. Typically, it forms steep cliffs, with small embayments developed along joints and faults. In the Grole area, northeast-southwest trending faults have served to form the southeast, smoothly-curved margins of embayments, with more irregular western shorelines not associated with fault planes. The Grole gabbro also outcrops in the Sandyville area, along the shore of Connaigre Bay.

Two additional granitic intrusive complexes complete the suite of Late Proterozoic plutonic rocks (O'Brien *et al.* 1998). The Hardy's Cove granite forms a short segment of coastline to the northeast of Hardy's Cove. Much more areally extensive are the plutons of the Harbour Breton Granitic Complex. The Northeast Arm pluton, composed of biotite-hornblende granite, forms the shorelines at Black Island Rock and Backside Cove, along small segments of Northeast Arm adjacent to Rocky Point and Poole Rock, and at the head of the arm inland from Harry Youden's Head. The Jerseyman's Harbour porphyritic hornblende granite forms the rounded summit of Jerseyman's Head, and the steeper slopes of the eastern shore of the harbour. The southern shore of Jerseyman's Harbour is defined by pink equicrystalline granite of the Northeast Arm pluton.

East of East Bay, Late Proterozoic sedimentary, volcanic, and volcaniclastic rocks of the Long Harbour Group dominate the northern shoreline of Belle Bay, Mal Bay, Long Harbour, and Terrenceville Harbour (O'Brien *et al.* 1998). The major north-south embayments are developed along faults displacing banded sequences of the rhyolites and volcaniclastic rocks of the Belle Bay Formation (within the Long Harbour Group). Narrow WNW-ESE embayments and leads, such as those in the Rencontre East area, are associated with erosion of the softer sedimentary and metamorphosed sedimentary rocks. Resistant conglomerate at the base of the Rencontre Formation (within the Long Harbour Group) forms headlands and islands, including Belle Island, Potato Point, and Long Point. Another resistant assemblage within the Long Harbour Group is the stratified fine-crystalline rhyolites of the Mooring Cove Formation. These rhyolites support headlands at Ironskull Point, Dog Cove, Lally Cove Island, and Stones Cove.

Arkoses and arkosic conglomerates of the Rencontre Formation, another unit within the Long Harbour Group, also form resistant headlands and cliffs. Typical examples are located at Mal Bay Island, along the southern shore of Rencontre Island, at Bob Head (Corbin Bay), and on the northern shore of Chapel Island.

Brunette Island is also composed of strata of the Long Harbour Group, deformed by northeast-southwest trending folds and faults into alternating ridges and valleys. Resistant pebble conglomerate forms the northwestern shore of Brunette Island, and the northern shore of Mercer's Cove. Softer siltstones have been eroded along the south coast, and along Little Cape Neck. Rhyolite forms the headland at Mercer Head. The Bird Islands archipelago, to the southwest of Brunette Island, consists of basaltic flows within the Long Harbour Group.

Younger Cambrian rocks overlie the Proterozoic units (O'Brien *et al.* 1998). The Early Cambrian Chapel Island Formation, consisting of greywacke, subgreywacke, arkose, and quartz feldspatharenite sandstones, with micaceous siltstone, is generally less resistant than the Precambrian units. At the head of Cinq Isles Bay, the Chapel Island sandstones lie in a fault-bounded trough, flanked by resistant conglomerate strata. The head of the embayment is linear, eroded evenly into the softer sandstones. The Cinq Isles Bay exposure forms part of a northeast-southwest trending trough, generally fault-bounded, that has been eroded to form Salmonier Pond, Cinq Isles Bay, and the east arm of East Bay. To the south, a parallel trough has been eroded in the Chapel Island Formation to form Corbin Bay. On Chapel Island itself, the sandstone has been eroded on the eastern shore. It is protected on the south by the resistant Belloram Granite, and to the north by sandstone of the Rencontre Formation. More resistant conglomerate is present at West Point, Blue Pinion Harbour, and on the southern shores of St. Jacques Islands. Locally, the finer-textured units of the Chapel Islands Formation have been metamorphosed to hornfels, which greatly enhances their resistance to erosion, as along the southeast tip of Chapel Island.

Small areas of outcrop of Cambrian limestone, shale, and orthoquartzite of the Young's Cove Group are exposed at Otter Cove Point and Sagona Island. Steeply dipping quartz sandstones at Otter Cove Point serve to protect the more friable Chapel Islands Formation at Blue Pinion Harbour. On Sagona Island, ENE-WSW trending ramparts of orthoquartzite flank and serve to protect beds of friable flaggy limestone and shale. These units are open to hurricane winds from the WSW, however, and have been eroded to form a narrow, linear embayment along the central groove. The weakest shales are preserved above sea level to the north of a fault which has cut across all the strata, elevating the northeast side of the island relative to the southwest.

Younger granitic rocks, associated with the tectonic activity of the Devonian (middle Palaeozoic) Acadian Orogeny, have intruded the older units. The oldest of these intrusions is the Pass Island Granite, which crops out along the southwestern Connaigre Peninsula and produces a shoreline with rolling slopes and conspicuous granitic pebble beaches from Pass Island Tickle eastward to Seal Cove and The Bight. In this area, the shoreline tends to be straighter with shallow embayments flanked by granite headlands, notably Basse Terre Point, in contrast to the deeply embayed shorelines associated with Precambrian sedimentary rocks. Younger Devonian granites include the Ackley Granite, which crops out at the heads of Belle Harbour, Rencontre Bay, and Long Harbour, and the Old Woman Granite, exposed along the northeast shore of Old Bay, Great Bay l'Eau (O'Brien *et al.* 1998).

The youngest granite in the region is the Devonian Belloram Granite, which forms the shoreline from the head of Blue Pinion Harbour northeast to Belloram, and along the southwestern shore of Chapel Island. A resistant granitic porphyry forms Red Head, west of English Harbour West. Although the Belloram Granite is a resistant unit, forming steep-sided hills with rounded summits at Belloram, St. Jacques, and other locations, it has been heavily modified by glaciation along the valleys between the intervening hills. Blue Pinion Harbour, St. Jacques Harbour, and the channel between Chapel Island and Belloram (maximum depth 123 m) all served as conduits for glacial flow.

Indented shorelines are associated with the youngest sedimentary rocks of Devonian and Carboniferous age. A fault-bounded assemblage of sedimentary rocks of the Cinq Isles and Pool's Cove Formations lines the northwestern shore of Great Bay l'Eau from Eastern Head to Old Bay. Small embayments are developed along NE-SW trending faults, particularly near Eastern Head. The conglomerates and sandstones are resistant to erosion, and few embayments are present. Little Bay, the major exception, is developed along the axis of a NNW-SSE trending flexure which is aligned approximately normal to the regional strike. On the southeast side of Great Bay l'Eau, a less resistant exposure of Pool's Cove sandstone has been eroded to form Wreck Cove. Along Belle Bay, conglomerates and sandstones are exposed in coastal escarpments from the northern side of Cinq Isles Bay north to Pool's Cove, North Bay, and East

Bay. NW-SE trending faults have been exploited to form the larger embayments in northern Belle Bay.

The Devonian volcanic rocks of the area, assigned to the Great Bay l'Eau Formation, are generally less resistant to erosion, and tend to form embayed coastlines. Typical shorelines are found along the southeast margin of Great Bay l'Eau, and at Coomb's Cove, Boxey, Mose Ambrose, and along the southeastern shore of Cinq Isles Bay. To the northeast of Boxey Point, interbedded volcaniclastic rocks and resistant mafic sills (notably at Friar Head) give the shoreline a finely crenulated configuration.

Resistant Devonian diabase and gabbro intrusions form straight linear ridges. The best example is the northeast-southwest trending intrusion forming the Cinq Islands. Another gabbro sill crops out along the shore at Corbin.

3.1.3 Avalon (Eastern) Zone: Avalon Peninsula

The Avalon Peninsula represents the easternmost land mass of North America. It contains several areas of rolling uplands, interspersed with small plateaux regions, and is connected to the main part of Newfoundland by the Isthmus of Avalon, with a minimum width of 4 km at its northern end. The peninsula and isthmus encompass approximately 10,000 km^2 The Avalon Peninsula can be conveniently divided into four sub-peninsulas: Placentia, Carbonear, St. John's, and Trepassey. Each of the sub-peninsulas trends northeast-southwest. The heights of land follow the axes of the major sub-peninsulas, resulting in the development of drainage systems marked by short, steep gradient streams with small catchment areas.

The bedrock and topography of the Avalon Peninsula are the results of numerous geological events since the formation of the oldest rocks during the Late Proterozoic (~700-900 million years ago), representing the youngest part of Precambrian geological time (King 1988, 1990). Plate tectonic activity during the Late Proterozoic resulted in the formation of a mid-ocean rift valley system to the west of the present location of the Avalon and Burin Peninsulas. This ocean, a predecessor of the modern Atlantic, is referred to as the "Iapetus Ocean" (Bambach *et al.* 1980; Stanley 1986; Hodych and King 1989; Environment Canada 1990; Evans 1992). As coastal sediments accumulated and volcanoes erupted along the flank of the widening Iapetus Ocean, the Precambrian bedrock units of the Avalon Peninsula were formed and modified. During the Late Proterozoic, the Avalon and Burin Peninsulas formed part of a continent that also included northwesternmost Africa, the majority of Europe, England, southern Scotland, and Ireland. St. John's lay at approximately 35° South latitude, and the climate was temperate, allowing some of the earliest multi-celled metazoan organisms to flourish in the warm seas and to subsequently be preserved as fossils in rock of the Conception Group, exposed near Cape Race (Hoffman 1981; Colman-Sadd *et al.* 1990).

The remainder of Newfoundland was attached to a 'North American' continent, including the Canadian Shield, New Brunswick, Greenland, the Scottish Highlands, the northern part of Ireland, and Norway, on the far (northern) side of the Iapetus Ocean (Scotese *et al.* 1979; Bambach *et al.* 1980; Allegre 1988). Nova Scotia, Prince Edward Island, and parts of New

England were attached to a third palaeo-continent, which included most of Africa, and lay over the Late Precambrian South Pole (Hambrey and Harland 1981).

The Avalon Peninsula is dominated by Late Proterozoic (latest Precambrian) clastic sedimentary, metasedimentary, and bimodal volcanic rocks, assigned to the Harbour Main, Connecting Point, Conception, St. John's, Musgravetown, Long Harbour, and Signal Hill Groups (McCartney 1967; King 1988, 1990; Colman-Sadd *et al.* 1990). These stratigraphic units each contain a variety of lithologies, and rock types which dominate any particular Group are frequently encountered in subordinate positions in outcrops of other Late Proterozoic units. For example, although marine sandstone dominates the St. John's Group, similar marine sandstones also are associated with the Connecting Point, Conception, Musgravetown, Long Harbour, and Signal Hill Groups. Rocks of the St. John's and Signal Hill Groups crop out on the St. John's sub-peninsula (separating Conception Bay from the open Atlantic Ocean), and on the Carbonear sub-peninsula (between Trinity and Conception Bays).

Coastal morphology is related to lithology of the adjacent rock outcrops. Sandstone and conglomerate units, such as those associated with the Bay de Verde and Cuckold Formations of the Signal Hill Group, tend to produce steep cliffs, pocket beaches, and embayed coves. Less resistant shale, siltstone, and argillite units, such as the Fermeuse Formation (St. John's Group), are associated with lower cliffs or gently sloping shorelines.

The overall physiography and morphology of the Avalon Peninsula, however, is more closely related to the region's tectonic history and structural geology. The rocks of the peninsula have been deformed by a series of northeast-southwest trending folds and associated faults during the Late Proterozoic-Cambrian Avalonian and the Palaeozoic Acadian Orogenies (King 1988, 1990; Colman-Sadd *et al.* 1990). As a result, the northeast-southwest trending sub-peninsulas are aligned with their long axes paralleling the dominant direction of folding and faulting. Along the open Atlantic shoreline from Cape St. Francis to Cape Race, Late Proterozoic sandstones, and siltstones and shale which largely have been metamorphosed to argillites, are the dominant rock types. Breccia beds, formed of angular fragments produced by Proterozoic volcanic eruptions, are also present. These units were folded and deformed during the mountain-building Avalonian Orogeny, forming ridge-and-valley topography.

The oldest of these Late Proterozoic rocks in St. John's are sandstone, siltstone, argillite, conglomerate, and chert units of the Conception Group (King 1990). The folds trend northeast-southwest in the Petty Harbour region, gradually deflecting to north-south in the area north of St. John's (King 1990), and control the position of the ridges throughout the city north and west of the Waterford Valley and the harbour. South and east of the Waterford Valley, younger Precambrian rocks of the St. John's Group (sandstone and shale) and the Signal Hill Group (sandstone, shale, conglomerate, breccia, and volcanic tuff) are present, forming the steep cliffs of the South Side Hills and South Head, at Fort Amherst lighthouse (King 1990). These units have been deformed into the Blackhead Syncline fold.

The southwest-northeast trending ridges, combined with the intervening valleys, form undulatory topography marked by embayments (Spear Bay, Deadman's Bay, Blackhead Bay, Freshwater Bay, St. John's Harbour) and depressions (such as that occupied by Quidi Vidi Lake), separated by linear flat-topped to rolling ridges reaching elevations of 180-200 m asl (Snaggle

Hill, South Side Hills, White Hills). The valley areas are occupied by river systems, including the Waterford River and its tributaries. The differences in elevation between valleys and ridges increase towards the northeast. Embayment depths locally exceed 50 m, and the total relief is greater than 230 m.

In the northern and western parts of the northeast Avalon Peninsula, the alternating ridge and valley pattern is modified due to additional geologic deformation and glacial sedimentation. These areas, including the terrain adjacent to Windsor Lake, Oxen Pond, and Octagon Pond, are marked by rolling uplands, interspersed with small plateaux. Locally, the ridges are cut by faults or weaknesses in the bedrock, permitting erosion and the development of narrow valleys across the trend of the topography. The Narrows of St. John's Harbour represents one such valley, with adjacent parts of the bisected ridge represented by Signal Hill (elevation 180 m asl) and South Head.

The structural influence on topography is particularly evident in the configuration of the shoreline of Conception Bay between Holyrood and Bay de Verde. From Holyrood north to Colliers Bay, embayments trend northeast-southwest, developed along the major faults and fold axes associated with the Avalonian Orogeny. Holyrood Bay, for example, is eroded into the Harbour Main Group volcanic rocks, and is flanked by more resistant clastic rocks of the Conception Group (Drook Formation). A resistant stratum of the Conception Group, bounded to the west by the Brigus Fault, extends seaward to form Salmon Cove Point and Colliers Point. Alternating friable and resistant units of the Harbour Main Group create the crenulated shorelines between Avondale and Kitchuses, and along the southern side of Colliers Bay from James Cove to Colliers.

To the north of Brigus, the structural geology consists of northeast-southwest trending faults (such as the Shearstown Brook Fault) superimposed on SSW-plunging anticlines and synclines. This structural geology results in the development of deep northeast-southwest trending embayments, such as Bay de Grave, Bay Roberts, Spaniards Bay, and Harbour Grace. These shorelines are marked by local crenulations and alternating areas of rock cliffs and low coastal bluffs, created by the differential resistance to erosion of units oblique to their strikes. Along the north shore of Bay de Grave, the resistant Trepassey sandstone forms a ridge at Ship Cove, as the adjacent coves have developed through erosion of the softer Mistaken Point (to the southwest) and Fermeuse Formations.

From Perry's Cove north to Grates Point, and along the shoreline of Trinity Bay south to New Perlican, the lithological units are aligned parallel to the trend of the Carbonear sub-peninsula. This alignment, coupled with the absence of major faults, has limited embayment development. Along the southeastern and southern shores of Trinity Bay west to Tickle Bay (Bellevue Beach), embayments form in eroded areas of the Late Proterozoic Heart's Content Formation (shale) and siltstone beds of the Big Head Formation. Both of these formations are contained within the Musgravetown Group, the stratigraphic equivalent to the Signal Hill Group of the eastern Avalon Peninsula.

In structural geology, the northeastern shoreline of Placentia Bay resembles that of Conception Bay from Brigus to Carbonear. NNE-SSW trending folded Late Proterozoic rocks of the Bull Arm, Big Head, Maturin Ponds, and Trinny Cove Formations of the Musgravetown

Group are cut by faults, producing embayments such as Pumbly Cove, Fair Haven, and Long Harbour. The youngest unit of the Musgravetown Group is the resistant Crown Hill conglomerate, which forms the Brine Islands.

Along the shore of Placentia Bay south from Placentia to Cape St. Mary, and northeastward along the St. Mary's Bay shoreline to Cape Dog, the rolling uplands are aligned northeast-southwest, producing the relatively straight Cape Shore, marked by few embayments and short, steep-gradient rivers. Cliffs up to 65 m high mark the shoreline. The scarcity of deeply indented embayments indicates the alignment of physiographic ridges and bedrock units parallel to the coast. Few good harbours are present, as embayments are shallow and directly open to strong southwesterly winds. The physiography thus has acted to limit human utilization of the Cape Shore, in contrast to the more densely settled coastlines of Conception Bay and the Southern Shore.

Intrusive igneous rocks of Late Proterozoic to earliest Cambrian age also contribute to the formation of the Avalon coastline, although these have a limited areal distribution. Although a variety of lithologies are represented, two dominant suites are present. Mafic intrusions, predominantly gabbro, crop out in the Kitchuses area (Whalesback gabbro and equivalents of King, 1988). Granitic intrusions, which locally include mafic units, crop out throughout the Holyrood-Witless Bay Barrens area, and south of Harbour Main (intrusive units of Harbour Main Group and Holyrood Intrusive Suite of King, 1988). Intrusive rock units are resistant to coastal erosion.

After the Proterozoic rocks were deposited and deformed, the Iapetus Ocean continued to widen. Throughout the period from 700 million to 500 million years ago, additional younger marine sediments were deposited along its margins. The youngest sedimentary rocks exposed on the Avalon Peninsula are limestones, shales, and conglomerates of Cambrian (~570 million years) age and sandstones, shales, and limestones of Ordovician (~500 million years) age on Bell Island (King 1990; Colman-Sadd *et al.* 1990).

In stratigraphic order, the Cambrian units consist of the resistant orthoquartzite Random Formation, the moderately to weakly resistant limestones, shales, and slates of the Adeyton Group, and the friable black shales and resistant limestones of the Harcourt Group (including the Manuels River, Elliot Cove, and Clarenville Formations). The limestones of the Cambrian Manuels River Formation are notable for the presence of *Paradoxides* trilobite fossils which are not found in Cambrian strata elsewhere in Atlantic Canada. The presence of these fossils indicates that the Avalon Peninsula was attached to the palaeo-European continent during the Cambrian Period (Hutchinson 1962; Williams and Hatcher 1982).

The Random Formation, composed of orthoquartzite sandstone and conglomerate, is the most resistant to coastal erosion of the Palaeozoic sedimentary units. It is a relatively thin unit, however, and thus forms only isolated headlands along southern Trinity Bay, southwestern St. Mary's Bay, and southeastern Placentia Bay. Typical examples include the west shores of the Dildo Islands, the southwest margin of Collier Bay (Isthmus of Avalon), Cross Point (St. Brides), and Jigging Cove Head (St. Mary's Bay).

The Adeyton Group is more areally extensive than the Random Formation, and also contains a wider variety of lithologies. It crops out along Holyrood Bay south of Seal Cove (east shore) and at Chapel's Cove Point. The Adeyton Group forms the outermost fringe of the shoreline of Trinity Bay from Heart's Desire southward to Hopeall Head and Spread Eagle, cropping out on the headlands between the embayments. Resistant beds of the Adeyton Group form the western shoreline of Chapel Arm. These rocks also are exposed at St. Brides, Branch, Jigging Cove, and Cape Dog.

The Harcourt Group underlies Quaternary sediments along the Conception Bay South shoreline from Seal Cove to Topsail Beach, but is not exposed on the surface as coastal cliffs. It also crops out along the eastern shore of Chapel Arm. The largest area of outcrop is associated with the Point Lance Syncline, in the Lance Cove- Branch area of southwesternmost St. Mary's Bay. Here, the north-south trending syncline has deformed the Harcourt Group strata into a series of folds. In addition, younger Silurian diabase has been intruded and folded with the Harcourt Group rocks, producing a pattern of alternating resistant Silurian diabase and friable Harcourt sedimentary rocks exposed along the coastline. The result is a jagged, deeply embayed shoreline, with narrow heads such as Bull Island Point and Point Lance. Where the Harcourt Group strata are thin or steeply dipping, deep, narrow, linear north-south trending embayments separate the headlands. In areas where the strata are thicker and dip less steeply, broader embayments have developed, including Lance Cove, Gull Cove, and Red Cove.

The youngest sedimentary rocks in the Avalon region are those of the Ordovician Bell Island Group (Kelly's, Little Bell, and the majority of Bell Island), and the Wabana Group (northwesternmost Bell Island surrounding Wabana and Upper Grebes Nest Point). The resistant sandstones of the Kelly's Island, Little Bell Island, and Beach Formations, in stratigraphic order within the Bell Island Group, are cliff-forming units. The limestones and oolitic ironstones of the younger Dominion Formation of the Bell Island Group (Lower Ore bed), and the Wabana Formation, do not form high cliffs and are subject to attack by waves, especially in the Wabana area.

During the Late Ordovician, the rift valley in the centre of the Iapetus Ocean basin ceased to spread, and Iapetus began to close (Hodych and King 1989, Environment Canada 1990, Evans 1992). As the result of plate tectonic motion, Gros Morne lay on the Tropic of Capricorn, and the Equator ran through the present locations of Winnipeg, Iqaliut, and Bergen, Norway. Georges Bank, off the southwest coast of Nova Scotia, lay at the South Pole, and mainland Nova Scotia lay under Late Ordovician glacial ice (Schenk 1978; Hambrey and Harland 1981).

When the Iapetus Ocean basin closed completely, the Avalon Peninsula was attached to North America for the first time. The impact caused a mountain building event, the Acadian Orogeny, which deformed much of central Newfoundland. As a result of the orogenic activity, Palaeozoic granitic and gabbroic plutons locally intruded the sedimentary rocks. Devonian granites form the shores of Fox Island and Red Island (Placentia Bay). Devonian gabbroic plutons are exposed on the Iona Islands. A NW-SE trending Devonian diabase dyke crops out at Lears Cove and Golden Bay on the southwestern tip of the Placentia sub-peninsula northeast of Cape St. Marys.

3.1.4 Avalon (Eastern) Zone: West Trinity Bay-Bonavista Peninsula

The western shore of Trinity Bay from Tickle Bay to Cape Bonavista lies within the Avalon Geological Zone, and rocks here have close affinities with those of the Avalon Peninsula. The oldest rocks, sedimentary shales, siltstones, sandstones and conglomerates, with igneous gabbroic and diabasic dykes and sills of Late Proterozoic age, are assigned to the Connecting Point Group. This unit is broadly correlative to the Conception and St. John's Groups recognized on the Avalon Peninsula, but has been less intensely studied and subdivided. The Connecting Point Group is fault-bounded on the west by the SSE-NNW trending Come-by-Chance Fault, and on the east by the NE-SW trending Long Beach Fault. North of Northwest Arm, both faults are overlain by younger Cambrian strata. The Connecting Point Group crops out as a northward-widening wedge, influencing the shoreline at Sunnyside, between Queen's Cove and Long Beach on Southwest Arm, between Weybridge and Hickman's Harbour on Northwest Arm, and between Gin Cove and Clifton along Smith Sound. These shorelines are straight, with few embayments, and are marked by steep cliffs. Some embayments, such as Hatchet Cove, are related to NE-SW trending fault lines. The dogleg of central Smith Sound is the result of erosion along a fault system trending ENE-WSW from Aspey Brook across the Sound to Monroe, and extending northeastward to Lady Pond.

The youngest Late Proterozoic rock units are assigned to the Musgravetown Group, stratigraphically equivalent to the Signal Hill Group of the eastern and central Avalon Peninsula. These rocks form the coastline to the east of the Long Beach Fault, and extend northward to Cape Bonavista. To the south of Smith Sound, the strata are deformed in a series of NNE-SSW trending synclines and anticlines. The oldest strata within the Musgravetown Group, belonging to the Bull Arm Formation, are exposed at the core of the Centre Hill Anticline east of Sunnyside, and in other anticlinal cores at Little Chance Cove and Rantem Cove on the Isthmus of Avalon. The youngest strata of the Musgravetown Group are the conglomerates and sandstones of the Crown Hill Formation, exposed at St. Jones Harbour, St. Jones Within, Burn Point (Smith Sound), and Delby's Cove. Strata of intermediate age, tentatively assigned to the Big Head, Maturin Ponds, and Trinny Cove Formations by King (1988), form the majority of this shoreline. To the west of the Come-by-Chance Fault, strata of the Bull Arm Formation crop out along the shore at the heads of Southwest Arm, at Shoal Harbour, and at Clarenville.

The deepest embayments, Bull Arm, Random Sound, and Smith Sound, are linked to bathymetric depressions offshore beneath Trinity Bay. Water depths exceed 300 m in Random Sound, southeast of Bull Island, and northwest of Ireland's Eye. Although glacial activity has played a contributory role in these areas, most of the erosion has resulted from exploitation of joints and minor faults aligned approximately normal to the bedding strike and the fold axial trends. Lesser embayments such as Deer Harbour, St. Jones Harbour, and Little Hearts Ease Inlet, are not associated with bathymetric depressions. Subaqueous outwash fans and glaciofluvial fan deltas are submerged at the mouths of several inlets.

The youngest sedimentary strata south of Smith Sound are the Cambrian rocks of the Random Formation and Adeyton Group, and the Cambro-Ordovician deposits of the Harcourt Group. Outcrops and coastal morphology of these strata resemble their correlatives exposed on the Avalon Peninsula. The Random Formation and Adeyton Group are more resistant than the Harcourt Group strata, and have formed cliffed shorelines with few embayments at Sunnyside, east of Adeyton, Flower's Cove, St. Jones Within, Perley, east of Hickman's Harbour, Fosters Point, and Clifton. Slate is quarried from the Adeyton Group near Hickman's Harbour, Burgoyne's Cove, and along the southern shore of Northwest Arm.

The Devonian Clarenville Granite has intruded the Proterozoic strata at the head of Northwest Arm, forming outcrops south of Clarenville, at Red Point, and north of Shoal Harbour. The resistant granite forms steep cliffs at these sites. This granite is associated with the Acadian orogeny.

From Delbys Cove north to Cape Bonavista, all of the strata along the coast are assigned to the Musgravetown Group (Jenness 1962; Greene *et al.* 1984). Anticlinal and synclinal axes are curved, oriented NNE-SSW along the shoreline of Trinity Bay and gradually swinging northeastward inland. Major anticlines intersect the shore at Old Bonaventure, at Huzzie Head (east of Champneys), and at Spillers Point. A major synclinal axis crosses the shoreline at Robin Hood Bay, east of Port Rexton. A second synclinal axis crosses the shoreline north of Little Catalina, underlies the lighthouse on the north side of Catalina Harbour, crosses the harbour east of Port Union, and enters Trinity Bay at Norther Point.

Although the lithological variation within the Musgravetown Group is limited, numerous small-scale folds and faults provide structural complexity, which is reflected in the coastal geomorphology. In the Trinity-Port Rexton-English Harbour area, the convoluted, deeply indented coastline is the product of three major fold axes trending and plunging in different azimuthal directions and with varying dips, combined with secondary folding and minor faulting, and accentuated by lithological differences.

3.1.5 Avalon (Eastern) Zone: Northwestern Placentia Bay-Burin Peninsula

The bedrock units exposed on the islands and along the shoreline of northwestern Placentia Bay include Late Proterozoic (Precambrian) volcanic and siliciclastic rocks, Late Proterozoic granitic intrusions, and lesser outcrops of Cambrian sedimentary strata. Devonian igneous plutons, including the Red Island, Ragged Islands, and Sail-the-Maid granitic suites, and the Powder Horn diorite-gabbro complex, are the youngest rock types present. The coastal topography is largely the result of the pre-existing structural geology, marked by major northeast-southwest trending faults, such as the Paradise Sound Fault, and numerous intersecting lesser faults.

The oldest rocks exposed along the northwestern coast of Placentia Bay are volcanic rhyolite porphyries, felsic and mafic tuffs, ignimbrites, basaltic and other mafic lava flows, and associated volcanic breccias, volcanogenic sandstones and conglomerates, and metamorphosed shales, all of which are assigned to the Proterozoic Love Cove Group (O'Brien *et al.* 1981). Tuffs, ignimbrites, and conglomerates tend to form the steepest cliffs. The western shore of Paradise Sound is bordered by high cliffs developed where the Paradise Sound Fault has exposed felsic tuffs and ignimbrites. On Sound Island, the straight, steep cliffed shoreline of the west is developed in felsic tuffs. In contrast, the more embayment, irregular southern and eastern shorelines are developed in sandstones and conglomerates of varying resistance, with coarser units at Sandy Point and Brimstone Point separated by finer, more friable bedrock units at Catens Cove and Muddy Hole.

The Late Proterozoic Connecting Point Group contains conglomerate, sandstone, and shale strata. Along the south coast of the Isthmus of Avalon, the Connecting Point Group strata represent the southern extension of the fault-bounded wedge exposed on Random Island and along Smith Sound. They form a jagged, cliffed shoreline between Pinchgut Point (Pumbly Cove) and Come-by-Chance. Pinchgut Point's western shoreline is defined by a splay from the Jack's Pond Fault, a southeasterly extension of the Long Beach Fault to the north. Additional splay faults have been exploited to form Little Harbour, La Manche Cove, Little Southern Harbour, Great Southern Harbour, and Arnold's Cove. Strata strike parallel to the trend of the faults, aligned NNE-SSW.

The Connecting Point Group also underlies Long Island. Northeast-southwest trending faults split Long Island diagonally at North Wild Cove-Harbour Buffett, Port Royal Cove-Collett Cove, Hennesy Cove-Southwest Cove, and at Spencers Cove. Northeast-southwest faults also have isolated the Haystack and formed Haystack Harbour, and separate Bread Island, Cheese Island, and the Jerseyman from Long Island Point. Long Island thus consists of a series of blocks of resistant sandstone and conglomerate strata of the Connecting Point Group, separated by faults.

The youngest Late Proterozoic sedimentary and metasedimentary rocks are assigned to the Musgravetown Group, correlative to exposures on the Avalon Peninsula. Rock types include conglomerates, sedimentary breccias, arkosic and greywacke sandstones, orthoquartzites and felsic quartzites, siltstones, argillites, shales, and slates. Lesser mafic intrusions and flows, and isolated tuffs and volcanic breccias are also included in the Musgravetown Group. The eastern shore of Paradise Sound represents a typical coastline developed in Musgravetown rocks.

Late Proterozoic igneous activity includes mafic units, although granitic plutons are dominant. The Swift Current Granite has the largest areal extent of these Late Proterozoic units, exposed along both shores of the Swift Current embayment and estuary inland to the rapids at Bear's Folly. The granite has weathered to produce domal hills, such as Grip's Nest and Toby Lookout, separated by undulating depressions.

Cambrian sedimentary rocks are present on the western and northern fringes of Red Island (e.g. Blue Point, west side of Wild Cove), on Little Seal and Great Seal Islands, at Rose-au-Rue Point (Merasheen Island), at Baker Cove, and along the northeastern shore of Paradise Sound in a fault-bounded block. Most coastal exposures of these units are resistant orthoquartzite sandstones of the Lower Cambrian Random Formation. Also present are readily erodable shales and slates, and somewhat more resistant algal limestones, assigned to the Bonavista, Smith Point, and Brigus Formations of the lower part of the Adeyton Group.

The youngest rocks exposed along the shores of northwestern Placentia Bay are Devonian igneous plutons, including the Red Island, Ragged Islands, and Sail-the-Maid granitic suites, and the Powder Horn diorite-gabbro complex. The irregularly crenulated shoreline of Red Island, marked by numerous small geos embayments (notably at Rocky Cove) is typical of those developed on Devonian plutons.

The Burin Peninsula and northern Fortune Bay contain some of the same lithologic units found around northwestern Placentia Bay and on the Avalon Peninsula. Other strata are correlative to those found to the east. Additional older and younger units are present, however. The oldest unit is the Proterozoic Corbin Head Formation, consisting of breccias, sandstones, siltstones, and argillites. Outcrop of this unit is confined to a small area of Corbin Head and the islands directly offshore.

The Late Proterozoic Burin Group is dominated by volcanic rocks. Pillow basalts, formed by submarine volcanic eruptions, are found at Pardy Island, Port-au-Bras, Spanish Room, and Beau Bois, among other sites. The pillow basalts are susceptible to chemical weathering under a boreal climate, but physical weathering is confined to frost exploitation of the curved pillow contact surfaces. Where aligned horizontally, the pillow basalts form resistant shelves and platforms. The Wandsworth tholeiitic gabbro, quartz diorite, and granodiorite form resistant shorelines at Wandsworth and Epworth, south of Burin. Lesser thicknesses of limestone, argillite, and siltstone are also included within the Burin Group. These rocks are more readily eroded than the volcanic units, as is evident at Sculpin Point.

The next youngest Late Proterozoic strata are assigned to the Love Cove Group. These strata, consisting of volcanic rhyolite porphyries, felsic and mafic tuffs, ignimbrites, basaltic and other mafic lava flows, and associated volcanic breccias, volcanogenic sandstones and conglomerates, and metamorphosed shales, are correlative to those exposed to the north along Placentia Bay. Typical shorelines developed in Love Cove Group rocks are found in the Baine Harbour area, on the eastern of the Flat Islands, and at Point Enragee.

The Marystown Group stratigraphically overlies the Love Cove Group in part, and in part is laterally equivalent to the younger units within the Love Cove Group. The Marystown Group is also of Late Proterozoic age. Coastal morphology associated with the Marystown Group depends upon aspect and lithology. Along the northeastern shore of Taylor's Bay, resistant rhyolitic flows and silica-rich tuffs alternate with less resistant basaltic flows, mafic-rich tuffs, and unwelded beds of Late Proterozoic tephra. The concave shoreline north from Taylor's Bay Point is developed in the less resistant mafic material, with the promontory at supported by rhyolite. Flow-banded rhyolites crop out on Point-au-Gaul to the southwest, affording protection to the basaltic rocks from waves driven by southwesterly winds. In contrast, waves from the southeast, notably the tsunami resulting from the earthquake of 18 November 1929, are funneled into Taylor's Bay around the resistant Point-au-Gaul and Squid Point. Similarly, the tsunami was funneled into the adjacent Lamaline Bay by Point-au-Gaul on the east and Allan's Island on the west.

The Garnish Formation, another stratum included within the Marystown Group consists of resistant clastic rocks, including granule-cobble conglomerate and sandstone. This unit crops out along the coastline at Garnish, forming a resistant cliff. Less resistant shales associated with the Garnish Formation have been eroded east of Lanse-au-Loup Point to form a recessive shoreline. Similar geomorphic variation in response to lithological changes is evident in the shoreline developed in the Calmer Formation, between Lamaline and Calmer. This unit, also contained within the Marystown Group, consists of resistant rhyolite and plagiophyric flows, less resistant mafic flows and tuffs, volcanic breccias varying greatly in susceptibility to erosion, and weak chlorite schists. Exposure of these rock types in succession along the shore produces a crenulated pattern, where the rock is not overlain by younger Quaternary sediments.

The youngest Late Proterozoic sedimentary units exposed on the Burin Peninsula are included in the Rock Harbour Group. The type area is located at Rock Harbour, east of Spanish Room. Here, siltstone, sandstone, and conglomerate of varying resistance crop out along the shoreline, producing a crenulated topography.

Late Proterozoic igneous rocks are also present on the Burin Peninsula. These include the Swift Current granite, Cape Roger Mountain granodiorite, Anchor Drogue granodiorite, Seal Cove quartz diorite/granodiorite, and the Laughlin's Hill gabbro. Outcrops of these units along the shore, however, are rare. Granodiorites and granites, such as the Seal Cove pluton south of Frenchman's Cove Provincial Park and those exposed east of Jacques Fontaine, are resistant to erosion and form straight, non-embayed shorelines. The Laughlin's Hill gabbro does not crop out along the shore.

The Burin Peninsula is noted for its sequence of Eocambrian and Cambrian sedimentary rocks. Eocambrian rocks, straddling the Cambrian-Proterozoic boundary, are represented by the Admirals Cove Formation (red pebble conglomerate overlain by red micaceous mudstone and fine sandstone); the Grand Bank Formation (grey and green siltstones); and the Bay View Formation (red micaeous sandstone and green siltstone, with thin beds of resistant orthoquartzite). With the exception of the thin orthoquartzite beds in the Bay View Formation, all of these units are friable and subject to wave attack. Along the shoreline, they are generally covered by Quaternary material and are exposed only at the bases of bluffs or on subaqueous platform surfaces. In the Grand Bank area, the Admirals Cove and Grand Bank Formations (Fortune Group) are exposed at the base of Grand Bank Head. The Grand Bank Formation also forms low cliffs and platforms along the shoreline southwestward from Fortune to Great Dantzic Cove, and in the Point Crewe area. Strata of the Admirals Cove Formation have been eroded to form Lannon Cove and the shallow embayments at Lories and the community of Point May, partially protected to the southeast by resistant Marystown Group strata at Point May. Resistant strata of the Bay View Formation (Inlet Group) form the coastline at Lawn Head.

Lower Cambrian shales of the Salt Pond Formation (Inlet Group) are readily eroded along the margins of Burin Inlet at Burin Bay Arm, and at the mouths of Little Salmonier and Big Salmonier Brooks. The readily erodable Salt Pond Formation has been scoured into an oval basin protected from Placentia Bay by the resistant Wandsworth gabbro to the south. The equivalent strata of the Fortune Group in the Fortune area consist of friable mudstones of the Fortune River Formation, and resistant quartzites of the Pieduck Point Formation.

The youngest Cambrian rocks are Middle Cambrian shales, siltstones, and limestones, assigned to the Little Dantzic Cove Formation (Fortune Group) in the Fortune area, and to the Pleasant View Farm Formation (Inlet Group) in the Burin Inlet area. These formations are friable, eroding to form embayments.

Devonian and Early Carboniferous granitic intrusions, associated with the Acadian Orogeny and correlative to the Devonian intrusions of the Belloram and northwest Placentia Bay areas, crop out inland but do not form shorelines. The youngest granite pluton in the area is the

Carboniferous St. Lawrence alkaline/peralkaline alaskite, which underlies glacial sediments along the shoreline at the heads of Great St. Lawrence and Little St. Lawrence Harbours.

The youngest sedimentary rocks are the friable sandstones and siltstones, and more resistant conglomerate, of the Terrenceville Formation; and the friable limestones, black shales, and breccias, and more resistant conglomerates of the Spanish Room Formation. Both these units are of Carboniferous age, and have very limited areal extent. The Devonian-Carboniferous Grand Beach Complex, consisting of rhyolitic ash flow tuffs, rhyolitic porphyries, volcanic breccia, and vesicular basalt, crops out in the Grand Beach area.

The faults of the Burin Peninsula are not tectonically active at present. Offshore earthquakes, however, have occurred on the Grand Banks. The most recent major earthquake to affect eastern Newfoundland, the Grand Banks earthquake of 18 November 1929, triggered a destructive ocean wave (tsunami) event which affected coastal communities in the Burin Peninsula, killing 28 people (Ruffman 1991, 1995; Anderson *et al.* 1995). On the southern Avalon Peninsula, a destructive wave which washed ashore at St. Shotts in 1864 may have also been a tsunami due to an offshore earthquake (Alan Ruffman, Geomarine, Halifax, personal communication). With the exception of the 1929 event, however, no tsunami deposits have been recognized and there are no other confirmed accounts of tsunami events in the region. Large, destructive waves which have caused substantial damage and loss of life in coastal areas have been associated with storm activity rather than with earthquakes.

4. Quaternary History and Sediments

4.1 Glacial Chronology

The Quaternary period of geological time is defined in the Northern Hemisphere to encompass the time from the initiation of continental glaciation in North America, up to the present instant. The Quaternary is subdivided into the Pleistocene and Holocene Epochs. The Pleistocene is the earlier epoch of the Quaternary period, and is characterized by extensive glacial activity, particularly in eastern North America. The age of the lower boundary of the Pleistocene epoch is not firmly established, and the criteria employed by glacial researchers, terrestrial palaeontologists, marine palaeontologists, climatologists, marine specialists, and sedimentologists and stratigraphers working in unglaciated areas differ considerably. Consensus among Quaternarists indicates that extensive continental glaciation capable of influencing world climate developed in the northern hemisphere between 2.5 and 3 million years ago, suggesting that these time values should represent the commencement of the Quaternary period and the Pleistocene epoch.

The younger Holocene Epoch (also termed 'Recent') is the final epoch of the Quaternary. The Holocene/Pleistocene boundary has been arbitrarily defined at precisely 10,000 years B.P. by several International Quaternary and Stratigraphic Commissions, and this definition is generally accepted in North America and glaciated Europe. A type section for the Holocene/Pleistocene series boundary near Göteborg, Sweden has been proposed, but has not as yet won general acceptance. As many events transgress the arbitrarily-defined 10,000 year B.P. boundary between the Pleistocene and the Holocene, "Quaternary" has largely replaced "Pleistocene" as the preferred time term used by researchers working with the last 3 million years. The term 'Holocene', however, is generally used.

The onset of Quaternary glaciation in the Northern Hemisphere saw the formation of glaciers ranging in size from individual cirques, confined to a single mountain, to continent-wide complexes of glaciation. The Quaternary was marked by multiple glacial advances, lasting on the order of 50,000-100,000 years each, termed 'glacials'. The glacials were separated by interglacials, times of minimal glacial activity or retreat. Interglacial deposits are generally recognized through their palaeoenvironmental indicators, and usually the inferred climate must be comparable to or warmer than the region's present climate.

The glacials are further subdivided into 'stadials' (periods of glacial advance) and 'interstadials' (times of lesser glacial activity separating two subordinate stadial episodes of glacial expansion. Stadials and interstadials are shorter and generally more regionally restricted events than are glacials and interglacials. Interstadial deposits are generally recognized through their palaeoenvironmental indicators, and usually the inferred climate is considerably more conducive to glacial expansion than the region's present climate. Some interglacials have also been subdivided into interstadials and stadials.

The Wisconsinan was the last major glacial, *ca.* 80,000 BP to 10,000 BP (Table 4-1). The Wisconsinan is divided into the Early Wisconsinan Stadial (80,000-50,000 BP), the Mid-Wisconsinan Interstadial (50,000-28,000 BP), and the Late Wisconsinan Stadial (28,000 -10,000 BP). Late Wisconsinan ice was responsible for the formation of most of the glacial landforms and sediments of eastern Canada. In eastern Newfoundland, glaciers followed the preexisting faults and embayments, modifying the topography. The terrain which existed prior to the Late Wisconsinan glaciation did not differ greatly in relief or form from that which was exposed when the glaciers ablated at the conclusion of the episode.

Table 4-1. Quaternary chronology and events, eastern Newfoundland.

Subdivision of Quaternary Period	Duration	Events
Holocene	0-10,000 BP	establishment of vegetation
Late Holocene	0-3,000 BP	rising sea level
Mid-Holocene	3-7,000 BP	lower sea level
Early Holocene	7-10,000 BP	falling sea level
Late Wisconsinan	10-28,000 BP 11,000 BP 14,000 BP	Glaciation; ending prior to elevated sea level following beginning of deglaciation *ca.*
Mid-Wisconsinan	28-50,000 BP	Glaciation; sea level lowered
Early Wisconsinan	50-80,000 BP	Glaciation; sea level lowered
Pre-Wisconsinan Events	± 110,000 BP	Langlade beds deposition, Burin Peninsula & Miquelon
	>110,000 BP	Main Brook Till deposition, Burin Peninsula

Although eastern Newfoundland has been the subject of prior investigations, the timing and number of glacial events which affected the region during the Quaternary is uncertain. The Burin Peninsula is the only part of the region which contains Quaternary sediments definitely deposited during pre-Wisconsinan events. Grant (1989) and Tucker and McCann (1980) documented evidence of four glacial episodes and a marine event on the Burin Peninsula. The oldest event, and the only one which definitely predates the Wisconsinan, was responsible for deposition of the Main Brook Till. The Main Brook Till underlies the Langlade Silt, and is tentatively linked to weathering zones recognized in the Long Range Mountains of Newfoundland. At present, the assumed age of the Main Brook Till is dependent on the assigned age for the overlying Langlade Silt.

The Langlade Silt beds represent one of few Quaternary deposits that predate the most recent, Late Wisconsinan glaciation. The Langlade Silt beds have been assigned ages from Mid-Wisconsinan interstadial (Oxygen-Isotope stage 3), to pre-Wisconsinan interstadial (5a), to Sangamonian (5e) (see discussion in Grant 1989). Reliable numerical dating of the deposit has not been achieved. The Langlade silt contains floral and faunal remains indicative of a warmer climate and warmer ocean waters along the Burin coast.

Deposits predating the Late Wisconsinan were also recognized in the Head of Bay d'Espoir, Pass Island Tickle, and Little Barasway areas (Leckie 1979; Leckie and McCann 1983). A foraminiferal assemblage preserved in marine sediments at Little Barasway has been interpreted to represent nearshore-estuarine conditions by Vilks (in Leckie and McCann 1983), although similar assemblages have more recently been suggested to represent glacial-marginal conditions (Miller 1999). These deposits have not been numerically dated, and cannot be directly correlated to those exposed on the Burin Peninsula.

In common with all other areas of Newfoundland, there are two schools of thought concerning the extent of Late Wisconsinan ice sheets. The "maximalist hypothesis" envisages extensive ice sheets sweeping across the entire land and marine region of eastern Canada in Late Wisconsinan time. The "minimalist hypothesis", however, presents a contrasting view involving restricted coverage by Newfoundland-based ice during the Late Wisconsinan, confined largely to terrestrial areas and not extending offshore in most localities (see summary in Grant 1989).

For the Burin Peninsula and the South Coast, Grant (1989) presented two models. The minimum concept suggested that Late Wisconsinan ice terminated at the northeasternmost margin of the Burin Peninsula, along the Burin Moraine in the Terrenceville area. Extension of this concept to the South Coast suggests that the tips of the Connaigre Peninsula, the area south and west of Harbour Breton, and much of Bay d'Espoir, remained unglaciated during the Late Wisconsinan (Leckie 1979; Leckie and McCann 1983). The alternative maximum concept of Grant (1989) suggested that the entire Burin Peninsula, and all of the South Coast, were covered by Late Wisconsinan glacial ice, including southwestward flow from the interior of Newfoundland and northwestward flow from an offshore ice centre in Placentia Bay. The Burin Moraine would represent a recessional, Latest Wisconsinan event under this hypothesis.

These two models have substantially different implications concerning sea-level history, the palaeo-oceanology of the Grand Banks during the Last Glacial Maximum, and the regional correlation of glacial events throughout eastern Newfoundland. Ongoing research in the Burin and South Coast regions is under way to assess the relative applicability of these two models. The data from preliminary investigations, however, suggests that the 'maximum' concept viewpoint seems to be more reasonable. The offshore record (discussed below) also suggests that terrestrial ice reached the coastline of the Burin Peninsula during the Late Wisconsinan, and that the Burin Moraine represents a recessional event in the latest part of the Late Wisconsinan.

Previous research (Widmer 1950; Tucker and McCann 1980; Grant and King 1984; Grant 1989) has led to suggestions that the Burin Peninsula was glaciated by a combination of local ice cap activity; by two or more ice lobes originating from the main part of Newfoundland, flowing southward across Fortune and Placentia Bays; and by ice flowing northwestward from an offshore centre in Placentia Bay. The investigations along the south coast of the Burin Peninsula, which Grant (1989) used to suggest that flow from an offshore source in Placentia Bay could have occurred, were based primarily upon striation analysis and other erosional indicators. Although more research needs to be conducted, preliminary work suggests that the major glacial features were formed as two streams of southward-flowing ice from the interior of

Newfoundland impinged upon the Burin Peninsula from both the Fortune Bay and Placentia Bay coasts.

Studies have also been conducted in the offshore areas. Fader *et al.* (1982) determined that the shelf southeast of Newfoundland was extensively glaciated during Late Wisconsinan time. King and Fader (1986) compiled a composite stratigraphic section for Placentia Bay. Benthic foraminifera within the sediments indicate subglacial, ice-proximal, and ice-distal environments (cf. Miller 1999). Fader *et al.* (1982) suggested that the western banks were covered with buoyant Late Wisconsinan ice that was in contact with the seabed over bedrock topographic highs. Large recessional moraines, including the Burin Moraine which continues eastward into Placentia Bay for at least 97 km, were formed at this time.

In Halibut Channel, Bonifay and Piper (1988) recognized a late glacial surge (dated at 11.5-12 ka) extending to the continental slope off St. Pierre Bank, linked with terrestrial-based ice to the north. Miller (1999) completed an integrated study and interpretation (lithology, physical properties, seismostratigraphy and foraminiferal analyses, coupled with chronological control) of a succession of glacial-marine and glacial till sediments in southern Halibut Channel. This investigation suggests that Late Wisconsinan ice was grounded on the outer banks and separated from Newfoundland-centred ice by either floating ice or open water. The sequence shows evidence of three glacial advances: an early event; a second, dating from Mid-Wisconsinan or the initial part of the Late Wisconsinan (between 41 ka and 19 ka BP); and a third following the terrestrial Late Wisconsinan Glacial Maximum (13-11 ka BP). The youngest ice advance corresponds to that advance recognized by Bonifay and Piper (1988), although the seismostratigraphy indicates that this advance was centred offshore in southern Halibut Channel. The sediment record suggests that the Burin Moraine is correlative with the youngest till in outer Halibut Channel, and hence the moraine is also of Latest Wisconsinan age.

The coastline of Trinity Bay north of Sunnyside was also glaciated during the Late Wisconsinan. Eastward-moving ice glaciated the coast from the Middle Ridge area southwest of Terra Nova National Park. The park was ice-covered throughout the Late Wisconsinan. At its maximum extent 20,000 years ago, glacial ice covered all of Bonavista and Trinity Bays and extended more than 100 km offshore. Erosional roche moutonnées and striations and deposits of glacial till indicate that the ice flowed northeastward and eastward towards the coast.

Ice from the Middle Ridge area also covered the western part of the Isthmus of Avalon. The presence of clasts derived from outcrops of Palaeozoic granite to the northwest (Swift Current area), and the silty texture of the diamictons resulting from the incorporation of marine sediments from Placentia Bay (Stehman 1976; Willey 1976), indicate ice flow from the Newfoundland mainland (Henderson 1972; Vanderveer 1977; Catto 1998a). Throughout the area north of Pumbly Cove and Tickle Bay, striations and bedrock streamlined features indicate that ice flowed across the isthmus, directly into Trinity Bay, and continued to flow to the northeast. The deep embayment acted to funnel the flow seaward. Large quantities of sediment, including granitic clasts, were transported seaward, resulting in the construction of a moraine at the grounding line at the mouth of Trinity Bay (King and Fader 1992). Ice also flowed southward along the Central and Eastern Channels of Placentia Bay, across Merasheen, Long, and Red Islands, terminating in Placentia Bay.

The glacial history of the Avalon Peninsula has also been investigated. Erratic boulders and glacial features on the Avalon Peninsula were recognized by several early researchers (Jukes 1842, 1843; Kerr 1870; Milne 1874, 1876, 1877; Packard 1876). The 'maximum' and 'minimum' concepts, summarized by Grant (1989), emerged shortly after these initial studies. Several authors, including Murray (1883), Flint (1940), Twenhofel and MacClintock (1940), and Tanner (1944), suggested that the Avalon Peninsula was glaciated by ice originating to the northwest, either from the main part of Newfoundland or from the Laurentide complex based in western Labrador. In contrast, Chamberlin (1895), Coleman (1926), and Summers (1949) suggested that the Avalon Peninsula had been covered by an independent, radially-flowing ice cap.

A comprehensive study of Quaternary events on the Avalon Peninsula was undertaken by Henderson (1972), who recognized that the Avalon Peninsula had supported independent ice caps throughout the Wisconsinan. Ice from the mainland of Newfoundland overrode the Isthmus of Avalon from Placentia Bay to Trinity Bay, but was precluded from covering the remainder of the peninsula by Avalon-based local glaciers.

Henderson (1972) recognized three distinctive glacial source areas on the Avalon Peninsula. He suggested that the Placentia and Trepassey sub-peninsulas, southeastern Trinity Bay, and southern Conception Bay were glaciated by ice flowing radially from a source in St. Mary's Bay, in the vicinity of Great Colinet Island. Ice divides were also recognized on the St. John's and Carbonear sub-peninsulas by Henderson (1972). Ice flowed seaward from a linear divide along the axis of the St. John's sub-peninsula, reaching the coastlines of Conception Bay north of Holyrood and the Atlantic Ocean north of Bay Bulls. On the Carbonear sub-peninsula, Henderson (1972) identified ice flow seaward from a divide aligned along the axis of the peninsula.

Rogerson and Tucker (1972) suggested that glacial retreat was marked by progressive recession from the coastal areas to the highest parts of the interior plateaux, particularly the Hawke Hills. The backwasting hypothesis for the Hawke Hills area was countered by Macpherson (1982, 1996). On the basis of palynological research, Macpherson argued that the uppermost summits were deglaciated before the lowermost areas, and suggested a down-wasting model for the northeastern Avalon Peninsula (Macpherson, 1996). Vanderveer (1975, 1977) mapped most of the Avalon Peninsula and all of the isthmus. He identified additional striation sites and streamlined bedrock forms, the orientations of which were generally compatible with Henderson's (1972) model of ice flow.

Recently, analysis of the available data has revealed a complex pattern of glaciation throughout the Avalon Peninsula, marked by shifting accumulation areas and variable directions of flow. Three major phases of glaciation, each involving several distinct ice centres, can be recognized (Catto 1992a, 1993a, 1994a, 1995, 1998a, 1998b; Catto and Taylor 1999).

Phase 1 was marked by the accumulation of ice at centres located along the axes of the major sub-peninsulas, and by expansion seaward. Ice advanced from centres located in the Heart's Content Barrens and the headwaters of Western Bay Brook to cover the Carbonear Sub-Peninsula north of Harbour Grace, reaching both Trinity and Conception Bays. Ice flow from centres at White Hearts Pond (south of Markland) and Franks Pond (Avalon Wilderness Area) reached the Conception Bay shoreline between Harbour Grace and Black Ridge (northwest of Holyrood). The Conception Bay South area was covered by ice originating from the Witless Bay Barrens, flowing northwestward across the bay to cover Bell Island. Ice from the Frank's Pond Centre expanded eastwards to reach the southern Shore, and westwards to reach St. Mary's Bay. The northeast Avalon was covered by ice from the Witless Bay Barrens Centre.

The shoreline of southeastern Placentia Bay was glaciated by ice moving westwards and west-northwestwards from the Castle Ridge ice centre. Ice flowed radially from this centre towards Placentia Bay and St. Mary's Bay, coalescing with other glaciers to the north and east. Tongues of Castle Ridge ice reached the coastline of Placentia Bay through river valleys south of Placentia Roads. Initially, the ice was diverted parallel to the coastline, generally towards the southwest. Subsequently, as the glacier grew and thickened, flow was reoriented normal to the coast, and the converging flow noted in the larger embayments was replaced with a more regionally consistent northeast to eastward flow pattern. The expanding Castle Ridge ice covered the Placentia Bay shoreline south to St. Brides, and expanded over the entire sub-peninsula to Cape St. Mary's.

As no direct indication of the date of initiation of glaciation on the Avalon Peninsula exists, and no preglacial deposits have been recognized, Phase 1 could represent any part or all of the period between the initiation of glaciation and the Last Glacial Maximum. In addition, the individual ice centres of Phase 1 need not have developed synchronously. The absence of weathering features and non-glacial deposits suggests that the conclusion of Phase 1 was directly followed, without intervening deglaciation, by Phase 2. This relationship of Phase 1 in an apparent continuum with the glacial maximum of Phase 2 suggests a Wisconsinan age for the transition between the phases. The time of initiation of any part of Phase 1 glaciation, however, remains uncertain.

During Phase 2, all parts of the Avalon Peninsula were glaciated, and the ice extended beyond the modern shoreline. This phase was marked by the development of the St. Mary's Bay ice centre, as recognized by Henderson (1972). Ice expanded from St. Mary's Bay, covering most of the Avalon Peninsula. Flow from the St. Mary's Bay Ice Centre crossed the spine of the Placentia sub-peninsula, and expanded westward beyond the shoreline of Placentia Bay. Independent centres persisted in the St. John's and Carbonear sub-peninsulas and on the Isthmus of Avalon. Ice from the Newfoundland mainland overran the northern part of the Isthmus, and extended as an ice stream into Trinity Bay.

As the St. Mary's Bay Ice Centre could not develop until sea level had fallen to at least 65 m below its present value, its existence is directly associated with the drop in sea level precipitated by the widespread glaciation of the Northern Hemisphere. The initiation and duration of the St. Mary's Bay ice centre thus coincide with the period of maximum glacial activity in eastern Canada.

A Late Wisconsinan age for the conclusion of Phase 2 is suggested by the absence of weathering features or subaerial deposits separating the Phase 2 landforms and sediments from those of Phase 3. The time of initiation of Phase 2, however, is less certain. Although the Late Wisconsinan maximum of the Laurentide Inlandsis occurred *ca.* 22,000-16,000 BP (Dyke and Prest 1987; Grant 1989; Vincent 1989; Piper *et al.* 1990), the St. Mary's Bay ice centre could have begun to accumulate as soon as relative sea level fell below approximately -65 m. Thus, the initiation of Phase 2, and the duration of the preceding Phase 1, could have preceded the Late Wisconsinan Laurentide maximum.

Approximately 14,000 years ago, Phase 3 was initiated when the St. Mary's Bay glacier began to melt and disintegrate. Existence of the St. Mary's Bay Ice Centre depended upon sea levels substantially lower than that at present. Under current sea level, the modal depth of the bay south of Great Colinet Island is 120 m, and some areas adjacent to the ice accumulation centre exceed 150 m depth. The pattern of flow associated with the St. Mary's Bay Ice Centre, involving radial flow towards land masses on three sides, also indicates that a lower sea level precluded excessive drawdown to the open ocean to the south. South of St. Mary's Bay, sea level during the Late Wisconsinan Laurentide maximum was at least 110 m lower than at present. As the maximum depth in the mouth of the bay, over St. Mary's Bank, is 65 m, St. Mary's Bank and the Grand Banks would be above sea level and the centre of St. Mary's Bay would be isolated from the ocean.

When the glacial ice in Labrador and along the eastern seaboard of North America began to melt, *ca.* 15,000-14,000 BP (Dyke and Prest 1987; Piper *et al.* 1990), rising sea level caused the ice mass in St. Mary's Bay to disintegrate rapidly. The subsequent deglacial Phase 3 of ice flow activity was marked by the collapse of the major ice flow centres, and the initiation of flow from several short-lived ice centres in the headwaters of Northern Bay Brook and on the Bay de Verde Peninsula. Flow also continued from the ablating centres on the Heart's Content Barrens, and on the Witless Bay Barrens. Although this event was the most recent glacial phase to affect the entire Avalon Peninsula, its effect on the landscape was limited in most instances. Deglaciation of all of the Avalon Peninsula was completed before 10,100 BP, as indicated by a ^{14}C date of 10,100 " 250 B.P. (GSC-3136) from Golden Eye Pond in the Hawke Hills (Macpherson 1995, 1996).

Palynological and diatom analyses (Macpherson and Anderson 1985; Macpherson 1990; Anderson and Macpherson 1994; Wolfe and Butler 1994) have established the succession of vegetational events following deglaciation in Newfoundland. Following deglaciation, coastal areas were colonized by sparse herb-shrub tundra assemblages. Throughout the Latest Wisconsinan to early Holocene, *ca.* 12,000 BP to 8,500 BP, Anderson and Macpherson (1994) recognized three post-glacial cooling episodes, of which only the second is represented in eastern Newfoundland. This episode, recognized throughout Atlantic Canada (Levesque *et al.* 1993, Stea and Mott 1993), is dated from *ca.* 11,100 to 10,400 BP and correlates to the European Younger Dryas cooling event (Wright 1989, Peteet 1995, Isarin 1997). Although precise ^{14}C dating in this time interval is complicated by plateau effects (Bard and Broecker 1992, Sulerzhitsky 1997) and local contamination problems (Anderson and Macpherson 1994), the available dates constrain the cold period to approximately 700 years between 11,100 ± 120 and 10,400 ± 110 BP (Anderson and Macpherson 1994). This event is recorded in pollen spectra across Newfoundland, with the exception of those from the Avalon Peninsula and the Bonavista Peninsula (Macpherson 1996). Diatom analyses from Pine Hill Pond in Terra Nova National Park reveal a similar pattern of climate fluctuation (Wolfe and Butler 1994). Periglacial features attributed to this event have been recognized at Swift Current, Port Blandford, and Point Verde (Liverman *et al.* 2000).

After 10,000 BP, the climate warmed rapidly, and the last glacial ice disappeared from the interior of Newfoundland shortly thereafter. As temperatures rose, trees began to establish themselves in eastern Newfoundland, with initial colonization by black spruce and shrubby birch being followed by the arrival of balsam fir, tree birch, red pine, and red maple. The critical indicator species in this area is red pine (*Pinus resinosa*), which is currently confined to 10-12 sites in sheltered locations in the Gander area, near Buchans, and surrounding the village of Terra Nova (Ryan 1978, Damman 1983). During the early-mid Holocene, *ca.* 6,000 B.P., red pine expanded its range to the coast in central Newfoundland (Macpherson 1993a, 1993b).

This vegetation assemblage persisted until the climate began to cool, *ca.* 4000 years ago, allowing peat development to begin in most regions of north-central Newfoundland (Davis 1993). Fens and bogs expanded throughout the study region. Analysis of a blanket bog in the St. Shotts area indicates the peat accumulation began *ca.* 5,000 B.P., when increased moisture retention in the soil (probably due to decreased evapotranspiration) caused the heathland vegetation to be replaced (Irwin 1993). This area has not supported arboreal vegetation throughout the late Holocene. Oscillations between drier (*ca.* 2300 -*ca.* 1500 B.P.) and wetter (*ca.* 1170 B.P.) conditions are indicated by fluctuations in the palynological assemblages (Irwin 1993).

4.2 Glacial and Glaciofluvial Sediments

The distribution of glacial and other Quaternary sediments throughout eastern Newfoundland has been mapped at 1:50,000 scale (Catto 1992, 1993a, 1994a, 1998b; Catto and Taylor 1999; Catto *et al.* in preparation; Batterson in preparation; Sommerville 1997; Vanderveer 1975; also see Leckie 1979; Brookes 1989). Glacial sediments produced during the Late Wisconsinan are primarily diamictons, containing particles ranging in size from clay to boulders. Most of the diamictons of eastern Newfoundland are characteristically coarse-textured, with silt concentrations of <2%-30%, and large clasts (pebbles, cobbles, and boulders) comprising 30%-55% of the sediment (Henderson 1972, Catto and Thistle 1993, Catto and St. Croix 1997, Sommerville 1997).

The diamicton assemblages are dominated by debris flow and slurry flow deposits, with other reworked sediments. Primary ‘till’, deposited directly from glacial ice with little or no subsequent modification, is relatively rare. Although the majority of the diamictons were glacially transported, and were most likely initially deposited as till, most have undergone substantial amounts of reworking since the initial deposition. Therefore, most deposits do not preserve a primary glacial signature, and hence cannot be regarded as "till". The distribution and genesis of these diamicton deposits have been discussed elsewhere (Catto and St. Croix 1997; Catto 1998a).

Shoreline diamicton cliffs are moderately resistant to erosion, and are commonly flanked by a fringing barricade of glacially-transported boulders which have remained after marine waters have removed all of the smaller clasts. These boulder barricades act to stabilize the coastline, and will largely preclude further marine erosion unless sea level rises substantially.

Glaciofluvial gravel and sand units are formed by the discharge of subglacial rivers, and in areas where streams debouching from the glaciers have transported and reworked glacial deposits. Glaciofluvial sediments are typically present marginal to the major rivers and at the heads of fjords and embayments (Catto 1997; Catto and Taylor 1999). They locally form bluffs to 15 m height. Locally, these deposits are susceptible to coastal erosion, and contribute coarse material to gravel-dominated coastal landforms.

The largest expanse of glaciofluvial sediment flanks the coastline from Topsail Beach southwestward to Holyrood, locally forming bluffs to 25 m height. These sediments form a series of laterally coalescent kames and kame deltas, developed as meltwater debouched northward from the retreating glacier standing along the margin of Conception Bay. The glaciofluvial deposits are locally capped by peat veneers and blankets, as at Upper Gullies and Seal Cove (Catto 1994a; Catto and St. Croix 1997). Their presence along the coastline of Conception Bay has contributed to the susceptibility of this area to coastal erosion, and to the development of gravel-dominated mixed sediment shoreline features.

4.3 Sea Level Fluctuations

During glaciation, sea level was lower than at present around eastern Newfoundland, because large volumes of water were frozen in the major Laurentide Inlandsis glacier complex centred in Labrador (Table 4-1). The thickness and areal extent of the St. Mary's Bay glacier, and the other smaller glaciers on the Avalon Peninsula were not sufficient to overcome the glacio-isostatic distortion induced by the much larger Laurentide Inlandsis. Although the Middle Ridge glacier and the other glaciers centred in the interior of Newfoundland were larger, the pattern of Late Wisconsinan marine features throughout Newfoundland (Liverman 1994) indicates that glacio-isostatic deformation and sea levels were controlled almost exclusively by the Laurentide Inlandsis.

As deglaciation began, sea level rose throughout eastern Newfoundland. The isostatic depression of the land surface allowed marine waters to reach up to 55 m asl at St. Veronicas, 35 m asl at the head of Hermitage Bay, 25 m asl at McCallum and Rencontre East, and 15 m asl at English Harbour West and Pass Island. All areas of the South Coast were subjected to marine inundation. Raised marine deposits in the Hermitage area (Leckie 1979; Leckie and McCann 1983; Shaw and Forbes 1995; Shaw in preparation) and in the English Harbour West-Boxey area are similar texturally to those formed along the modern beaches.

Similar elevated sea levels are recorded along Bonavista, Trinity, and Conception Bays. Sea levels up to 35 m above the present shoreline are recorded by terraces at Eastport, Traytown, and Little Sandy Cove, Bonavista Bay and by erosional benches at Charlottetown (Sommerville 1997). At St. Chad's, north of Eastport, shells of the marine mollusc *Hiatella arctica* indicate that the sea stood about 40 m above its present elevation *ca.* 12,400 BP. Near Port Blandford, marine clays preserved in coastal bluffs also indicate higher sea levels. Around the shoreline of Conception and Trinity Bays, higher sea levels carved erosional benches and deposited gravel terraces at elevations between 5 m and 20 m above sea level, with the northwestern shore suffering the greatest inundation and the southern tips the least (Catto and Thistle 1993, Catto 1994 b, Liverman 1994). A similar picture is evident along the east shore of Placentia Bay north of St. Brides, and along the western shore north of Marystown. After the initial latest Wisconsinan deglaciation, sea level varied from its present elevation near St. Brides and Marystown, to 20 m asl at Swift Current.

Earliest Holocene sea level history was substantially different on the southernmost part of the Burin Peninsula, and along the open Atlantic coastline south of Cape St. Francis, where raised marine features have not been recognized. Cores taken from St. John's Harbour indicate that a freshwater lake existed shortly after deglaciation, *ca.* 11,000 year B.P. (Lewis *et al.* 1987). This suggests that sea level at this time was at least 14 m below present, the elevation of the controlling sill in The Narrows. Marine transgression is recognized by a transition from a brackish thecamoebian (*Centropyxis aculeata*) to a marine foraminiferal assemblage, *ca.* 9,900 B.P.

Sea level in St. John's Harbour appears to have remained below present throughout the Holocene. No raised marine deposits have been encountered in excavations in downtown St. John's, although marine deposits at elevations to 5 m above sea level are present along the southern shore of Conception Bay at Portugal Cove, St. Philips, and Conception Bay South (Brückner 1969; Catto and Thistle 1993; Catto and St. Croix 1997).

Interpretation of the earliest Holocene sea level history of the southernmost Burin Peninsula is complicated by the uncertainty concerning the chronology and extent of the Late Wisconsinan glaciation. Raised marine features recognized by Tucker *et al.* (1982) were attributed to pre-Late Wisconsinan events, at least partly under the assumption that Late Wisconsinan glaciation did not extend to the south of the Burin Moraine in the Terrenceville area. These features, however, could be of Latest Wisconsinan-earliest Holocene age if the entire Burin Peninsula was glaciated in Late Wisconsinan time. Further research is required to resolve this question.

At Lears Cove, north of Cape St. Mary, Placentia Bay, benches cut in bedrock extend to 6 m asl. The age of these features is controversial. Grant (1989) considered the benches to be wave-cut features, the product of a sea level higher than present, and suggested that they were of Sangamonian age, predating the Wisconsinan glaciation. His arguments were based primarily on his estimates of sea level fluctuations and chronology for Point Verde, Little Barasway, and other sites to the north along the Cape Shore, and on his suggestion that the Cape St. Mary's area was not glaciated during the most recent (Late Wisconsinan) glaciation, *ca.* 28,000-11,000 B.P. The initial research by Henderson (1972), and later work by Catto (1992, 1998a) recognized glacial deposits, landforms, and erosional features in the Cape St. Mary's area, indicating that this area was ice-covered at some time during the Quaternary. At present, no evidence for assigning any of the several glacial phases recognized on the Avalon Peninsula (Catto 1998a) to pre-Late Wisconsinan activity exists. The benches are not striated, and show no signs of glacial erosion, although glacial features are found to seaward. It is thus possible that these benches may post-date the most recent glaciation, and they may represent postglacial sea level positions. The deposits overlying the surfaces in some areas are the products of terrestrial mass movements. As is the case for the postulated older features along the Burin Peninsula, further research is required.

Following deglaciation, sea level fell around most of the eastern Newfoundland coastline. The decline in sea level is attributed to a reaction from glacioisostatic over-compensation, following the "Type B" model proposed by Quinlan and Beaumont (1981, 1982) and modified by Liverman (1994). Shaw and Forbes (1995) documented sea-level minimum positions around Newfoundland. Although the sea level minimums were not synchronous in all localities, all date from the early to mid-Holocene. In areas without raised marine features, such as St. John's Harbour and the tip of the Burin Peninsula, early Holocene sea levels were lower than the present 0 m asl contour.

The pattern of the postglacial lowstand in eastern Newfoundland is a series of concentric loops, centred on the Middle Ridge area west of Terra Nova National Park (Shaw and Forbes 1995). This pattern indicates that the Newfoundland-centred glacier had a greater influence on postglacial sea level history than was the case for the preceding pattern of glacially-related marine maxima. The upper marine limits were produced by the glacio-isostatic influence of the Laurentide Inlandsis in Labrador, whereas the lower marine limits along the shoreline appear to be the products of glacio-isostatic deformation associated with Middle Ridge glaciation. Glacio-isostatic influences of the postulated glaciers developed on the offshore banks (Miller and Fader 1995) are not apparent in the pattern of sea-level minima on the South Coast, or in Fortune and Placentia Bays.

Along the South Coast and Burin Peninsula, the postglacial lowstand varies from -12.4 m asl at Long Harbour (Fortune Bay), -15 m to -16 m asl at the Head of Bay d'Espoir, to -17.8 m in North Bay and East Bay (Bay d'Espoir), -19.5 m asl at Marystown Harbour, and -19.4 m asl at Facheux Bay (Shaw and Forbes 1995). The southward displacement of the lowstand curves across the Burin Peninsula, and the relatively high (-12.4 m asl) position recorded in Long Harbour, suggest that Late Wisconsinan glaciation extended south of Terrenceville.

Along northwestern Placentia Bay, the presence of submerged estuarine and deltaic sediments southeast of Swift Current indicates that sea levels stood approximately 8 m below present levels in the northernmost part of the bay. Other submerged deltas are located at -13.9 m in Paradise Sound and -18.9 m at Long Harbour (Shaw and Forbes 1995). Wave-cut terraces offshore of Argentia and Ship Cove are submerged to depths of 19.6 m. In addition, along the Cape Shore and St. Mary's Bay, ^{14}C dated terrestrial peat deposits indicate that sea levels were at or below the present level throughout the mid-Holocene (Catto 1993b, 1994b). All of these sites represent exposed seacoast locations subject to coastal erosion, high winds, and salt spray, where trees are currently unable to grow and peat cannot form or accumulate.

Offshore of the Conception Bay coast, submerged shoreline features have not yet been located. Extrapolation from the data available for northeastern Placentia Bay and western Trinity Bay suggests that sea level fell to between 10 m and 25 m below present during the early Holocene (Grant 1989; Shaw and Forbes 1990, 1995; Liverman 1994; Shaw *et al.* 1994). The available data from Trinity Bay is restricted to Random Sound, where terraces offshore of the mouths of Shoal Harbour River, Little Shoal Harbour River, and Northwest Brook lie at -9.7 m asl (Shaw and Forbes 1995).

Following the lowstand in the mid-Holocene, *ca.* 6,000 years ago, sea level has risen steadily to its current position. All of the coastline of eastern Newfoundland is currently submerging, in common with all of coastal Newfoundland south of St. Barbe and Hare Bay on the Northern Peninsula (Catto and Thistle 1993; Liverman 1994).

During the past 1300 years, sea levels have continued to fluctuate, in response to ongoing isostatic adjustment. At Ship Cove, south of Placentia, marine sediments above sea level capped by terrestrial peat indicate that marine water rose to at least " 1 m above present *ca.* 1340 B.P., although this may represent storm surge activity. Drowned forests and peat at Biscay Bay Brook and at numerous locations on the Burin Peninsula indicate that sea levels have risen in the past 1000 years. Building foundations uncovered by archaeological excavations at Ferryland, along the Southern Shore, suggest that sea level may have been " 3 m lower than present in the early 1600's (Catto 1993b, 1994b, 1995). A similar rate of rise was suggested by archaeological evidence from the site of Fort Frederick, adjacent to the lift bridge at Placentia (Royce Gaines, personal communication, 1993).

Evidence of enhanced erosion along many Avalon, Burin, and South Coast beaches suggests that transgression is currently occurring. Terrestrial peat deposits have been destroyed or partially inundated by rising marine waters at Patrick's Cove (Placentia Bay), Ship Harbour (Placentia Bay), Dog Cove (St. Mary's Bay), Biscay Bay, and Mobile (Southern Shore), among other sites.

Coastal erosion accelerated by rising sea levels has occurred at several localities, notably in Conception Bay South (Taylor 1994, Liverman *et al.* 1994a, b, Batterson *et al.* 1999). Areas affected by coastal erosion are identified elsewhere in this report. Although the dimensions of the problem are not as severe as along the south coast of Nova Scotia (Taylor *et al.* 1985, Shaw *et al.* 1993, 1994), local property losses due to coastal erosion have occurred.

No definitive documentation of the rate of submergence has been recorded for much of the study region, particularly along Trinity Bay and the South Coast. The data available along the Burin Peninsula (Grant 1989, A. Ruffman personal communication, Shaw in preparation) and that from the southwest coast of Newfoundland (Grant 1989, Shaw and Forbes 1995) suggest that the rate of submergence approximates 1-2 mm/a along the South Coast and southern Burin Peninsula.

At Mobile, south of St. John's, a submerged forest of *Picea* stumps rooted in terrestrial peat was exhumed as a result of storm action in 1994 (Jones 1995; Catto *et al.* 2000). Subsequent storms have eroded the peat, causing some stumps to be removed, and have periodically exposed and buried others in sediment. At least 16 stumps have been identified (Catto *et al.* 2000). The exposed bases of the stumps extend to 0.7 m below low tide level (approximately 1.5 m below mean sea level), and two were exposed at low tide along the beach between April and October 1999. In at least one instance, a rooted stump was subsequently used to secure a vessel, and an old stage (abandoned *ca.* 1966) is present at the southern end of the beach. Caution must be exercised, therefore, in assuming that erect 'trunks' represent rooted trees. ^{14}C dating of the outer rings of one rooted stump, excavated to verify its rooted and *in situ* character, indicated an age of 310 " 50 B.P. (GSC-5836). As spruce cannot survive if their roots encounter salt water, the presence of these stumps indicates that sea level was at least 2 metres lower than present *ca.* 300 years ago (Catto 1995). If the ^{14}C date from Mobile is valid, sea level has risen at this site along the Atlantic shoreline of the Avalon Peninsula at a rate of approximately 6 mm /a, a value similar in order of magnitude to those inferred from the archaeological data at Ferryland and Placentia.

Two additional sites with tree stumps inundated by late Holocene sea level rise on the Avalon Peninsula have recently been ^{14}C dated (Catto *et al.* 2000). At Ship Harbour, Placentia Bay, approximately 50 *Picea* tree stumps are preserved along the sheltered north-facing shoreline of Big Seal Cove (Griffiths 1999). At mean low tide, the stumps furthest offshore lie beneath 1.5 m of seawater, and all the stumps are inundated at high tide. A part of one stump from Big Seal Cove yielded a ^{14}C date of 2260 "60 BP (Beta-132317), correlative to a calendar age between 405 BC and 180 BC, 2355-2130 years ago. As the base of the rooted stump was located 2 m below modern mean sea level, the minimum rate of sea level rise here is 1.0 mm/a. In the modern environment, trees do not grow at elevations less than 2 m asl. If the stump was killed when sea level was 2 m below its elevation of B2 m asl, the rate of sea level rise would be approximately 2 mm/a over the past *ca.* 2200-2300 years.

At Port-de-Grave, dredging to deepen the harbour in May-June 1999 resulted in the recovery of numerous (more than 100) large fragments of tree stumps (Catto *et al.* 2000). The initial depth of the harbour floor prior to the commencement of dredging was 6 m below modern sea level. Wood submitted for ^{14}C dating yielded an age determination of 2630 " 60 BP (Beta-132316), corresponding to a calendar age of 2845-2720 years, equivalent to 895-770 BC. Assuming that the base of the stump was no higher than B6 m asl at the time of its death, an estimate of between 2 B 3 mm/a appears appropriate for sea level rise over the past 2800 years in Port-de-Grave Harbour.

Data is lacking for the Trinity Bay shoreline. Investigation of the 'Straight Shore' to the northwest of Bonavista Bay suggests that sea level has risen only slightly (± 70 cm) in the past 3,000 years (Shaw and Forbes 1990). However, sea level rise is partly responsible for coastal erosion of The Beaches archaeological site north of Burnside, where a tombolo is actively undergoing submergence (Catto *et al.* 2000). Protective measures have proven necessary to protect the site from further erosion as archaeological excavation proceeds, and some parts of the site are below present mean sea level. A site with inundated tree stumps has been reported at Salt Pond, Burnside (Laurie McLean, personal communication), but the stumps have not as yet been ^{14}C dated. Interpolation among results from the Avalon Peninsula (Catto 1994b, 1995; Catto *et al.* 1999; Catto and Thistle 1993), those from the Straight Shore (Shaw and Forbes 1990), and the observations from The Beaches, suggest that sea level rise along the northern part of the Trinity Bay shoreline (southern Bonavista Peninsula) currently approximates 2 mm/a.

Exact quantification of rates of sea level rise over short periods (decades to hundreds of years) is complicated by many factors, including local subsidence (c.f. Belpeiro 1993), confusion of storm and tsunami deposits with those associated with modal marine conditions (Dawson *et al.* 1991, Foster *et al.* 1991, Dawson 1999), and erosion induced above mean high water (e.g. Bryan and Stephens 1993). A further complication is induced by landward migration of barachoix and other coastal features (examples are discussed in detail by Taylor *et al.* 1985, Shaw and Forbes 1987, Shaw 1990, Forbes *et al.* 1991, Forbes *et al.* 1995, Orford *et al.* 1995, Orford *et al.* 1996, Shaw *et al.* 1998). More dated sites are required throughout eastern Newfoundland before a definite statement concerning the precise rate of sea level rise is possible. Although the exact rate of change is uncertain, and although the relative importance of anthropogenic and natural factors contributing to sea level rise on a continent-wide scale (c.f. Kemp 1991) and the nature of regional climate change (Pocklington *et al.* 1994, Morgan and Pocklington 1996) are also unclear, sea level is rising along the eastern Newfoundland shoreline.

5. Previous Work

Despite the cultural and historical significance of the eastern Newfoundland coastline, and despite its interest from the environmental and geomorphological perspectives, previous research concerning coastal morphology and processes has been relatively limited. The coastline was discussed in general terms in studies concerned with the Quaternary geology, glacial history, and glacioisostatic response of the region (e.g. Daly 1921, Coleman 1926, MacClintock and Twenhofel 1940, Twenhofel and MacClintock 1940, Brückner 1969, Henderson 1972, Tucker 1976, Grant 1977, Grant 1980, Grant and King 1984), although coastal processes and dynamics received lesser attention. Researchers interested in the glacial history of the Hermitage area (Leckie 1979, Leckie and McCann 1983), the Burin Peninsula (Tucker 1979, Tucker and McCann 1980, Tucker *et al.* 1982), and the Bonavista Peninsula (Jenness 1960, 1963; Brookes 1989), and those engaged in regional mapping (e.g. Vanderveer 1975) also identified coastal features. The most recent major and comprehensive synthesis of the Quaternary history of Atlantic Canada, including Newfoundland, was compiled by Grant (1989). Numerous research efforts of the Geological Survey of Canada (Atlantic) and their colleagues from other institutions have revealed details of the Quaternary stratigraphy, palaeoenvironments, and history of the offshore deposits and features (e.g. Bonifay and Piper 1988, Fader 1989, Fader *et al.* 1982, Grant and King 1984, King and Fader 1986, Piper *et al.* 1990, Miller 1999).

Research primarily concerned with the geomorphology, processes, and dynamics of the modern shoreline environment has been conducted at several localities in eastern Newfoundland by the Geological Survey of Canada (Atlantic) since 1980 (previously referred to as the Bedford Institute of Oceanography and the Atlantic Geoscience Centre). The numerous publications and reports of researchers of the Geological Survey of Canada (Atlantic) have greatly advanced the understanding of the eastern Newfoundland shore (Forbes 1984; Forbes and Syvitski 1995; Forbes and Taylor 1994; Shaw and Edwardson 1994; Shaw and Forbes 1987, 1990a, 1995; Shaw and Frobel 1992; Shaw *et al.* 1989; 1990; 1992a, 1992b, 1998, 1999; Syvitski and Shaw 1995).

Throughout the 1990's, the Geological Survey of Canada (Atlantic) and the Geological Survey of Newfoundland and Labrador have cooperated in a programme of coastal monitoring, involving assessment of geomorphic and textural changes and shoreline erosion, particularly at sites with shoreline bluffs of Quaternary sediment (Liverman *et al.* 1994a, 1994b). In 1999, active sites for shoreline monitoring in eastern Newfoundland included Topsail Beach and Long Pond (Conception Bay), Point Verde, Ship Cove, and Big Barasway (Placentia Bay), Holyrood Pond Barrier (St. Mary's Bay), Biscay Bay, and Portugal Cove South. The Geological Survey of Newfoundland and Labrador has an ongoing program to assess coastal erosional hazards along the shoreline of southern Conception Bay (D.G.E. Liverman, personal communication; also see Batterson *et al.* 1999).

Research has been conducted at several locations along the coastline of eastern Newfoundland by workers based at Memorial University. Sites investigated include Long Pond

(Pittman 1999, Pittman in preparation), Conception Bay South (T. Taylor 1994; Connors and Tuck 1999), Topsail Beach (Prentice 1993), Mobile (Jones 1995), Biscay Bay (White 1999), Peter's River (Nichols 1995), Mill Gut (Hamlyn 1996), Whiffen Head and Ship Harbour (Griffiths 1999), and Ship Cove and Big Barasway (Boger and Catto 1992, 1993a, 1993b; Boger 1994). Additional research has been conducted by the author throughout eastern Newfoundland, supported primarily by Fisheries and Oceans Canada and the Natural Sciences and Engineering Research Council of Canada, and also logistically by the Geological Survey of Newfoundland and Labrador, the Geological Survey of Canada (Atlantic), and by Memorial University of Newfoundland (Catto 1991, 1993b, 1994b, 1994c, 1999; Catto *et al.* 1997, 1999a, 1999b, 2000; Catto and St. Croix 1997; Catto and Thistle 1993).

6. Classification Systems

Adoption of any classification system creates potential problems for diverse users. A classification scheme represents a first approximation of nature, and hence is prone to error and over-simplification. Development of classification schemes for coastal regions is especially difficult because of the multiplicity of different users. Each user has different interests, requiring particular information about the coastal environment. A classification scheme which attempted to incorporate all types of information available about the coastal zone environment-climatological, biological, geomorphological, sedimentological, oceanological-would be extremely complex and cumbersome. The requirement to consider human influences and factors-cultural, historical, economic, resource management, demographic, aesthetic-and to integrate these with the physical environmental conditions, adds still further complexity (Cendrero and Fisher 1997; Cooper and McLaughlin 1998).

Development of a usable classification of coastal and shoreline systems requires understanding of the temporal variability of both the natural environment and the anthropogenic influences. In eastern Newfoundland, variations in the shoreline in response to different wind and ocean conditions, and to other climate and meteorological fluctuations ranging from decadal to hourly scales, are ubiquitous. Shorelines respond to changes in the terrestrial environment, which influence sediment availability, flux, and coastal erosion. Changes in the population numbers, demography, economic activity, and shoreline utilization for commercial, residential, and recreational purposes have affected the eastern Newfoundland shoreline greatly in the past twenty years, with the effects of the Northern Cod Moratorium (imposed 1992) being particularly marked. Longer-term changes related to population and resource management, such as those associated with the resettlement programs of the 1960's and the growth of suburban areas since the 1970's, are also evident locally. Human perceptions of the coastal zone have also changed, with the advent of ecotourism and evolving attitudes towards shoreline utilization.

These components of temporal variation must be accounted for in coastal classification. Schemes designed to classify and explain coastal zones over "geological" time intervals (>10,000 yr) may give unsatisfactory results when applied over shorter time spans. This is especially evident in situations such as eastern Newfoundland, where a combination of recent climate change and human utilization of coastal zones has resulted in changes in sedimentation and geomorphology.

Repeated observations will produce results that are superior to an individual observation, but will also add complexity to any discussion of coastal classification. Classification based on short-term observation of the shore may fail to describe fluctuations over longer terms. Most classification systems assume that classification will be based on a single observation of the coast, and that conditions will not vary substantially throughout the seasons or from year-to-year. If variations is anticipated, it is frequently assume that the changes will be cyclic and/or seasonal, and that the inter-annual variation will be relatively minor and largely confined to the position of transitory features such as berms, rather than resulting in fundamental changes in the character of the shore. Observations of many of the beach systems throughout eastern Newfoundland discussed in this report indicate that the assumption of relatively constant sediment textures and shoreline morphology throughout the interval from 1981 to 1999 is not valid. Both spatial and temporal transitions are ubiquitous. Further changes are evident for those regions where older aerial and ground-level photographs provide a record of events. At some sites, the changes are significant enough to entirely change the geomorphically-based shoreline classification that would be determined at different times.

The effects of spatial variation (scale) should also be accounted for in a coastal classification scheme (Cooper and McLaughlin 1998). If a classification is to be of use in local areas, rather than serving as a broad overview, abundant detail must be provided, on the scale of 10's of metres or even finer. Broad generalizations are appropriate to study of a coastline as a whole, but are of limited value in individual embayments and coves, and may locally be highly misleading or even deleterious. To be of value, a good classification scheme must be appropriate for the task involved. Schemes designed exclusively for academic purposes may not be fully appropriate for technical applications or be useful for coastal land management. Faced with these difficulties, it is not surprising that researchers who have studied the coastline have devised numerous classification schemes, each geared to investigate particular aspects of the coastal zone for particular interests.

In this report, classification of the coastline has been accomplished through the use of several systems, including:

1) the geomorphically-based system developed for Fisheries and Oceans Canada, employed in several regions of coastal Newfoundland (e.g. Catto *et al.* 1997, 1999a; Catto 1997, 1999a). This system focuses upon shoreline substrate, slope, and sediment texture;

2) evaluation of the sedimentary processes, magnitude and location of energy expenditure, transport directions and geomorphic response, and influence of seasonal ice. This data for specific sites is presented in the geomorphic discussion, and in summary tabular form;

3) assessment of the sensitivity of the shoreline to erosion and sea-level rise, following the criteria established by Gornitz (1990, 1991, 1993; Gornitz *et al.* 1993; Gornitz and Kanciruk 1989; Shaw *et al.* 1998), presented in map form;

4) assessment of the sensitivity of individual sites to pollution originating from both marine and terrestrial sources;

5) assessment of factors influencing aquaculture operations at individual sites;

6) assessment of other forms of anthropogenic impact at individual sites; and

7) discussion of the evaluation of the shoreline from a human/environmental/aesthetic perspective.

In addition, a second geomorphically-based system, which has developed from those proposed by Fricker and Forbes (1988), Owens (1993, 1994), and the Geological Survey of Canada (Atlantic), has been applied to parts of the coastline of Newfoundland (Edwardson *et al.* 1993; Sherin and Edwardson 1995). Ongoing efforts are under way to classify the eastern Newfoundland coastline using this methodology, which incorporates landform types; foreshore, nearshore, and backshore processes and forms; and anthropogenic structures (A. Sherin, Geological Survey of Canada (Atlantic), personal communication).

These classification systems are discussed further below.

7. Geomorphic Classification Scheme

The classification system used in this part of the report follows that used by Fisheries and Oceans Canada in other regions of Newfoundland and Canada, including the Placentia Bay, Conception Bay, and Coast of Bays regions of Newfoundland discussed in previous reports (Catto *et al.* 1997;, 1999a; Catto 1997). This system was initially based on the schemes proposed by John Harper for the Pacific Coast of Canada, and by SeaConsult Ltd. for the west coast of Newfoundland (see discussion in Owen 1993). The classification system is outlined in Table 7-1. Although difficulties have been observed in the application of this scheme to eastern Newfoundland, as are outlined below, it has been retained in the interests of regional consistency and to facilitate comparisons with other, similarly mapped shores.

Table 7-1. Shoreline Classification Scheme for the Coastline of Eastern Newfoundland.

Class	Substrate	Sediment	Width	Slope	Type	Selected Examples
1	Rock	none	wide	low	Wide Rock Platform	Copper Island Flatrock
2	Rock	none	narrow	low	Narrow Rock Platform	Abrahams Head Bay de Verde Bay du Nord Butler Head Coomb's Cove Cousin Head Elliston Point Fort Point Gaskiers Green Harbour Point Island Point Cove Lannon Point Little Sagona Island Maberly North Harbour Point, SMB Sagona Island Pump Cove Shoal Cove, PB Taylor's Bay Point White Point, PB Winging Head, PB

Table 7-1. (Cont'd.)

Class	Substrate	Sediment	Width	Slope	Type	Selected Examples
3	Rock	none	narrow	steep	Rock Cliff	Baccalieu Island Bauline Bay d'Espoir Bell Island Brigus Broad Cove Cape Dog Cape Bonavista Cape St. Mary's Cape St. Francis Cappahayden Dantzic Cove English Harbour West Facheux Bay Flambro Head Paradise Sound Smith Sound Western Bay Head numerous others
4	Rock & Sediments	Gravel	wide	low	Gravel Beach on Wide Rock Platform	Lannon Cove Maggoty Cove, Sound Island s. of Port Royal Cove, PB southeast shore, King Island Perry's Cove

Table 7-1. (Cont'd.)

Class	Substrate	Sediment	Width	Slope	Type	Selected Examples
5	Rock & Sediments	Gravel	narrow	low	Gravel Beach on Narrow Rock Platform	Adams Cove northeast Bois Island Grates Cove Kingston Lear's Cove Little Brule Little Ma Jambe Long Beach, Colliers Pt. St. John's Harbour, Coast of Bays
6	Rock & Sediments	Gravel	narrow	steep	Gravel Beach with Rock Cliff	south shore of Bell Island Brigus n. of Buffett Head, PB Cappahayden Middle Beach Cooper's Cove, Long Island southern Cape Shore Gallows Cove Lance Cove, Calvert Bay, SS Island Cove, Cape Broyle Frogmarsh Cove Lord and Lady Cove Hibbs Cove LaPlante Cove, PB Healys Cove Pass Island Beach Shoe Cove Ship Cove, CB Turks Gut Useless Bay, SS Watern Cove numerous others

Table 7-1. (Cont'd.)

Class	Substrate	Sediment	Width	Slope	Type	Selected Examples
7	Rock & Sediments	Gravel & Sand	wide	low	Gravel & Sand Beach on Wide Rock Platform	Perrys Cove Woody Island Davis Island Flat Islands Goose Cove, PB Snooks Brook Cinq Islands
8	Rock & Sediments	Gravel & Sand	narrow	low	Gravel & Sand Beach on Narrow Rock Platform	Spout Cove Biscayan Cove Bacon Cove Little Catalina Little Dantzic Cove Coalpit Point Wreck Cove St. John's Head Little Ma Jambe St. Jacques Island Brent Cove Dunfield, TB Coachman Islands Northeast Cove, Long Island, PB Bradley's Cove, CB Coffin Cove Dick's Island Catalina Scott Point, FB Gaskiers Bear Cove, Witless Bay

Table 7-1. (Cont'd.)

Class	Substrate	Sediment	Width	Slope	Type	Selected Examples
9	Rock & Sediments	Gravel & Sand	narrow	steep	Gravel & Sand Beach with Rock Cliff	Jugglers Cove Freshwater Cove, Bell I. Bishops Cove Golden Bay Coldeast Point Ferryland Double Road Point Maurice Poole Cove Maricot Island Cove Coffin Cove Red Land Cove Dough Ball Cove Silver Bay, PB Northeast Arm, Trepassey Bay South West Brook, Cinq Islands Bay Cock-and-Hen Cove Great Dantzic Cove Garnish Fox Hummocks
10	Rock & Sediments	Sand	wide	low	Sand Beach on Wide Rock Platform	Lance Cove
11	Rock & Sediments	Sand	narrow	low	Sand Beach on Narrow Rock Platform	Northern Bay Lance Cove Jeans Cove, Woody Island north Barred Island Three Sticks Cove

Table 7-1. (Cont'd.)

Class	Substrate	Sediment	Width	Slope	Type	Selected Examples
12	Rock & Sediments	Sand	narrow	steep	Sand Beach with Rock Cliff	Northern Bay Salmon Cove Brunette Island Saltwater Cove Murphy's Cove Little Lawn Harbour south and west of Dock Point D'Argent Bay southern Flat Island south and west Roche Peak
13	Sediments	Gravel	wide	low	Wide Gravel Flat	Bay Roberts Kings Beach, Harbour Grace Clarkes Beach north Big Barasway Ship Cove Haystack Harbour O'Donnells John's Pond Gooseberry Cove Saltwater Cove Big Barachois Arnold's Cove Angel's Cove, P.B. Harricott Pond Green Point, Point Verde Patrick's Cove Peter's River Beach Mill Gut Coombs Cove Holyrood Pond Beach Placentia

Table 7-1. (Cont'd.)

Class	Substrate	Sediment	Width	Slope	Type	Selected Examples
13	Sediments	Gravel	wide	low	Wide Gravel Flat	Whiffen Head Biscay Bay Portugal Cove South Bellevue Beach Spaniards Bay
14	Sediments	Gravel	narrow	low	Narrow Gravel Flat	Grates Cove Easter Beach Holyrood Heart's Ease Tombolo Hodges Cove, Random Sound Bellevue Beach Ferryland Meadow Point, Trepassey St. Shotts Point LaHaye Shoal Bay Pond O'Donnells Big Barachois Branch Little Barasway Southern Harbour Otter Cove

Table 7-1. (Cont'd.)

Class	Substrate	Sediment	Width	Slope	Type	Selected Examples
15	Sediments	Gravel	narrow	steep	Steep Gravel Beach	Bristol's Hope Caplin Cove Chapel Cove Bryant's Cove Big Barasway Peter's River Holyrood Pond southern Margery Cove Point, Red Island Scrape Cove, Merasheen Island north Arnold's Cove Little St. Lawrence Clement's Cove Witless Bay Cappahayden(Gull Pond Brook Outlet) Maddox Cove Cap Cove Mall Bay Admiral's Shore Mobile Ferryland Head St. Joseph's Fox Harbour Little Gallows Harbour, St. Joseph's Haystack Harbour Back Cove Belle Bay Dog Cove, S.M.B. Avondale Cape Broyle River Calvert River Aquaforte Port Kirwin Brigus South

Table 7-1. (Cont'd.)

Class	Substrate	Sediment	Width	Slope	Type	Selected Examples
15	Sediments	Gravel	narrow	steep	Steep Gravel Beach	Renews Britannia Burgoyne's Cove
16	Sediments	Gravel & Sand	wide	low	Wide Gravel & Sand Flat	Kelligrews Chamberlains Big Barawsay Seal Cove St. John's Bay Boxey Deadman's Bight Great Harbour Bight Frenchman's Cove Doughball Barachois Brown Harbour Cochrane Cove Taylor's Bay Lansey Back Cove Bellevue Beach Dunfield Island Cove Port Rexton Champneys West

Table 7-1. (Cont'd.)

Class	Substrate	Sediment	Width	Slope	Type	Selected Examples
17	Sediment	Gravel & Sand	narrow	low	Narrow Gravel & Sand Flat	Coleys Point Beach Kettle Cove Long Pond Beach Rencontre East Pool's Cove Boxey Mose Ambrose Morrisville English Harbour West Barasway de Plate Seal Cove Island Rock Point White Point, F.B. Fair Haven Mooring Cove New Bridge, SMB Sandyville Creephole Point Jean de Baie north Burnt Island, Nonsuch Inlet Beck's Bay Saltwater Cove Bellevue Beach Bittern Cove

Table 7-1. (Cont'd.)

Class	Substrate	Sediment	Width	Slope	Type	Selected Examples
18	Sediment	Gravel & Sand	narrow	steep	Steep Gravel & Sand Beach	Jobs Cove Bell Island terminal Broad Cove Upper Gullies Salmon Point Champneys West English Harbour, TB New Melbourne, TB New Chelsea Old Perlican Hants Harbour Heart's Delight Gull Island Topsail Beach Mt. Carmel Little Barachois Arnold's Cove Hogan Cove Merasheen Island Scrape Cove, Merasheen Cross Point, Merasheen Doughball Head Great Jervais Fox Cove Venison Cove Sandyville Furby's Cove Bill's Cove Deadman's Bight English Harbour Back Cove Beck's Cove

Table 7-1. (Cont'd.)

Class	Substrate	Sediment	Width	Slope	Type	Selected Examples
19	Sediment	Sand	wide	low	Wide Sand Flat	Salmon Cove Northern Bay Flat Island Harbour, PB Salt Cove, PB Lance Cove Piper's Hole River, Cow Head north Red Head, PB Point May Pond Flat Island Cove east Boxey Harbour
20	Sediment	Sand	narrow	low	Narrow Sand Flat	Salmon Cove Northern Bay Swift Current east Burin Bay Arm Lansey Back Cove Patrick's Island, PB Bay de l'Eau North Harbour, PB
21	Sediment	Sand	narrow	steep	Steep Sand Beach	Lansey Back Cove Burin Bay Arm southwest Woody Island
22	Sediment	Mud	wide	low	Mudflat	Black Duck Hole, Bay d'Espoir Calmer, Point May Pond

Table 7-1. (Cont'd.)

Class	Substrate	Sediment	Width	Slope	Type	Selected Examples
23	Sediment	Organics & Mixed Clastics	wide	flat	Estuary & Fringing Lagoonal	Riverhead SMB Riverhead CB North Harbour, PB Black River Swift Current Cape Roger Bay Bay de l'Eau Salt Pond Point May Pond Ship Harbour, PB Northeast Brook Long Harbour Salmonier Colinet Rocky
24	Sediment	Mixed	wide	flat	Tidal Flat	Connaigre Bay Swanger Cove, Bay d'Espoir Cribb Cove, Bay d'Espoir Dawson's Cove, Sandyville Come-by-Chance

Classification was accomplished through:

- field observations conducted from July 1989 through March 2001;

- analyses of videotaped records of surveys of the coastline, including those conducted in summer 1981 as part of the Environmental Impact Assessment process undertaken by the Hibernia Development Corporation, and those conducted by the Geological Survey of Canada (Atlantic);

- analyses of aerial photography previously conducted by the Governments of Canada and Newfoundland and Labrador, dating from 1941;

- analyses of photographs held in the Archival Collection of Newfoundland and Labrador, in the collection of the Department of Mines and Energy, Government of Newfoundland and Labrador, and by private individuals;

- discussions with residents of the coastal communities; and

- observations and analyses reported and documented elsewhere by numerous colleagues, referenced throughout the discussion.

Multiple, repetitive observations are vital to analysis of any coastline. Classification based on short-term observation of the shore may fail to describe fluctuations over longer terms. Analysis of a coastline based on a single observation of the coast (e.g. during an aerial survey operation, such as that conducted in the summer of 1981 for eastern Newfoundland), with the assumption that conditions will not vary substantially throughout the seasons or from year-to-year, may prove invalid. Observations of several of the beach systems throughout the study region, in addition to those observed in other parts of Newfoundland (Forbes 1984; Forbes *et al.* 1993; Nichols 1994; Sherin and Edwardson 1995; Hicks 1995; Shaw *et al.* 1999, and numerous others), indicate that spatial and temporal changes in sediment texture and shoreline morphology throughout the interval from 1981 to 2001 are ubiquitous. Further changes are evident for those regions where older aerial and ground-level photographs provide a record of events. In some areas, the changes are significant enough to entirely change the shoreline classifications that would be determined at different times. These shorelines are designated with compound symbols in this report and on the maps (e.g. 14/17).

The classification system divides shorelines according to the substrate, specifying 'rock', 'sediment', or 'rock and sediment'. 'Rock' refers to consolidated bedrock *in situ* which has not been disturbed by mass movement or glacial transportation. 'Sediment' refers to all clastic material which has been transported, detached, or weathered from the underlying bedrock, regardless of grain size. Although this division would require modification in regions with easily eroded or partially consolidated bedrock (e.g. Tertiary sediments) or with indurated or cemented Quaternary sediments, neither condition occurs in eastern Newfoundland. 'Rock and sediment' refers to sites which have areas of sediment separated by exposed rock, or which have thin (<30 cm) and transitory veneers of sediment overlying bedrock. Where such areas are subject to temporal variation in the extent and/or thickness of sediment cover, they are considered to retain their 'rock and sediment' substrate classification.

The second criterion is the texture of the overlying sediment. Texture is defined according to the dominant clast size present, as 'sand', 'gravel', 'gravel and sand', 'mud', 'mixed clastics', 'organics and mixed clastics', or 'none'. The textural divisions follow those of the Wentworth-Udden classification system (Udden 1898; Wentworth 1922; Krumbein 1934; Pettijohn *et al.* 1987). Gravels are subdivided into "granules" (2-4 mm diameter), "pebbles" (4-64 mm in diameter), "cobbles" (64-256 mm in diameter), and "boulders" (>256 mm in diameter). Pebbles and cobbles may be further subdivided into fine, medium, and coarse grades. Sand is subdivided into "coarse" (0.5 mm-2 mm in diameter), "medium" (0.25-0.5 mm in diameter), and "fine" (0.0625-0.25 mm in diameter) grades. Clasts between 0.0039 mm and 0.0625 mm in diameter are considered as "silt", and those less than 0.0039 mm in diameter are "clay". The term "mud" encompasses both silt and clay.

'Sand' beaches are defined as those containing a volumetric majority of clasts with diameters between 2 mm and 1/16 mm (0.0625 mm). Under this classification system, most 'sand' beaches contain more than 90% sand by volume and more than 75% by mass. The human perception of 'sand' differs from the sedimentological one, however, as most non-geologists consider a sandy beach to be dominated by medium-fine to very fine sand (0.20 mm to 0.0625 mm). Some sites classified as 'sand' beaches under this system, therefore, may not be perceived as 'sandy' by all users.

'Gravel' is defined as all materials of granule size or coarser, ranging from 2 mm diameter to the largest boulders. This designation includes granules, pebbles, cobbles, and boulders. Gravel beaches have a volumetric majority of gravel, and the mass fraction of gravel commonly exceeds 90%. An additional criterion is that no distinctive or temporally persistent areas dominated by sand are present. As the gravel designation encompasses all clasts larger than sand, a 'gravel' beach could theoretically be composed entirely of granules, or entirely of boulders, or have a textural assemblage of a variety of gravel classes. Differentiating among these assemblages is of importance in the assessment of beaches for several purposes, including suitability as capelin spawning areas, harlequin duck habitat (Golden Bay), sensitivity to marine pollution, assessment of dynamics and sediment flux, and ecotourism potential. Although this classification does not differentiate among gravel textures, several of the other classification systems presented in this report incorporate these differences.

'Sand and gravel' beaches are defined as those with volumetric proportions of sand greater than 30% and less than 70%, or those with clearly segregated lateral or vertical sand and gravel assemblages. At several sites, sediments are texturally segregated, with sand dominating the intertidal and subtidal areas, and gravel dominating the exposed beach ridges. These sites are classified as 'sand and gravel' beaches if the textural segregation is preserved throughout the majority of the year (with the exception of conditions during and following storm events). Sites where sand is only dominant sporadically in the intertidal and subtidal zones, particularly those that require long periods of quiescence or specific episodes of longshore sediment transport to develop concentrations of sand, are classified as 'gravel' beaches.

At some sites, gravel and sand are mixed together in undifferentiated assemblages. These beaches are considered as 'sand and gravel' systems if the volumetric proportion of sand exceeds 50% (although the mass proportion will be considerably less than 50%), or where the gravel clasts are supported within a sand matrix.

Designation of particular systems as either 'gravel' or 'sand and gravel' shores is subject to change after storm events, or after prolonged periods of modification under winds originating from specific directions. For these reasons, a site classified as 'gravel' may display mixed textural assemblages on some occasions. Here, the textural designation refers to the modal status of the site. Sites which show repetitive alternation in textural status are designated by compound symbols (e.g. 15/18; 6/9).

Sites designated as having 'mud' sediment have totals of less than 50% sand and gravel by volume. The majority of the sediment is thus silt and clay. Mud-dominated shores are very rare in eastern Newfoundland, and at all sites silt is present in excess of clay. Several 'mud' sites contain <5% clay-sized particles. Fine organic detritus and individual lenses and thin layers of organic sediment are also commonly present.

Sites designated as 'organics and mixed clastics' are associated with estuaries and fringing lagoons. An estuary and fringing lagoonal (class 23) shoreline incorporates many small zones varying in texture and morphology, such as individual tidal channels, fluvial bars, areas of bank erosion and deposition, and vegetated and unvegetated zones. In these instances, subdivision of textural zones is impractical at the scale of mapping, and is also hindered by temporal changes in the configuration and position of individual small-scale features.

'Mixed clastic' shores are defined as those containing a range of inorganic clasts ranging from mud to cobble or boulder gravel. These shorelines represent areas where coastal processes have not completely re-worked preexisting glacigenic sediment, but where the sediment is incorporated into the active shoreline and is influenced by shoreline processes, rather than representing an underlying substrate. These shorelines are associated with 'bouldery tidal flats' (Class 24).

The third element in the classification system involved designation of the width of the foreshore zone. An arbitrary division was made between 'wide' (>30 m) and 'narrow' (30 m) conditions. Although the widths of foreshore areas will vary in response to tidal action, variation is minimal under the microtidal regimes prevalent throughout most of the study region. Mesotidal areas are frequently associated with bouldery tidal flats, mudflats, and estuarine shores. Foreshore widths are also subject to temporal variations resulting from storm activity, and areas with such variations are designated with compound symbols (e.g. 16/17).

The fourth element within the classification system arbitrarily separates foreshore slopes (above low neap tide line) into 'flat' and 'steep' categories, with slopes measured normal to the tide lines. The numerical distinction between flat and steep is subject to temporal variation, and also depends upon where at the site the slope is measured. No sites, with the exception of those with completely uniform exposed rock platforms, have slopes which are constant from the highest berm to the neap tide line, and lateral variations controlled by aspect and sediment flux are ubiquitous. The critical angle of repose varies with sediment texture, packing, and interstitial water content, so that a sand shore considered as 'steep' will have a lower modal angle than a steep gravel shore. In this classification system, 'steep' gravel, and sand and gravel shores are considered to have maximum angles of at least 20° measured normal to the tide line. These shores are designated as 'steep beaches', and those with lesser slopes are termed 'flats'. Sand-dominated shores are considered to be 'flats' if slope angles are generally less than 5° throughout the site, and if no conspicuous subordinate berms are present below the limit of storm wave action. Sites with temporally variable conditions are indicated by compound symbols (e.g. 13/15).

These four elements-substrate, sediment, width, and slope-are considered together to produce a classification system with 24 possible members (Table 7-1). Some potential combinations of variables are mutually exclusive.

Some difficulties are encountered in application of this classification system. Individual classes within the system encompass different ranges of variability of morphology and sediment texture, with estuarine and tidal flat systems (Classes 23 and 24) showing much spatial variability in contrast to the more homogeneous steep beaches (Classes 6, 9, 15, and 18).

Designation of a shore area as Class 23 also entails consideration of terrain inland from the mean high tide line, in contrast to the designation of a steep beach or a gravel flat, both of which will be covered with marine water during storm events. Problems are thus encountered when variations normal to the shore (cross-shore) are considered. Although the classification scheme adopted is designed primarily to reflect conditions at the shoreline edge, in many instances cross-shore variability is important when considering sediment supply, seasonal changes, and overall stability of the segment of shoreline. Throughout this report, the impacts of cross-shore successions are considered in the discussion of both individual shoreline classes and particular sites.

Cliffed shorelines are assumed to be dominated by bedrock cliffs in the classification system (Classes 3, 6, 9, 12). Along some parts of the eastern Newfoundland shore, however, steep sediment bluffs in excess of 5 m high back gravel beaches or narrow gravel flats. Examples are found along the shoreline of Conception Bay South, in embayments between Bay Roberts and Carbonear, along the northeastern shoreline of St. Mary's Bay, at Holyrood Pond and St. Vincents, at Big Barasway (Placentia Bay), and along the southern shoreline of the Burin Peninsula, among other sites. These sediment bluffs supply sediment to the beach areas during storm events, and in areas where the vegetation is anthropogenically disturbed. The beaches and gravel flats developed in association with these bluffs differ in terms of stability and morphology from those present at the bases of bedrock cliffs.

Anthropogenic modification of the shoreline is not explicitly considered as a classification unit in this system. In one sense, human activity can be regarded simply as the mechanism by which a new shoreline class is created, and the resulting shore treated as any other-i.e., a shoreline backed by a concrete wall can be compared to one backed by a resistant bedrock cliff. For other purposes, however, anthropogenic activity significantly alters the physical characteristics of the shoreline (Nakashima and Mossa 1991; Titus *et al.* 1991; Kelletat 1992, Gornitz *et al.* 1993, Pilkey *et al.* 1993, Anthony 1994, among many other studies), inducing changes that have not finished propagating through adjacent areas, in addition to the biological effects. In many sites throughout the study region, significant modification of the shoreline by direct human intervention is evident. The impacts of anthropogenic activity are considered in the discussions of individual sites presented in this report.

8. Coastal Classification Zones

8.1 Class 1 -- Wide Rock Platform

The wide rock platform class is defined as a bedrock platform, largely or totally devoid of sediment, which slopes seaward at a shallow angle (< 20°) and is in excess of 30 m in width. In other coastal regions of Atlantic Canada, such platforms are generally associated with gently dipping sedimentary, metamorphosed sedimentary, or extrusive volcanic strata. They are frequently developed in areas with upper mesotidal or macrotidal regimes and limited sediment cover inland, such as the Bay of Fundy. In areas marked by mesotidal or microtidal conditions, sediment fluxes from either landward or seaward sources must remain low to keep the platforms exposed.

Sites with persistent high energy waves (especially waves of high amplitudes) and strongly reflective conditions can also develop wide rock platform shores, providing that the dip of the strata is moderate (15-30°). Structural weaknesses, including joint patterns, faults, and bedding planes, must generally be aligned parallel to the platform surface. Joints aligned normal or oblique to the surface are susceptible to widening by frost action, producing a stepped surface with areas where sediment can be trapped, and other locations where wave energy can be focused. Under these circumstances, a bare, regularly-sloping rock platform will not develop.

Rock platform development is thus confined to areas with moderately dipping sedimentary bedrock, which has not been subjected to sufficient tectonic stress to permit the formation of multiple sets of joints of differing alignments. This scenario is more prevalent along the northeast coast of Newfoundland (Bonavista Bay, Notre Dame Bay, Hamilton Sound, Baie Verte) than along the Avalon and Burin Peninsula shores. Excellent examples of rock platforms developed under these conditions are displayed along the western shore of Blackhead Bay and at Keels, along the northern shore of the Bonavista Peninsula.

Seasonal ice activity, as occurs along the Northern Peninsula of Newfoundland at St. Barbe, Flowers Cove, Eddies Cove, Cape Norman, and at numerous other locations in northeastern Newfoundland (Forbes and Taylor 1994, Hicks 1995), can also act to remove sediment and expose wide rock platforms. Seasonal ice action is a factor at Blackhead Bay and Keels. In some locations, the influence of seasonal ice shove results in the construction of a boulder rampart, or the emplacement of individual boulders perched on the rock substrate. Seasonal ice activity, however, cannot totally denude a rock platform that is routinely subjected to sediment influx from the adjacent land area. In addition, the impact of seasonal ice activity is directly related to tidal range, with greater effects evident in macrotidal areas, such as Ungava Bay and Cumberland Sound (Gilbert and Aitken 1981; Owens and Harper 1983; Gilbert 1990) than in microtidal regions.

The combination of steeply dipping bedrock, locally high sediment fluxes, and microtidal conditions throughout much of eastern Newfoundland effectively precludes development of this style of coast. Areas with gently dipping bedrock, or where friable sedimentary bedrock is exposed, are commonly associated with abundant onshore sediment sources. Seasonal marine ice is most common in the area north of Cape St. Francis, although it does form or is forced ashore at more southerly locations during some years. Persistent scour by sea ice driven aground, however, would be expected only along the most northerly segments of the Conception Bay and Trinity Bay shorelines. Sea ice must be driven aground, either by waves or tides, in order to be effective as an erosional agent.

Examples of wide rock platforms (class 1 shores) are located on the northwest shore of Copper Island, south of Port Elizabeth (Jude Island map-sheet, Placentia Bay). The platforms are developed on Late Proterozoic fine clastic strata of the Musgravetown Group (Colman-Sadd, personal communication, 2000). At Copper Island, the wide rock platforms are areally restricted, and are interspersed with sand and gravel-covered wide platform (class 7) and narrow platform (class 8) zones. The lateral extent of the exposed rock platforms has varied throughout the 1980's, continuing to 1999, with the areal proportion of sediment cover ranging from approximately 20% to greater than 50%.

Variations can be attributed to influx and removal of sediment by southwesterly winds associated with hurricanes, as no local supply of sediment exists on the island. Fetch is restricted to the northwest. Hurricane-driven southwesterly winds are thus subject to a minor degree of cornering as they impact the southwestern shore of Copper Island, although the low relief (30 m) limits topographic obstruction. Winds sweeping across the island would be capable of initiating seaward movement of sediment. The distribution of the exposed and sediment-covered zones suggests that both landward and seaward sediment motion occurs. Features attributable to sea ice activity were not observed, as would be expected in western Placentia Bay, an area not commonly subjected to sea ice activity.

The only other example of a class 1 zone is located at Flatrock, on the open Atlantic coast north of Torbay. Here, resistant red conglomerate of the Late Proterozoic Signal Hill Group (King 1988) dips seaward at angles of 10-30°. Where the conglomerate is exposed to waves and grounding seasonal drift ice originating from the northeast, sediment is routinely removed, exposing the platform and allowing erosion of the bedrock. Although individual boulders transported by ice shove exceed 50 cm in diameter, erosion is primarily due to frost activity over the periodically exposed rock surface. The margins of the coarse clasts within the conglomerate accentuate frost weathering, and wave action (with some gravitational rolling) rapidly removes the debris. Periodic removal of painted surfaces suggests that the mean erosion rate is on the order of # 1 mm/a, although most erosion appears to take place by plucking of individual clasts.

Clasts range from medium-grained sand to boulders, with pebbles and fine cobbles predominating. A large majority of the clasts (modally >80%) are derived locally from the red conglomerate, with small proportions originating from adjacent sandstone and argillite strata of the St. John's Group. All the clasts are locally derived, indicating that distal transport of clasts by ice-rafting does not occur. Clasts are predominantly moderately to well-rounded, suggesting that any frost-wedged clasts have been subjected to modification by wave abrasion. Equantic and discoid shapes dominate. The clasts show no preferential alignment.

The wide rock platform is most exposed during early to mid-spring. Small amounts of sediment cover, ranging from 10-35% gradually accumulate throughout the summer months, and are partially removed during autumn storm events. Individual storm events with northeast winds, such as those of October 1992 and October 1994, account for the majority of sediment removal. During most years without strong northeasterly winds (1991, 1993, 1995-2000), sediment generally accumulates.

Lesser amounts of removal are associated with sheet wash over the bedrock generated by precipitation upslope. Hurricane winds are ineffective at removing sediment directly, but high precipitation events associated with hurricanes cause redistribution of sediment through sheetwash. Although terrestrial precipitation contributed little to sediment removal during most spring periods between 1990 and 1998, two high-precipitation events in April 1999 (" 70 mm of precipitation associated with each) were highly effective at removing sediment. Following the second event, the platform was swept clean of all sediment finer than medium cobble size. Subsequently, sediment, including angular roadbed aggregate, became detached from the upslope banks and moved across the platform. These clasts are readily distinguished from the marine sediment by their angularity and lithology. Much of this sediment, however, was removed seaward by a 30 mm precipitation event in January 2000. Sediment accumulated gradually through summer 2000, but was actively being removed in April 2001.

The lateral extent of the exposed rock platform also has varied in accordance with the degree of ice shove activity throughout the 1980's until spring 2001. In years marked by large amounts of ice shove (spring 1991), the lower part of the platform is swept completely clean of sediment, and the boulders form several (discontinuous) lines across the upper part representing different ice shove events. In years when ice shove activity was less (spring 1993) or non-existent (spring 1998), no boulders may be present above mean high tide level.

The clast distribution and amount of sediment cover on the Flatrock platform is the result of several processes working sequentially. Following a summer of lesser hurricane activity and minimal autumn northeast gales, a winter marked by severe ice conditions results in a greater amount of sediment, larger boulders, and higher limits of ice shove. These conditions were apparent during the period from summer 1990 to spring 1992. In contrast, a period marked by strong northeast gales, lesser sea ice activity, and enhanced hurricane frequency, as from summer 1992 to summer 1995, resulted in removal of sediment from the platform. Sediment cover increased from winter 1995-96 to summer 1997, in conjunction with increased sea ice influence and limited hurricane activity, and then declined from autumn 1997 to spring 1999, the result of a lack of sea ice formation in the winter of 1997-98 and the high precipitation events of April 1999. Small amounts of sediment accumulated throughout the summer of 1999, but a precipitation event in late January 2000 once again swept the platform clean.

8.2 Class 2 -- Narrow Rock Platform

The narrow rock platform class is defined as a bedrock platform, largely or totally devoid of sediment, which slopes seaward at a shallow angle (# 20°) and is less than 30 m in width. These platforms develop in areas of moderately to steeply dipping sedimentary or volcanic bedrock, or in areas of metasedimentary bedrock. Although rock platforms that are elevated above present sea level may indicate former marine limits (Grant 1989), platforms can also be formed above mean high tide by terrestrial weathering processes (Bryan and Stephens 1993). The development of narrow rock platforms is related primarily to the attitude of the bedrock, and its susceptibility to frost weathering, rather than to the duration or intensity of marine erosional processes. Severe northeast storms and hurricanes during the period 1989-98 have not succeeded in forming any new narrow rock platforms, suggesting that an individual storm event, or several closely-spaced storm events, are ineffective at erosion of consolidated bedrock.

Inland areas are frequently marked by limited sediment cover. However, the narrowness of the platform facilitates removal of sediment by marine processes. Thus, a narrow rock platform can develop at a site backed by inland sediment cover, if the rate of removal of sediment by shoreline processes exceeds the rate of terrestrial supply. In eastern Newfoundland, however, most narrow rock platforms are associated with areas characterized by low terrestrial sediment influx. Narrow rock platforms can develop in all tidal regimes, and under a variety of sea ice conditions.

The development of narrow rock platforms is primarily of result of frost weathering during intervals when the rock is exposed, rather than being the product of direct abrasion by waves, tides, or sea ice. The rate of formation is controlled by the number of freeze-thaw cycles, with each freezing event (to at least -4°C) subjecting the rock to 1.4×10^6 kg/m^2 stress as the ice expands its volume by 9.2% (Trenhaile and Mercan 1984, Tharp 1987, Trenhaile 1987, Bloom 1998), and is therefore dependent upon climate.

The second factor involved is the fracture pattern within the rock unit, which facilitates water percolation below the surface. The tensile strengths of all the rock units in eastern Newfoundland, even the most resistant finely crystalline granites, gabbros, and quartzites are significantly less than the stress induced by freezing (Catto and St. Croix 1997). The stress induced by freezing in natural rock exposures is less than the theoretical maximum, because the ice has infiltrated along a fracture plane or other surface of weakness, and is not totally confined (Tharp 1987). However, where fracture planes are narrow or tortuous, or where multiple micro-fractures occur, confinement is more extensive, and more pressure can be induced. The crystal margins within igneous rocks also represent weaknesses that can be exploited by frost. Thus, although the lithology of the bedrock does not serve to directly control its susceptibility to frost weathering, specific lithologies such as argillite, slate, stratified volcaniclastics, and volcanic flow units, are more susceptible to the development of fractures and joints along planes of weakness, and hence are more easily weathered.

In eastern Newfoundland, conditions are ideal for the formation of rock platforms at elevations ranging from mean low tidal position to several metres above present sea level. Platforms as much as 12 m above the present sea level are actively undergoing erosion and modification at present, notably along the Coast of Bays shore adjacent to Coomb's Cove (St. John's Harbour-Harbour Breton), along Bay de Nord, and on the Cinq Islands. The presence of a rock platform at an elevation above sea level in an exposed coastal situation thus cannot be considered as evidence for a former high stand of the Atlantic Ocean. Similar phenomena responsible for active rock platform formation above mean sea level have been noted in different climate regimes (Johnson 1933; Trenhaile 1987; Bryan and Stephens 1993), and complicated shorelines with alternating pocket beaches, cliffs, and platforms are common (Scott and Johnson 1993).

The amount of frost-induced erosion increases in the higher intertidal areas, where sea water only covers the rock for short periods each day at high tide. In contrast, abrasion by tidal action is most effective in the lower parts of the intertidal zone, where the rock is only exposed at low tide. Along the dominantly microtidal eastern Newfoundland shore, the intertidal zone is relatively narrow. Along a rock platform sloping at 15°, a tidal range of 1.5 m produces an intertidal zone only 6 m in width. Rock platforms of greater width developed under microtidal or lower mesotidal environments reflect incremental formation in a frost-dominated environment, influenced by changing sea level, as has occurred on the strandflats off Norway (Holtedahl 1998) and the submerged limestone platforms of the northwestern shore of the Northern Peninsula. Although extensive strandflats are not found in eastern Newfoundland, some rock platforms currently submerged at low tide were formed during periods of lower sea level, when frost action was able to effectively weather the subaerially exposed bedrock. At Elliston Point, the abraded rock platform extends to 6 m below the present mean low tide level, substantially below the lowest tidal position, and several other examples are present in eastern Newfoundland.

Along the eastern Newfoundland shoreline, comparison of the relative amounts and effectiveness of abrasion in the higher and lower intertidal zones indicates that frost action is the dominant erosive process. Bedding planes exposed on the surfaces of some rock platforms are truncated in the upper intertidal zones, indicating that erosion has been more effective in those areas. The development of gently convex surfaces on rock platforms with regularly dipping bedding planes also suggests that erosion has been more effective in the upper intertidal areas, and in exposed areas above the mean high tide line. The distribution of *Ascophyllum, Fucus,* and other taxa within the rockweed communities (Catto *et al.* 1999b) indicates that many platforms are not regularly subjected to sea ice activity or strong wave action, but continue to be eroded in the intertidal and supratidal zones by frost wedging.

Along the northwestern Trinity Bay shore, narrow rock platforms are developed at Elliston Point, Maberly, and Fort Point. On the western flank of Elliston Point, sandstone of the Musgravetown Group dips westward at 10° (Jenness 1962). The rock platform's eastern flank is supported by resistant conglomerate and sandstone exposed at Elliston Point and on North Bird Island. These features funnel waves driven by northeast winds into Sandy Cove, producing higher energy levels along the western shore of the cove. The rock platform thus has developed along the lower energy shoreline, where coastal erosion is minimal and the terrestrial sediment supply limited. Sediment thus is not delivered to the platform from either the marine or terrestrial areas, and the bedrock platform remains exposed.

At Maberly Brook, a similar geomorphic situation has resulted in the preservation of a small narrow rock platform along the western side of the cove. Here, the presence of a resistant headland and South Bird Island offshore act to limit the fetch in the platform area. The Musgravetown Group strata dip northwestward at 10-15°, normal to the shoreline, and are sheltered from the direct effect of the northeast winds. Storm wave energy is concentrated on the eastern flank of Elliston Point. Here, sea spray and frost action have created 10 stacks along the cliff, as joints within the resistant conglomerate strata have been exploited. Along the eastern side of the cove, energy levels are low and terrestrial sediment supply is minimal, and thus the rock platform remains exposed. The extreme microtidal range at Maberly Brook largely precludes tidal abrasion of the platform, and the configuration of the shoreline to the west effectively limits penetration of sea ice. At this site, frost weathering is almost exclusively responsible for eroding the platform. The few pebbles scattered across the platform are angular and derived from the underlying Musgravetown Group strata. The abraded platform extends approximately 2 m below the lowest tidal level.

At Fort Point in Trinity Harbour, strata of the Musgravetown Group dip ESE at 45-50° (Jenness 1962). Narrow rock platforms here are alternately exposed and covered with pebble gravel. Exposed conditions are associated with periods of wave reworking and an absence of winter ice influence. In contrast, the formation of landfast winter ice precludes storm reworking (especially by waves driven by northeasterly winds), resulting in sediment accumulation in the lower intertidal zone. The abraded platforms extend more than 2 m below the lowest tide level, indicating that sea level was previously lower.

Narrow rock platforms occur along several segments of the eastern Trinity Bay shoreline. At Green Harbour Point, slate and shale of the Late Proterozoic Heart's Content Formation dip west-northwest at 30° (King 1988), normal to the general trend of the shoreline. The rock platform here extends to 3 m below mean low tide level. Similar narrow rock platforms, interspersed with small gravel beaches developed on the rock platform surfaces (Shore Class 5) occur at Abrahams Head and Island Pond Cove. At these sites, the underlying bedrock is composed of friable red shale, sandy siltstone, and silty sandstone of the Maturin Ponds Formation.

Along Island Point Cove, rock platform shores interspersed with areas of gravel beach cover) occur along an 800 m expanse of shoreline. The platform has developed where the Maturin Ponds Formation dips seaward at 20-25° towards the northwest (King 1988) and is overlain inland by coarse grained glacigenic diamicton (Catto 1993b, 1998a). This shoreline is open towards the northwest, and northwest winds act to rework frost wedged debris derived both from the surface of the rock platform and from the glacigenic deposits. The wave-transported pebbles and fine cobbles are concentrated into patchy gravel beaches varying from 25 m to 100 m in length. Irregular, discontinuous ridges of gravel 0.5-2 m high oriented in poorly defined arcs convex to the shoreline mark the sediments from sea level to 10 m asl on a transitory basis. The intervening bare rock areas at these levels are actively undergoing erosion. The bare rock platform areas have represented between 50% and 85% of the shoreline throughout the previous 35 years. Variations in the extent of sediment cover are related to the prevalence and strength of the northwest winds. During periods of lesser wind activity from the northwest, the gravel beach ridges are lower, and the gravels cover larger expanses of the rock platform. Northwest winds act to focus gravel deposition, creating the ephemeral arcuate ridges.

The rock platform/gravel beach assemblage at Abrahams Head is similar to that at Island Point Cove. The appearance of both these areas varies, depending on the strength and prevalence of northwest wind activity, and to a lesser degree in response to sea ice conditions. The winter of 1997-98 was marked by an absence of landfast ice and brash ice along the eastern Trinity Bay shore. As a result, ongoing erosion throughout the winter resulted in the removal of most of the gravel veneers from the rock platforms.

The rock platform at Green Harbour Point is generally exposed throughout the year. Gravel beaches do not develop, and sediment deposits are confined to individual cobbles transported by sea ice shove. The Heart's Content Formation is more susceptible to erosion by both frost action and wave action than is the Maturin Ponds Formation. Erosion of the Heart's Content slates along planes of fissility produces smooth surfaces that minimize friction as clasts are transported across the rock. Clasts arriving at Green Harbour Point tend to move gravitationally down the smooth slopes, and do not remain on the surface to form beach deposits. This trend is accentuated during years when erosion continues unhindered by landfast ice, as between spring 1997 and autumn 1998.

Rock platforms are also present in the Bay de Verde area of northern Conception Bay. These platforms are developed on the red coarse sandstone-pebble conglomerate of the Baccalieu Member of the Bay de Verde Formation. In most areas, the Baccalieu Member is resistant to erosion, forming steep cliffs with local fringing gravel beaches. At Bay de Verde, however, the rocks have been deformed into a doubly-plunging syncline (King 1988), creating a low 'saddle' which has subsequently been eroded to form Bay de Verde Harbour. In the basinal area of the syncline, dips of rock units reach 0°, allowing the development of the rock platform and the harbour. Similar effects are present to the southwest, at Low Point. At both sites, the abraded platforms extend seaward below mean low tide level. In contrast, areas along the synclinal axis that are not associated with 'saddles', such as Horns Point, and those associated with the adjacent anticlines (Flambro Head), are marked by steep bedrock cliffs.

Narrow rock platform shorelines are located along the northern Conception Bay shore from Upper Small Point southwest to Perry's Cove (Kingston area). These platforms are associated with friable grey-green shales and siltstones of the Conception Group, in areas along fold and flexure crests. Numerous small flexures are present in this area, forming an undulatory pattern of rock platforms separated by low cliffs and sediment-covered zones. In this area, bedrock geology is the dominant control on morphology and sediment distribution, and the position and extent of the bare rock platform areas remains essentially constant throughout the year. Patches of bedrock platform offshore that are periodically swept clean of sediment and exposed indicate that frost action was effective as much as 5 m below mean low tide level earlier in the Holocene.

To the south of Perry's Cove, the increase in sediment cover inland (Catto 1993a) combined with the deeply embayed nature of the Conception Bay shoreline and the difference in bedrock attitude together preclude the maintenance of exposed rock platforms without sediment veneers. The sediment bluffs of the Conception Bay South area, and the steeply dipping rocks of the Southern Shore, also preclude the formation of Class 2 shorelines.

Rock platforms are exposed along the shoreline of St. Mary's Bay at Gaskiers and North Harbour Point. Between False Cape and Gaskiers, Late Proterozoic diamictite of the Gaskiers Formation crops out along the west limb of the LaHaye Point Anticline (King 1988; Eyles and Eyles 1989). This shore is directly exposed to the southwest, with a fetch extending southwestward towards Cape May NJ, in excess of 1500 km. The Gaskiers Formation is resistant to erosion, and thus few terrestrial clasts are available to form sediment veneers on the platform. Sea ice activity is rare in St. Mary's Bay, although landfast ice did form during the winters of 1991-92 and 1992-93. Subsequent winters, especially those from 1995-96 to 1998-99, have not resulted in any sea ice activity along this part of the St. Mary's Bay coastline. Sediment deposition by sea ice shove, therefore, does not commonly occur on these rock platform shores. The platforms extend seaward to water depths of more than 10 m.

The paucity of terrestrial sediment results in the platforms being swept clean by successive hurricanes. Although the effectiveness of the waves is limited by the inland dip of the strata (30-50° east-southeast) along the anticlinal limb, the strongest hurricanes have no difficulty in removing all the sediment veneer. Along this shore, the effects of the three 1995 hurricanes ('Felix', 'Luis', 'Opal') removed the small amount of sediment that had accumulated since 1991 (hurricane 'Bob'). Although these storms (particularly 'Opal') did erode coastal exposures of diamicton veneer landward of the rock platforms, almost all of the sediment produced was transported seaward by the storm wave backwash. Subsequent erosion driven by runoff from terrestrial precipitation removed the remainder. Although hurricane 'Hortense' (1996) had a relatively minor effect on this shoreline, sediment replenishment did not occur throughout 1999, as the site was subject to storm surge during hurricane 'Irene' (1999). Hurricane 'Michael' (2000) was not effective at modifying this shoreline.

At North Harbour Point, friable clastic strata of the Heart's Content Formation are also subject to erosion along an exposed shore by southwest waves. Although these strata have been folded obliquely to the trend of the shoreline (King 1988), the exposed point is subject to platform formation. Sediment was deposited over these rock platforms from 1996 through early 1998, but has been removed by several storm wave events between summer 1998 and August 2000.

Narrow rock platforms occur along several segments of the northern Placentia Bay coastline. In the vicinity of Winging Head and White Point, rock platforms interspersed with gravel beaches occur along a 5.5 km length of the east shore of North Harbour. During the summer months, approximately 10-20% of the shoreline is marked by narrow rock platforms devoid of sediment. Much of the thin veneer of sediment which covers the platforms along the shore is removed periodically during the autumn storms, leaving as much as 60% of the shoreline devoid of sediment cover. Episodes of sediment removal are associated with periods of strong storm activity during the summer and autumn, followed by ice activity that prevents accumulation of sediment during the winter. Unlike the Trinity Bay and northern Conception Bay shorelines, sea ice shove is rare in Placentia Bay. The unusual winters marked by ice foot formation (1991, 1993) serve primarily to preclude erosion and mobilization of beach and terrestrial sediment by waves, and hence the underlying rock platforms do not accumulate sediment veneers. During winters where sea ice does not form (1997-98; 1998-99), wave activity results in the accumulation of thin veneers of sediment over the rock platform. Veneers will develop most effectively when a hurricane-free summer and gale-free autumn are followed by a mild winter.

The sediment veneers are replenished by influxes from the land during spring, resulting from snowmelt runoff and enhanced freeze-thaw activity. Direct sediment transport by rivers plays a relatively minor role at Winging Head and north of Sail the Maid Island, and is not involved in beach development in the White Point area. Landward movement of sediment during storm events can result in changes of width of the area of sediment cover, thus changing the width classification of some zones.

The available data suggest that a classification based on a series of winter observations might differ from that based on summer records in the Winging Point area. This pattern is also apparent in other rock platform regions, such as those in the vicinity of Butler Head, Southern Harbour; Cousin Head; and probably on Goat Island. Areas where such seasonal transitions occur are designated 2/4 and 2/5.

Another example of a narrow rock platform zone is located along a 1.1 km expanse of shore east of Taylor's Bay Point. In this region, the supply of sediment from the shore is diverted away from the rock platform zones along two minor streams, leaving the intervening class 2 zones relatively deficient in sediment supply. These areas thus appear to be more consistent in nature throughout the year than is the Winging Head area. Even along this shore, however, isolated surfaces are covered with thin discontinuous mantles of gravel (dominantly pebbles) on a seasonal basis. Coverage is more extensive during years lacking in hurricane activity (1997), and sediment is periodically removed by late season hurricanes ('Gert-Harvey' and 'Irene' in 1999; 'Michael' in 2000) and by winter storms (e.g. January 21-23, 2000). Frost-wedged bedrock extends offshore to more than 4 m below the mean low tide line, indicating formerly lower sea levels during the mid-Holocene.

Along Placentia Bay, additional areas of narrow rock platform shorelines are located at Lannon Point, Pump Cove, Shoal Cove, north of Sandy Point on Sound Island, as well as at several other locations. Rock platforms cannot develop in areas of steep cliffs, such as the Cape Shore. At the tip of the Burin Peninsula, and along the south coast of Fortune Bay, narrow rock platforms are present at Pieduck Point, Little Dantzic Cove (in association with mixed sand and pebble gravel beaches and veneers, shore class 8), and Garden Cove (in association with pebble-cobble gravel veneers, shore class 5). At these sites, the distribution of gravel veneers is controlled by the effectiveness of hurricane activity. Sea ice is not a factor along the southern Fortune Bay shoreline.

Narrow rock platforms are also found along the Coast of Bays shoreline, developed on moderately to steeply dipping sedimentary (e.g. Coomb's Cove), gently dipping sedimentary (Sagona and Little Sagona Islands) or volcanic bedrock (e.g. Bay du Nord). In areas completely lacking sediment cover, such as Little Sagona Island, rock platforms remain bare throughout the year. Areas with restricted sediment cover (Sagona Island) do not develop persistent veneers. In areas with variable sediment flux (Coomb's Cove, Bay du Nord), the proportion of the rock platform that is overlain by sediment may vary seasonally from 20% to 80%.

At Coomb's Cove, along the southeast side of St. John's Harbour, rock platforms interspersed with narrow gravel flats (Class 5) and narrow mixed sand-and-gravel flats (Class 8) occur along the 400 m expanse of shoreline. The platform has developed where Late Proterozoic sandy siltstone and silty sandstone of the Great Bay l'Eau Formation (O'Brien *et al.* 1998) dips seaward at angles from 15° to 50°. The scarcity of sediment inland, combined with the aspect precluding direct attack by hurricane-driven waves, limits sediment production and acts to keep the rock platform partially exposed. The area is sheltered from the direct effect of southwest winds, but clockwise circulation in the harbour results in the removal of sediment from the rock platform, periodically clearing away the frost wedged debris. The wave-transported coarse sand, granules, and pebbles are concentrated into irregular patches of sediment, which change dimension following each major southwest wind event. Poorly defined, discontinuous ridges of pebble gravel are present following storm events, but do not persist. The intervening bare rock areas at these levels appear to be actively undergoing erosion.

8.3 Class 3 -- Rock Cliff

Rock cliffs are a ubiquitous feature of the eastern Newfoundland shoreline, occurring along virtually all segments of the coast. Cliff heights vary from less than 5 m to greater than 150 m, and range in slope from 30° to vertical. Numerous examples of overhanging cliffs, caves ('ovens'), and offshore arches and stacks are present, particularly in areas where sedimentary or metasedimentary bedrock crops out along the coast. Faulting is associated for much of the cliffed shoreline development, such as along the south shore of Hermitage Bay (Hermitage Fault) and along Paradise Sound (Paradise Sound Fault). However, not all high cliffed shorelines parallel fault systems. The Cape Shore of Placentia Bay, extending between Cape St. Mary and Point Verde, is dominated by cliffs exceeding 80 m in height. High cliffs represent approximately 65% of the shoreline length of the Cape Shore, but they do not parallel the faults which trend at right angles to the shoreline in the St. Brides area and obliquely to the shoreline in the Big Barasway area (King 1988). The effect of specific bedrock lithology on cliff development has been discussed previously in the "Bedrock" section of this report (Chapter 3).

All cliffed areas, regardless of cliff height, supply large quantities of sediment to the coastal environment as a result of frost wedging, the dominant weathering process along the entire eastern Newfoundland coast. The jointed, fractured, and bedded nature of much of the bedrock facilitates wedging (Tharp 1987; Trenhaile 1987). Granites and other acidic igneous rocks are susceptible to frost wedging along their orthogonal joint systems, and along crystal boundaries. Frost wedging at Mount Arlington Heights and Jerseyside (Placentia Bay), Petty Harbour-Maddox Cove (Southern Shore), and other sites forces rock apart at rates approximating 1-5 cm/a (Catto and St. Croix 1997).

Wedging by roots, and biochemical activity along the root surfaces, further accentuate weathering. Coastal sites lacking vegetation are more susceptible to frost wedging than those with vegetation cover, as the combined result of exposure of the rock to the atmosphere and removal of any potential snow cover insulation during the winter and spring. However, areas with tuckamore (krummholz) tree vegetation developed on thinly veneered or bare rock surfaces are more susceptible to wedging and erosion by block toppling than are sites with a continuous herbaceous or grass vegetation cover. Erosion is particularly accentuated at low cliff sites, where periodic kill or damage of the tuckamore by salt spray or ice storms results in removal of the vegetation, leaving wedged fractures vulnerable to frost activity.

Mechanical erosion of cliffs by terrestrial runoff from precipitation locally contributes substantial quantities of sediment to the marine system. In most instances, however, the transported material has previously been detached from the cliff by frost wedging. Direct abrasion of the cliffs by sediment is not an important erosive process.

Marine activity, including scour by sea ice and wave action, has relatively little direct erosive impact on the cliffs. Notches up to 3 m asl present along some segments of cliffed shoreline (e.g. Broad Cove-Adams Cove, Conception Bay; English Harbour West, and Dantzic Cove, Fortune Bay; Cape Dog, St. Mary's Bay; Shoal Harbour, Smith Sound, Trinity Bay; Cappahayden area, Southern Shore) are associated with anomalously friable bedrock units, commonly with fracture patterns oriented normal to the cliff faces, and are eroded by frost wedging of spray thrown against the cliffs by breaking waves. Notches and erosional features in the cliffs cannot be related to phases of higher sea level. In areas where sea level has exceeded 3 m asl since deglaciation, subsequent frost wedging has resulted in the removal of any coastal notches which were formerly present. Along the open Atlantic shoreline both north and south of St. John's, notches and other erosional features are present above sea level, although the available evidence from St. John's Harbour (Lewis *et al.* 1987; Liverman 1994; Catto and St. Croix 1997) indicates that sea level has not exceeded 0 m asl since deglaciation.

Direct weathering and erosion through crystallization of salts in fractures does not appear to be effective in most situations along the eastern Newfoundland shore. In contrast to frost wedging, erosion due to salt crystallization is inversely dependent on the number of crystallization cycles per unit time involved (Winkler and Singer 1972; Goudie 1989). Along a boreal coastline, frequent inputs of seaspray and the moist climate effectively dissolve the salt crystals before they are able to reach sizes capable of causing erosion. Hydration pressure generated from sea salt, which is most effective at high humidity and relatively low temperatures (Yatsu 1988; Goudie 1989), may be of some significance locally, although the effects have not been studied in eastern Newfoundland. The primary influences of airborne salt on erosion are to limit or destroy coastal vegetation, and to depress the freezing point of water, thus inhibiting frost wedging.

Direct anthropogenic influence is limited in coastal rock cliffed sites, in contrast to its central role in erosion of Quaternary bluffs. The primary anthropogenic influence in rock cliff shorelines is sheep herding. Along the Cape Shore, and to lesser extents along the northern Conception Bay and northwestern Trinity Bay shores, sheep are responsible for denuding vegetation from many cliff edges, causing enhanced runoff and frost wedging and thus generating large quantities of sediment. This material, washed down the cliffs and streams and into the ocean, is thus available for transport along the shore and re-sedimentation along sand and sand-and-gravel beaches. Sheep-derived sediments appear to be important components of several beaches along the Cape Shore, such as those at Cuslett's Cove, Patrick's Cove, Big Barasway, and Little Barasway. The increase in sheep herding following imposition of the Northern Cod Moratorium in 1992 was followed by an increase in sand influx to the beaches of the Cape Shore throughout 1993 and 1994, replacing sand removed during Hurricane 'Bob'. Along northern Conception Bay, the flux of sand to Northern Bay Sands has increased due to sheep herding, along with dredging and anthropogenic modification of littoral drift (Catto 1994b). Sheep herding on cliff-top sites also contributes sediment to the Cape Shore of the Bonavista Peninsula.

Sea cliff morphology reflects the lithology, fracture pattern, tectonic history, and terrestrial erosional processes (frost action, glaciation). Marine processes play a very minor and in many instances negligible role. Along the Coast of Bays area, cliff forms reflect glacial erosion of fjordal inlets (e.g. Bay d'Espoir, Facheaux Bay), and marine processes have not contributed to the form. The cliff shorelines of Hermitage Bay are a consequence of the bedrock geology. The shores developed along steeply sloping granitic outcrops resemble the fjord coasts of Sweden and the lacustrine shores of northern Ontario, and are controlled by the joint patterns and crystallization in the plutonic rocks. The form of the cliff above the sea spray limit is due entirely to terrestrial processes, whether the cliffs are low (5-10 m in the Taylor's Bay Point area) or high (in excess of 80 m along the western shore of Paradise Sound).

The absence of deep indentations or coves in the cliffs can result from several causes. Along the Cape Shore from Cape St. Mary to Big Barasway, the structural geology is the primary cause, with resistant rock units striking oblique to the coastline. A similar situation exists at Flambro Head, Conception Bay, where the steep cliffs along the northern side of the head are developed in the highly resistant medium-coarse grained Gibbett Hill sandstone of the Signal Hill Group. Along the southwest side of the head, the Gibbett Hill Formation parallels the shore, and is flanked by the more easily eroded Old Perlican siltstone and fine sandstone (King 1988). This shoreline location is controlled by the contact between the bedrock units. Around Conception Bay, resistant rock units are responsible for shoreline configurations at Western Bay Head (Renews Head sandstone), and on Baccalieu Island (Baccalieu conglomerate). The Trinity Bay shorelines northeast of Winterton, and along the Cape Shore of Cape Bonavista, are other examples.

A second type of cliffed shoreline develops where resistant igneous units are present, as along Hermitage Bay. Along Conception Bay, the longest segment of cliffed shoreline is present from Topsail Head north to Cape St. Francis. The lack of indentations and high cliffs are due to the presence of the resistant igneous rocks of the Harbour Main Group, which armours the shoreline throughout its length, except where broken at Portugal Cove-Beachy Cove.

Faulting creates long, straight cliffed shorelines, such as Paradise Sound. Many fault-created cliffs border fjords, which have been further modified by glaciation. Faulting is also responsible for shorter, lower segments of cliffed shoreline. At Brigus, the Brigus Fault trends north-south across the harbour. Local erosion along the fault contact has produced the westward-facing cliffs at Gallows Cove (north shore) and Frogmarsh (south shore). The more friable argillites and shales of the Fermeuse Formation in the harbour area have been eroded more rapidly than the resistant igneous units of the Harbour Main Group to the east.

Cliffs are also developed in the Ordovician sandstones and shales of Kellys, Little Bell, and Bell Islands (Bell Island and Wabana Groups, King 1988). These ferruginous sediments are highly susceptible to frost wedging, due to their well-developed bedding and orthogonal jointing. In most locations, the frost-wedged debris is rapidly removed by wave action, resulting in steep cliffs flanked by small talus aprons extending to the water's edge. In areas where the talus can accumulate undisturbed, talus cones with slopes up to 40° are present.

8.4 Class 4 -- Gravel Beach on Wide Rock Platform

Class 4 shores are defined as those having a gravel beach, composed primarily of pebbles, cobbles, and/or boulders, superimposed on a wide, gently sloping bedrock platform. The gravel forms a patchy veneer over the bedrock surface, and outcrops of bare rock are commonly present. Frequently, the beaches accumulate over the widest areas of the platforms, which are the areas of the bedrock that have the gentlest slopes. Intervening marginally steeper-sloped areas commonly lack gravel cover. This results in areas with alternating shoreline segments classified as bare rock platforms (Class 2), gravel beaches on wide rock platforms (Class 4) and narrow rock platforms (Class 5), and mixed sand and gravel beaches on wide (Class 7) and narrow (Class 8) platforms. Frequent gradations and seasonal variations among these classes are to be expected.

Class 7 shorelines (Gravel and Sand Beach on Wide Rock Platform) are differentiated from Class 4 shorelines on the basis of texture. Under this classification scheme, a Class 7 shoreline is defined as a beach containing between 30% and 70% sand (determined either from visual estimates or *in situ* sampling), and is developed on a wide rock platform. The morphology of both the Class 4 and the Class 7 beaches is predominantly controlled by the lithology and attitude of the underlying bedrock. The sediments form a veneer or blanket over the bedrock, patches of which are infrequently exposed. The extent of sediment cover is generally greater for a Class 7 than for a Class 4 shoreline, but seasonal variations and topographic irregularities can produce areas of exposed bedrock platform flanked by sediment-covered segments (c.f. Semeniuk *et al.* 1988). The beaches accumulate over the widest areas of the platforms.

In Placentia Bay, the western shore of Long Island south of Port Royal Cove is an example of a Class 4 shoreline. Gently sloping sandstone and metasedimentary bedrock of the Conception Group is overlain by a thin, discontinuous sheet of gravel, dominated by medium to coarse pebbles and cobbles from July 1981 to 2000. The proportion of the platform covered by the gravel has been high since July 1981, but variations throughout the past 20 years are evident in successive photographs. Such variations are created by differential sediment fluxes generated by individual storm events. Along this segment of shoreline, the gravel cover is sufficiently persistent to assign the shore to Class 4.

A second example of a Class 4 shoreline is located at Lannon Cove, east of Point Crewe on the Burin Peninsula. In this area, the bedrock platform is composed of fine sandstone and shale assigned to the Cambrian Grand Bank Formation. The gravel overlying this platform is dominated by fine to medium pebbles, with a small proportion of granules and sand, and is derived almost exclusively from the Grand Bank Formation. Slope angles vary from 8° to 23°, reflecting the attitude of the underlying bedrock. The slopes of fine pebble and medium pebble segments of the system show no significant differences. The differences in grain size between the Lannon Cove and Long Island beaches reflect the greater availability of finer sediments along the southwestern shore of the Burin Peninsula, coupled with the tendency of the bedrock to disaggregate into finer particles, rather than reflecting differences in energy level between the sites. Slope angles at both sites are controlled by the bedrock dip, rather than by the grain size of the sediment.

The Lannon Cove and Lannon Point areas represent somewhat higher energy environments than the Port Royal area, as these sites are exposed to hurricanes from the southwest. Following hurricane 'Bob', pebbles were largely removed from the lower intertidal area, with some deposition in hurricane berms and other pebbles removed to sea. Subsequently, the large sediment flux replenished pebble supply in the lower intertidal zone, and the storm berms were gradually reworked and flattened by gravitational movements and surface runoff, resulting in a seaward migration of pebbles. The absence of sea ice in this area allowed the reworking process to continue throughout most of the winter, and the effects of the hurricane were completely obliterated by 1993. In 1995-96, the succession of three hurricanes ('Felix', 'Luis', and 'Opal') followed by reworking resulted in a similar cycle of movement. The absence of hurricanes during summer 1997 allowed the gradual downslope movement of clasts to persist, leaving lower part of the system relatively over-supplied with pebbles. These sediments were thus available for reworking during the summer of 1998. The sediments were gradually eroded during the period from summer 1998 to winter 1999-2000. Thus, although the Lannon Cove area has higher energy conditions, especially during hurricane events, than does Port Royal, the greater sediment flux, lack of winter ice, and differences in source texture from the adjacent bedrock keep the Lannon beaches supplied with finer gravels.

Maggotty Cove, Sound Island, is a Class 4 shore dominated by coarse cobbles. At this site, many cobbles remain *in situ* throughout the year, as energy levels are generally not sufficient to mobilize these large clasts. Few new clasts are brought to the system, and as a result the beach remains cobble-dominated. In contrast, the southeastern shore of King Island south-southeast of Tacks Beach displays a Class 4 shoreline with a mixed assemblage of gravel of all grades. Here, gravel is concentrated at the site during hurricane events, and is left largely undisturbed throughout intervening periods. As a result, sorting is minimal during lower energy periods, and the mixed clast assemblage persists.

Along Conception Bay, the Perry's Cove area is the only shoreline that displays beach development overlying a wide rock platform. The Perry's Cove shoreline has alternating segments of bare rock platforms and beaches varying in texture with the seasons. Here, removal and replacement of granules, pebbles, and even fine cobbles, and burial and exhumation of coarse cobbles and boulders, are evident in response to northeasterly storms.

The complex at Perry's Cove extends for 1600 m. Beaches on wide rock platforms developed in the Renews Head Formation are present at five locations, separated by segments on narrow rock platforms (Classes 5 and 8). The Class 4 and 7 beaches are aligned facing south and southeast, which limits their exposure to the strongest waves generated by northeasterly gales. Segments of rock platforms facing northeast are narrow and marked by limited beach development.

The segments designated as Class 7 beaches at Perry's Cove contain more gravel (65-85%) than sand (15-35%). Gravel clasts are predominantly pebbles, and the sand is medium to coarse-grained. The clasts associated with the Class 4 gravel beaches are generally coarser (coarse pebbles-fine cobbles), and sand is not present. Yearly, seasonal, and daily variations in texture, involving removal of sand and mobilization of granules, pebbles, and fine cobbles, are evident throughout the area, but beds of fine-grained sand are not present. Slopes on the beaches range from 5° to 22°, and the angle of slope is generally proportional to the dominant clast size.

Variations in beach texture are controlled primarily by differential sediment fluxes generated from both terrestrial and marine activity (Bartholomä *et al.* 1998), but are not related primarily to wave energy levels. High energy events remove sand from all beaches, causing the development of gravel forms, but sand accumulation is largely due to input from the land in the intervals between storms. Sand is derived from the glacigenic and colluvial diamictons exposed above the bedrock along the shore, and is transported to the coast by colluviation associated with spring runoff and bank collapse (some anthropogenically-triggered), and by Perry's Cove Brook. Consequently, the proportion of sand in the area's beaches is controlled primarily by location with respect to terrestrial sediment sources, and secondarily by the period that has elapsed since the most recent high wave event.

In the Perry's Cove area, the most significant recent northeasterly storm was that of October 1994. Throughout the period 1989-April 2001, hurricanes accompanied by southwesterly winds have not had major effects on these systems. As a result, sand accumulation has steadily increased on these shores since October 1994. Sand accumulation has been further favoured during periods of ice foot and extensive sea ice development. Although sand is displaced landward by ice shove, it remains in the shoreline system above the high tide line and is quickly returned to the lower areas of the beaches by surface runoff and gravitational flow.

8.5 Class 5 -- Gravel Beach on Narrow Rock Platform

Class 5 shores differ from Class 4 in that they are developed on narrow rock platforms, generally marked by slightly greater slopes. The two classes form in similar geomorphic environments, and commonly grade laterally into each other. Individual Class 5 shores viewed by direct observation and on photographs taken at different times showed little variation attributable to tidal status, but seasonal variations similar to those that are characteristic of Class 2 and Class 4 shorelines were observed at some sites dominated by finer grades of gravel (granules to medium pebbles).

One typical location for a Class 5 shoreline is in a lower energy position adjacent to higher energy zones marked by narrow bare rock platforms (Class 2). This assemblage can develop where the geomorphology results in effectively 'shadowing' part of the shoreline from incoming strong waves, while other areas are exposed to direct attack. At the tip of the Carbonear sub-peninsula, an assemblage of this type occurs in the Grates Cove area. Grates Cove is exposed to winds from the northeast and northwest quadrants, but the effect of northwesterly winds is dominantly felt on the eastern side of the cove. In this area, resistant coarse sandstone and conglomerate of the Bay de Verde Formation is slowly being eroded. Debris is swept east-northeastward by the predominant current in the embayment, and is carried away from the shoreline towards Baccalieu Island. This zone is sheltered from direct northeasterly winds, and thus undergoes lesser erosion during these events. The nearshore bathymetry in the cove acts to create an east-northeast current, even under the influence of northeasterly winds, and hence sediment does not accumulate on this shore.

In contrast, the western side of the cove is exposed to northeast winds. The community of Grates Cove is located in this zone, developed on less steeply inclined slopes, and colluviated glacigenic diamicton is present inland. As a result, granules, pebbles, and fine cobbles are regularly supplied to the shore. Where not disturbed by anthropogenic activity, this gravel accumulates, forming beaches. The horseshoe configuration of Grates Cove precludes all but east-northeast winds from striking the western shoreline, allowing the gravel to remain. Storm events (such as those of autumn 1992 and 1994) that do result in the removal of gravel eastward along the shore also increase erosion in the terrestrial areas, allowing subsequent re-supply to the beach systems.

During the winter of 1997-98, the absence of an ice foot resulted in more sediment removal from the beach areas, particularly by northwest winds. Limited precipitation inland, and a reduction in freeze-thaw activity, reduced the rates of gelifluction and terrestrial sediment supply to the beach system. In consequence, the beaches at Grates Cove became narrower and slopes were reduced throughout the winter of 1997-98. In the summer and autumn of 1998, storm activity was limited, but terrestrial precipitation did result in increased sediment supply to the beach system. Ice activity during the winter of 1998-99 exceeded that of the previous winter, and as a result more sediment was present on the Grates Cove beaches in the spring of 1999. This sediment remained on the shoreline throughout the summer, autumn, and winter of 1999. The winters of 1999-2000, and especially 2000-01, were also marked by persistent and extensive ice foot development. Sediment supply to Grates Cove remained high throughout 2000.

Another assemblage of this type occurs in the St. John's Harbour area (Coast of Bays). At this site, the predominant wave direction is associated with southwesterly winds. During hurricanes, the zone of the coastline sheltered from direct southwesterly winds undergoes lesser erosion, and retains its sediment cover. The absence of ice foot activity, and the number of hurricanes during typical summers (1997 excepted) result in more sediment mobility, enhanced erosion, and a lesser expanse of gravel-covered platform area, with coarse pebbles predominating.

Class 5 shorelines dominated by finer cobbles and pebbles, such as Little Brule at the northern tip of Merasheen Island, are susceptible to modification by storm activity. These shorelines show seasonal and year-to-year transitions in the volume and texture of sediment cover, and may alternate in status between Class 5 and Class 2. At Little Brule, the beach is subject to modification by northeast, northwest, and southwest winds, and hence each storm has the potential to remove or redistribute sediment. Development of seasonal ice cover here is hindered by its exposed position in Placentia Bay, and hence the beach can be subjected to reworking by storms such as that of March 1993 ('The Storm of the Century') which have little impact on sites protected by snow or ice cover.

A different type of Class 5 shoreline is located along the western side of Little Ma Jambe. Gravel patches composed primarily of coarse pebbles are developed at the base of steep cliffs and over narrow sandstone rock platforms sloping seaward at approximately 15°. Waves generated by southwest winds remove sediment from the eastern side of the cove. This material is subsequently transported parallel to the shoreline towards the southwest. It gradually accumulates on the western side of the cove as patches of gravel (class #5) and mixed sand-and-gravel (class #8) overlying the rock platform. Locally, beach sediment may be completely removed, exposing bare rock platforms, while newer beaches develop to the southwest. Although the beaches are constantly subject to sediment transport to the southwest, replenishment from frost wedging of the cliffs along the eastern side of Little Ma Jambe acts to rebuild the beaches after each major storm event (most recently after the storms of autumn 1999).

Shelter from the southwest winds also contributes to the development of a class 5 shoreline along the northeastern shore of Bois Island (Lampidoes Passage). Sediment derived from the sedimentary rock cliffs to the southwest is transported along Lampidoes Passage, and accumulates in lee positions where bedrock headlands partially shelter coves to the southwest.

Additional sediment is contributed by frost wedging of adjacent cliffs, producing narrow coarse pebble flats. The class 5 shoreline at Little Salmonier Mouth, St. Mary's Bay, is similar.

Related examples are located at Kingston and Adams Cove, Conception Bay, where transitory beaches composed primarily of coarse pebbles are developed at the base of steep cliffs and over narrow rock platforms of sandstone beds associated with the Late Proterozoic Mistaken Point and Trepassey Formations. Slope angles on the beaches generally approximate 20°. The beaches are most susceptible to alteration during northeasterly storm events, which tend to move sediment landward against the cliffs and southwestward along the shoreline, causing the beaches to become steeper and narrower (up to 31° at Adams Cove after the autumn 1992 storms). During late spring, ice shove activity also contributes to creating narrower, more steeply sloping beaches, with angles temporarily exceeding the critical angle of repose. Locally, beach sediment may be completely removed, exposing bare rock platforms, while newer beaches develop to the southwest. Although the beaches are constantly subject to sediment transport to the southwest, replenishment from frost wedging of the cliffs and platforms and from southwesterly transport from adjacent Small Point act to rebuild the beaches after each major storm event. Along this shoreline, rebuilding generally occurs throughout the summer and early fall. The most extensive reworking is associated with the autumn northeast gales (especially in 1992). Enhanced ice foot activity is associated with colder temperatures and hence reduced frost action, as the temperature remains below 0°C for longer periods. A year without strong northeasterly winds, and with reduced ice foot activity, such as 1997, results in accumulation of sediment. Conversely, sediment coverage was at a minimum in the spring of 1993, when strong northeasterly winds in October 1992 were followed by ice foot development and abundant, persistent sea ice. In spring 2000, the combination of less effective hurricane activity during the previous autumn, together with extensive ice foot development in winter 1999-2000, resulted in patchy sediment cover, locally disturbed by thrusting of sea ice.

Class 5 shorelines are also located at Long Beach, Colliers Point, Conception Bay, where they are associated with a narrow rock platform developed on clastic sedimentary rock of the Drook Formation (King 1988). Aerial photograph analysis of this area indicates that the pebble-dominated character of these beaches has remained consistent since 1966. The sediments at this location are exposed to waves from the east, north, and west, and thus the beaches are consistently reworked and are subject to energy levels which show less variability than those at other Class 5 sites along Conception Bay, such as Kingston and Grates Cove. Seasonal ice shove has not been an effective agent of remobilization at this location from 1992 to 2000. The Colliers Point beaches typically are dominated by imbricated coarse pebbles, with beach surfaces sloping at angles from 18° to 24°. At Old Shop, Dildo Arm, Trinity Bay, a similar Class 5 beach is dominated by medium to coarse pebbles, and slopes seaward at angles of 19° to 24°.

A different type of Class 5 shoreline is represented by four short segments at Lears Cove, north of Cape St. Mary's. The rock platforms upon which these beaches are developed represent the lowest of a series of low, narrow benches that extend to approximately 6 m above sea level. Although the higher benches could represent older, Sangamonian sea level positions (Grant 1989), the lowest benches are forming in response to modern conditions.

The modern beaches at Lears Cove are composed primarily of medium to coarse subrounded cobbles, with lesser amounts of boulders and pebbles. Observations suggest that the texture of these beaches has remained constant from summer 1989 through autumn 2000, thus showing little variation in response to hurricane events. Platform cover beaches dominated by coarser cobbles and boulders exhibit less seasonal variation than finer textured beaches. In part, this indicates the relict character of much of the coarsest sediment. The coarser sediments were initially supplied to the beach areas by glaciofluvial discharges, when glacial ice stood some distance offshore in Placentia Bay. When the ice retreated, and the beaches began to form along the new shoreline when sea level was established at approximately its current position in the Holocene, wave and current energy levels proved insufficient to move or modify the largest clasts. Many of the coarsest clasts on narrow rock platform beaches show no sign of marine transport, and some retain glacial striations and other glacial erosional features on their surfaces.

8.6 Class 6 -- Gravel Beach with Rock Cliff

Class 6 shorelines are defined as those with small, fringing, generally steeply-sloping gravel beaches backed by rock cliffs. Frequently, the beaches develop in confined coves, flanked by rock cliffs. These are generally referred to as "pocket beaches".

Pocket beaches are common along shorelines dominated by rock cliffs. Numerous examples are present along the length of the eastern Newfoundland shoreline, and pocket beaches are absent only in areas that also lack bedrock cliffs. The pockets represent the accumulation areas for sediment derived from local frost wedging and other erosive processes of the rocks surrounding the cove, as well as areas where coarse sediment transported by wave and storm activity accumulates. Although most pocket beaches receive at least some of their sediment through wave action, sediment derived from terrestrial sources is dominant at the majority of pocket beach sites in eastern Newfoundland, as indicated by the angularity and coarse grained texture, and by the preponderance of locally-derived pebbles, cobbles, and boulders. This sediment is, however, subject to reworking by wave activity within the confines of the coves.

Pocket beaches range in length from less than 10 metres (in areas where narrow, steeply-dipping fractures, faults, or thin vertically-dipping non-resistant shale beds or fissile slates reach sea level) to 10's of metres (where the beaches are developed in small coves). Steep gravel beaches in excess of 100 m in length are assigned to shore class 15 under this classification. In plan view, most pocket beaches have a gently to sharply concave sea front. The width of pocket beaches varies from less than 1 metre to approximately 10 m. Widths tend to vary along the longer pocket beaches, with the greatest widths associated either with an area of stream discharge or on the downcurrent sides of the larger coves.

One of numerous examples of short, narrow pocket beaches formed at the base of a steep slope, where there is no significant channelized stream flow from land, is Healys Cove, Conception Bay. The active part of this beach varies between 12 m and 18 m in length, and is marked by a gently concave surface profile with a maximum slope of 32° aligned normal to the trend of the beach front. Sediment texture ranges from fine pebbles to medium cobbles. Periods of lesser storm activity result in greater sediment accumulation on the beach, resulting in an increase in overall elevation, a gentler surface profile, and an increase in clast size and angularity. This trend is especially evident after heavy precipitation events not accompanied by strong northeast winds. Ice foot development is rare at this site, but sea ice activity has occurred in some years, resulting in gentler surface profiles and preservation of angular clasts. In contrast, periods marked by enhanced northeast gale activity result in steepening of the beach profile, rounding of the larger clasts, and an increase in the proportion of pebbles and granules at the expense of cobbles. At Healys Cove, the sediment is derived from terrestrial downslope movement from the diamicton that mantles the slope (Catto 1993b, 1998a). The distributions of clast shapes and sizes are similar to those within the diamicton at most times, as is common where diamicton cliffs provide abundant sediment influx under moderate energy conditions (Jones *et al.* 1995). Following periods of intense northeast gale activity or minimal sea ice formation, permitting reworking throughout the winter and spring, the beach clasts are eroded, becoming finer, more rounded, and more discoid than those within the diamicton.

At the adjacent site of Ship Cove, Conception Bay, 150 m to the northeast, all of the sediment is derived from mass movements from the sandstone cliffs of the Conception Group (King 1988). Here, the clast characteristics and geomorphology are representative of a talus cone composed of sediment derived from a terrestrial source (Bertran *et al.* 1997). Clasts typically are angular to subangular coarse pebbles and cobbles, with isolated boulders. Shapes are controlled by the jointing pattern in the cliff, and tend to be tabular or bladed. Clast long axis fabric shows a weak alignment parallel to the cliff face, but is not related to the modal direction of wave attack. Wave energy levels are not sufficient to rework the sediment, except possibly during the strongest northeast gales, but removal of sediment at the waterline would trigger grain flow failure, restoring the talus cone configuration shortly after the storm event concluded.

Pass Island beach, Hermitage Bay, is also an example of a short, narrow beach formed at the base of a steep slope, where there is no significant channelized stream flow from land. The active part of the beach is approximately 10 m long, and is marked by a moderately concave surface profile with a maximum slope of 25° aligned normal to the trend of the beach front. Sediment texture ranges from pebbles to medium cobbles. Cuspate structures are not present, and storm reworking is generally limited. Erosion and frost wedging of the adjacent bedrock cliffs produces a constant supply of sediment. The configuration of the shoreline effectively precludes influx of marine sediment through longshore transport. The beach thus develops in isolation from activity elsewhere along the coast.

Short, narrow pocket beaches associated with steep, high cliffs are common in areas such as the western shore of Paradise Sound and along the Cape Shore between Ship Cove and Big Barasway. Along these cliffs, intensive frost wedging occurs within the area subjected to sea spray, resulting in local development of gently concave slopes in the cliff face above the high tide line. Notches are only developed where the bedrock is approximately horizontal (#10° dip). Debris from the upper part of the cliffs is also supplied through frost wedging, as well as through collapse of overlying diamicton veneers, surface runoff during extreme precipitation events, and (especially along the Cape Shore) disturbance resulting from grazing by sheep. Debris from the upper part of the cliffs is supplied incrementally to the beaches throughout the year, usually in association with high rainfall events or hurricanes (particularly along the Cape Shore as a result of hurricane 'Bob' in 1991, and to a lesser extent following hurricane 'Michael' in 2000). In contrast, frost wedging (and failure of partially wedged blocks) occurs throughout the autumn, winter, and early spring. Most debris is supplied through frost wedging from the sea spray zone, and the general absence of ice foot development or extensive sea ice cover allow continuous reworking throughout the winter.

On these beaches, slope angles are generally directly proportional to the dominant clast size. Clasts lie at or close to the critical angle of repose for dry sediment, ranging from 20°-25° for pebbles up to 40°-45° for coarse boulders. The Cape Shore beaches tend to have planar or gently concave surface profiles, commonly 5° less than the critical angle of repose, with the steepest slopes aligned perpendicular to the trend of the beach front. On the Paradise Sound shore, the beaches tend to have surface profiles approximating the critical angle of repose. Although accumulation of the sediment proceeds largely by mass movement of frost-derived debris along both shores, the gentler profiles of the Cape Shore beaches indicate that debris derived from the upper parts of the cliffs plays a role in beach formation, and that reworking by hurricane waves is more significant. On the Cape Shore beaches, coarse pebbles and cobbles are found above the mean high tide line, with pebbles dominating in the subtidal zones, indicating that the sediment has been partially reworked and sorted by wave action. In contrast, the surfaces of beaches dominated by talus accumulation coarsen seaward.

Storm reworking of these beaches is infrequent, and most commonly results in removal of finer pebbles and cobbles, creating instabilities in the beach system and triggering small mass movements on the beach surfaces. These disturbances alter the concave profiles of the beaches, producing temporary surfaces marked by alternating zones of convex and concave slopes. Characteristically, these irregularities are gradually eliminated as further material is provided to the beach, usually within a few weeks if no subsequent storms intervene.

Pocket beaches in areas influenced by ice foot development show profile variation from year to year. On the south side of Brigus harbour, short and narrow fine pebble to medium cobble beaches are formed at the bases of steep slopes, where there is no significant terrestrial river flow. The surface profiles are planar to gently concave, with maximum slopes of 15-33° aligned normal to the trend of the beach front. Lower, flatter beach profiles result where finer pebbles are present, or during years with reduced northeast storm frequency (1993, 1995) or winters without ice foot development (1995-96; 1997-98). The steepest profiles were measured following the severe northeast gales of October 1992. In July 1996, beach profiles were almost perfectly planar, with slope angles of 15-18°. Steepening resulted from hurricane 'Hortense' (1996) and ice activity throughout winter 1996-97, causing the profiles to steepen to 25-30°by July 1997. The absence of ice foot development during the subsequent winter, followed by limited storm activity in summer and autumn 1998, caused the beach profiles to flatten to 20-25°.

At Lance Cove, Calvert Bay, Southern Shore, the absence of sea ice and ice foot development, and the northerly aspect of the beach, sheltered from the effects of northeast gales and hurricanes, have resulted in the formation of a pebble-fine cobble pocket beach with a planar profile sloping at "15°. This beach has shown little change throughout the past 10 years. Its position, at the base of a steep cliff on the south side of Calvert Bay, has shielded it from anthropogenic modification. Island Cove, Cape Broyle Harbour, is similar to Lance Cove, although its open exposure to the south and its proximity to the community of Admirals Cove enhance erosion, causing steeper and more irregular profiles.

Another style of Class 6 shoreline is represented by pocket beaches developed at Hibbs Cove and Turks Gut, Conception Bay. At Hibbs Cove, shale of the Fermeuse Formation forms low cliffs on the seaward (northeastern) sides of roche moutonnées. Quartz veins within the shale provide additional strength to the rock, and also serve to focus erosion and frost wedging along their margins. Consequently, the beach receives a constant supply of discoid medium and coarse pebbles derived from the shale, with rare spherical or elongated quartz clasts. No rivers are present, and the configuration of the shoreline effectively precludes influx of marine sediment through longshore transport. The beach thus develops in isolation from activity elsewhere along the Conception Bay coast.

The Hibbs Cove beach is marked by a gently concave profile, with a maximum slope angle of 20°. The pebbles form well-oriented assemblages, imbricated with a modal angle of 12° seaward on the upper portion of the beach and # 3° seaward at the high tide line, in shingled layers bounded by concave erosional surfaces. Cuspate structures are not present. Storm reworking is generally minimal, and the texture of the beach sediments appears to have remained constant.

At Turks Gut, quartz veins encased in the softer argillite flanking the narrow embayment on the southeast focus erosion and frost wedging along their margins. As the cliffs face northwestward, frost activity is extremely effective. The beach thus receives a constant supply of sediment, except when frost action is relatively limited (as in the winters of 1997-98 and 1998-99). The configuration of the shoreline effectively precludes influx of marine sediment through longshore transport. The beach is marked by a gently concave profile, with a maximum slope angle of 26°. Storm reworking is generally minimal, and the texture of the beach sediments appears to have remained constant from 1990 to mid-December 2000.

Stream flow and terrestrial sediment supply results in the modification of pocket beach morphology. Shoe Cove, north of Torbay, is an example of a Class 6 shoreline developed in a narrow, enclosed cove flanked by cliffs, receiving sediment from a permanent stream. The stream influx contributes more texturally varied sediment, derived from Quaternary deposits inland, to the beach system, although gravel deposits comprise >90% of the total. The beach profile varies seasonally, from planar in the late spring and early summer, to slightly to strongly concave in mid- to late autumn. Clast size ranges from medium sand to coarse cobbles, with coarse pebbles predominating. Maximum slopes on this beach reach 30°, and are aligned facing northeast, slightly oblique to the beach front.

Modification of the beach system proceeds on a very sporadic basis, with long periods of quiescence separated by extreme reworking episodes associated with the strongest northeastward winds. During late August-early October 1992, a period marked by exceptional northeast gales, the beach was completely reworked into a strongly concave profile, with the most extensive erosion occurring at the southern end. Subsequently, the beach was gradually rebuilt, becoming wider, lower, and more planar in profile throughout 1993 and most of 1994. Northeast gales in autumn 1994 eroded the profile to a concave form, but the absence of comparable events since 1995 have enabled a more planar morphology to dominate again, and the planar profile has become well established.

LaPlante Cove, Placentia Bay; Cooper's Cove, Long Island, Placentia Bay; Useless Bay, Southern Shore; Cappahayden Middle Beach, Southern Shore; and Watern Cove, Southern Shore, are representative of many cobble and boulder-dominated pocket beaches, with slope angles of 27-35°. The surface profiles tend to be slightly to strongly concave. Cuspate structures are present during the spring and summer months on some of the more lengthy pebbly beaches. The steepest slopes tend to be aligned at sharp acute angles (60-85°) to the trend of the beach front, facing the direction of the prevalent waves. In more enclosed coves, different parts of the beach slope at different angles and trends, indicating differing wave strengths and angles of attack in consequence of the local bathymetry. Coves that are less enclosed (Useless Bay, Watern Cove, Cappahayden Middle Beach) show lesser lateral variability in beach slope.

Storm reworking of these beaches occurs relatively infrequently, but is more common in more exposed situations (such as at Cappahayden and Watern Cove). Storm waves lead to the formation of cuspate structures on the beaches, causing temporary irregularities in the profiles. The resulting profiles are made up of several superimposed concave cusps, giving a somewhat scalloped appearance to the overall concave shape. These irregularities may persist until the next storm season. Along many of these beaches, the net effect of storm activity is accretion, as sediment from the length of the cliffed shoreline is focused in the cove area.

Lord and Lady Cove, Deadman's Bight, is an exposed cobble-coarse pebble pocket beach, developed where cliffs enclose a narrow cove with a stream outlet. Although stream influx contributes texturally varied sediment to the beach system, gravel deposits comprise >80% of the total. The beach profile varies seasonally, from gently concave in the late spring and early summer, to strongly concave in mid- to late autumn. Maximum slopes on the gravel beach reach 35°. Deep, steep-backed symmetrical cusps spaced between 2 m and 5 m are present in late summer and autumn. Modification of the beach system appears to proceed irregularly, with long periods of quiescence separated by extreme reworking episodes associated with the strongest southwestward winds.

Pebble-dominated pocket beaches develop where the cliffs are less enclosing, the cove is less embayed, or the bedrock is more conducive to production of finer clasts, due to its lithology and/or jointing pattern. All of these factors contribute to the development of pebble pocket beaches at Gallows Cove, north of Harbour Main, Conception Bay, and Frogmarsh Cove, Conception Bay. Both beaches are fed in part by streams, and have a texturally varied sediment supply ranging from fine sand to fine cobbles. The slopes are slightly concave and gentle, with maxima ranging from 8-15°. Weakly developed cuspate structures are present during the spring and summer months. Gallows Cove, exposed to northeast winds, is texturally and morphologically more variable than the sheltered Frogmarsh Cove. Ice foot development is rare at both sites, but reworking generally persists longer during the winter months at Gallows Cove. The beach at Gallows Cove was reworked during the autumn 1992 and 1994 storms, and has undergone constant modification throughout the past five years. In contrast, Frogmarsh Cove has remained largely unaffected by storm and wave activity since autumn 1992, and refuse has remained undisturbed on the beach for several years.

Fringing Class 6 gravel shorelines, where rock cliffs back the shore but do not confine the sediment laterally, are not common in eastern Newfoundland. Two examples of this type of shoreline are found along the north coast of Long Island, northeast of Jude Island, Placentia Bay; and north of Buffett Head, Placentia Bay. These beaches develop where underwater obstructions serve to focus the sediment in a similar fashion to the exposed flanking cliffs of the pocket beaches. They beaches tend to be steep, narrow, and relatively unstable, and underwent severe degradation during hurricane 'Bob' (1991) and less extensive change during the hurricane seasons of 1995, 1999, and 2000.

The southern side of Bell Island, Conception Bay, also supports somewhat transitory fringing Class 6 gravel shorelines, developed where sediment supply from the bluffs exceeds the ability of waves and currents to rework and remove it. The erosional processes and the sediments are almost exclusively terrestrial in origin. The clasts are angular to sub-angular and unsorted, ranging from fine sand to boulders. The material accumulates at the base of the cliffs in talus aprons or cones, and remains until it is reworked by a major (northeast gale) storm event. Consequently, these shoreline deposits are not true marine 'beaches'. Although the talus cones are steep (slope angles locally exceed 40°), narrow, and unstable, removal of the sediment at the base of the talus apron during a storm often coincides with input of new material from the cliff above, generated by loosening of susceptible, frost-disturbed debris. Precipitation and runoff result in the addition of debris to the cones. The events responsible for sediment degradation thus also are largely responsible for replenishment.

8.7 Class 7 -- Sand & Gravel Beach on Wide Rock Platform

A Class 7 shoreline is defined as a beach that contains between 30% and 70% sand (determined either from visual estimates or *in situ* sampling), and is developed on a wide rock platform. Most of the Class 7 beaches in eastern Newfoundland contain more gravel than sand, and the sand is predominantly coarse-grained. Yearly, seasonal, and daily variations in texture are evident on many of the beaches, and should be expected on all. The beaches do not appear to have contained substantial amounts of medium- or fine-grained sand at any time since *ca.* 1966-70. Slopes on the beaches range from 10°-25°. In contrast to some gravel patch systems (Class 4), the angle of slope on a Class 7 beach is generally proportional to the dominant clast size.

Class 7 shorelines are relatively uncommon, as there are relatively few broad rock platforms and few areas where sand-sized material can accumulate in these settings. Examples are found on the southeastern shore of Woody Island, Placentia Bay (mixed coarse sand and pebble gravel, with isolated cobbles); on the southern and western shores of Davis and Flat Islands, Placentia Bay (textures ranging from sand to pebbles); in the Goose Cove-North Harbour area, Placentia Bay (medium sand- coarse pebbles); Snooks Brook, Placentia Bay (sand to pebbles); and Cinq Islands, Fortune Bay (sand to pebbles).

The geomorphology (slope angle and lateral extent) of a Class 7 shoreline is predominantly controlled by the bedrock. The sediments form a patchy veneer or blanket over the bedrock. The extent of sediment cover is generally greater than for a Class 4 or 5 shoreline, but seasonal variations and topographic irregularities can produce areas of exposed bedrock platform flanked by sediment-covered segments. The beaches accumulate over the widest areas of the platforms, produced by shorelines marked by alternating zones of Classes 7 and 2, as is evident along the southeastern shore of Woody Island and on the fourth of the Cinq Islands. Aspect is critical, as the beaches can only accumulate in areas sheltered from wave action. This is evident in the Cinq Islands area, where the strongest waves generated by southwesterly winds are blocked by Corbin Head.

The differences in grain size between the Class 7 beaches predominantly reflect the relative availability of sand, rather than indicating differences in energy level between the sites. The Davis Island and Flat Island beaches appear to contain more sand than those along Woody Island, although the Flat Islands are more exposed to storm events. The beaches in the Goose Cove area, and on the fourth Cinq Island, vary seasonally in texture. The summer and early autumn are marked by accumulations of sand, which tend to be removed during the late autumn and early spring. Winter storms and the accompanying runoff from terrestrial sources are effective in sediment removal at Goose Cove.

8.8 Class 8 -- Sand & Gravel Beach on Narrow Rock Platform

Class 8 beaches resemble those of Class 7, except that they are developed on narrow rock platforms with gentle to moderate slopes. Lateral gradation between these two classes occurs on Copper Island, Placentia Bay and southeast of Harbour Buffett. Temporal variations in sand content are common, and many Class 8 shorelines periodically are modified to form Class 5 gravel beaches. Lateral gradations between Classes 5 and 8 are also common. Typical examples, dominated by fine to medium pebbles with lesser amounts of sand, occur at Spout Cove, Conception Bay; Bradley's Cove, Conception Bay; Biscayan Cove, Pouch Cove area; Little Catalina, Trinity Bay; Little Dantzic Cove, Fortune Bay; Coalpit Point, St. Mary's Bay; Wreck Cove, Bay de l'Eau; St. John's Head; Little Ma Jambe; St. Jacques Island; Brent Cove, Facheux Bay; Dunfield, Trinity Bay; Goose Cove, Trinity Bay; Coachman Islands, south of Davis Island, Placentia Bay; Northeast Cove, Long Island, Placentia Bay; and Bacon Cove, Conception Bay.

The Class 8 beach at Bacon Cove is composed primarily of fine to medium discoid pebbles. Approximate sand concentrations vary seasonally and yearly between 20% and 40%, with the coarsest conditions characteristic of mid-late autumn and early spring. Minor amounts of coarse pebbles and cobbles are also present throughout the year. Sand clasts are derived from the diamicton exposed along the shoreline and overlying the Cambrian sandstone and conglomerate, from erosion of the Cambrian rocks, and from longshore transport from the north.

The beach slope is concave, with the steepest angles of 25-30° developed in the autumn and directed towards the east and northeast. Bacon Cove is directly open to winds from this quadrant. Asymmetrical cuspate structures indicate that longshore transport towards the south and southeast also remobilizes the discoid pebbles. Pebble fabric patterns suggest that the clasts are predominantly moved by longshore transport during the summer, whereas shore-normal transport associated with northeast winds is most effective in the autumn.

At Bradley's Cove, the Class 8 beach is composed of fine pebbles, primarily discoid in shape. Sand concentrations vary between 15% and 40%, but show no consistent pattern of seasonal change. The sand fraction tends to increase during periods of limited storm activity, decreases following terrestrial runoff events, and increases after winters marked by landfast ice development. The beach slope is irregularly concave, with maximum angles of 22°-27°.

The beach at Biscayan Cove is dominated by medium pebbles, and shows a consistent pattern of increasing sand concentrations throughout the late spring and summer, followed by decreases in autumn and winter. Sand concentrations reach maximum values of 60% in the most sheltered areas of the cove, with maximum values of 40% in the more exposed locations. The beach slope is slightly concave to planar, with maximum angles of 19° to 23°, decreasing with increasing sand concentrations.

The Class 8 beaches of the Coast of Bays area have higher proportions of sand, varying seasonally and yearly between 30% and 60%. Beach slopes are moderately to strongly concave, with the steepest angles of 20-30° developed in the autumn and directed towards the southwest, normal to the prevailing wind. Similar variations occur on the Coachman Islands and Northeast Cove, Long Island, shorelines.

Class 8 beaches composed primarily of medium to coarse pebbles, with lesser amounts of cobbles and sand, are present at Coffin Cove, Placentia Bay; Dicks Island, Placentia Bay; Catalina, Trinity Bay; Scott Point, Fortune Bay; south of Gaskiers, St. Mary's Bay; and Bear Cove, Witless Bay, Southern Shore. At these sites, sand represents 30-40% of the sediment. The beaches slope with concave profiles at angles between 14° and 31°. Seasonal variations in slope and texture appear to be relatively minor. Most of the variations in profile can be related to specific storm events, with hurricanes the dominant influence at the Placentia Bay (especially in 1991, 1999, and 2000), St. Mary's Bay (especially in 1995 and 1999), and Fortune Bay sites (especially in 1995 and 2000), and northeast gales critical at Catalina (especially in 1992 and 1994).

The Class 8 beach at Catalina is typical of this group. Cobbles comprise 5-10% of the beach sediment, generally increasing in proportion from spring to summer. Sand represents 20-25% of the sediment in the autumn, but sheltered areas of the beach contain up to 50% sand following spring breakup of shore ice. Periods of shore ice cover lead to an increase in sand content and poorer sorting of clasts, whereas periods of pronounced wind activity (particularly from the east and northeast) result in removal of sand and more textural uniformity. Most of the textural changes are due to the removal or deposition of sand, with the cobbles remaining largely immobile throughout the year. Slope angles vary seasonally and inversely with sand content, from 15° to 25°.

At Bear Cove, mass movement input from adjacent bluffs of glacigenic diamicton also influences the morphology of the upper part of the beach profile. This results in a concave slope, decreasing from >40° at the base of the bluff to 17-22° at the water's edge. The influx of colluvium results in a mixed textural assemblage on the beach, with lateral and longitudinal gradations controlled by mass movement events rather than by marine processes throughout most of the year.

8.9 Class 9 -- Sand & Gravel Beach with Rock Cliff

Class 9 beaches contain modal concentrations of between 30% and 70% sand. Seasonal and annual variations in texture are common. Lengths and widths are generally similar to those of the gravel-dominated pocket beaches of Class 6, and the Class 9 beaches can also be considered as "pocket beaches". Steep mixed sediment beaches in excess of 100 m in length are assigned to shore Class 18.

Mixed sediment beaches develop at the base of steep cliffs where frost-wedged clasts, generally boulders, cobbles, and coarse pebbles, are joined by pebbles, granules, and sand derived from other sources. Along the shoreline, sand may originate from Quaternary glaciofluvial units, glacigenic and colluvial diamictons, bluffs of Quaternary deposits up-current that are prone to slope failure, and from focusing of deposition of sand derived from distal up-current locations or from nearby offshore sources. The variety of bedrock units which crop out along the shoreline, and the mineralogy of the glaciofluvial and diamicton deposits derived from them, allows the provenance and transport direction of coarse sands and fine gravels to be determined. Distinctive clast assemblages are derived from granitic and volcanic bedrock, Palaeozoic sedimentary rock units, and glacigenic sediments formed through erosion of these lithologies.

The generally thin and discontinuous Quaternary sediment cover, especially in coastal regions, limits the formation of Class 9 shorelines. The coarser class 6 shorelines are more prevalent around the Avalon Peninsula, on the southern shore of the Bonavista Peninsula, and along the islands of Placentia Bay.

All examples along Conception Bay and southwestern Trinity Bay have gravel contents in excess of sand, with sand contents of 30%-40%. Along Placentia Bay, however, sand contents vary from >60% to <40%, in response to difference in bedrock sources and sea ice activity. Decreased sea ice influence allows reworking throughout the winter, resulting in erosion of the clasts and increased sand contents. This is especially noteworthy at Golden Bay (Cape St. Mary's reserve), where conditions have varied from gravel-dominated to sand-dominated in response to ice influence. Years where ice influence was minimal (such as 1997-98) result in increased sand concentrations. In contrast, years where ice foot development occurred (such as 1991-92) resulted in the formation of a gravel-dominated beach.

In the Bay d'Espoir-Connaigre Bay-western Fortune Bay region, the presence of lower modal energy conditions, the general absence of sea ice activity in many locations, and the production of sand-sized clasts from crystalline granitic and gabbro bedrock, favour the development of mixed sand-and-gravel beaches. Along Fortune Bay and the Coast of Bays, class 9 beaches are thus more common than the coarser pocket beaches of class 6.

Class 9 shores have lesser slopes than do Class 6 beaches. Slopes are controlled by texture, with angles generally between 6° (where sand contents are >60%) and 25° (sand contents <40%). Along Conception Bay, sand contents fluctuate seasonally and in response to reworking due to northeast gales, falling to <20% after a period of severe activity (e.g. October 1992). Maximum slopes on these beaches exceed 30°. On these beaches, the surface profiles are moderately concave. Similar beaches are present along the Southern Shore at Coldeast Point and Ferryland; at Double Road Point, St Mary's Bay; and along Placentia Bay at Maurice Poole Cove and Maricot Island Cove. At Double Road Point, slope angles decrease in response to hurricanes and winter storms. Following hurricane 'Irene' (1999), slope angles as low as 10° were noted.

On all of these beaches, the steepest slopes are aligned at sharply acute angles (60- 90°) to the trend of the beach front. Divergence of slopes along the shoreline may occur, but is less common than is evident on gravel pocket beaches. Cuspate features develop rarely, and when produced are generally poorly formed and ephemeral.

Storm reworking results in temporary modification of these beaches, particularly along the St. Mary's Bay and Placentia Bay shores. Coarse pebbles and cobbles are frequently exhumed by storms, but rapid re-burial by sand, granules, and fine pebbles commonly occurs. Coves that are confined by headlands, especially those aligned at 90° to the strongest storm winds, are marked by cyclical movement of the sand fraction, with sand being swept offshore during backwash from storm surges and then returning to the beach subsequently. These beaches, such as Jugglers Cove (Conception Bay), and Golden Bay, thus will appear to maintain a relatively consistent texture, unless they are photographed or visited within approximately 2-4 weeks of a major storm. However, fluctuations in beach texture from year to year will result from changes in storm frequency and sea ice influence: both processes tend to result in coarser-grained beaches.

Jugglers Cove, northeast of Bay Roberts, is the site of an abandoned settlement. During the period of human occupation, shoreline modification and land clearance resulted in the production of enhanced amounts of sand. This material has been washed downslope into the cove, where it has remained trapped by a submarine bedrock ridge. The cove is open to the southeast, and thus is sheltered from the full effects of northeast winds. Consequently, although the sand is moved alternately away from and towards the shoreline, it has remained in the cove, contributing to the beach morphology.

Coves that are less confined or unconfined are marked by substantial longshore movement of sand, and consequently show variations in texture with temporally shifting wind directions. Along Conception Bay, examples of this type of Class 9 shoreline include Bishops Cove, and Freshwater Cove, Bell Island. Although these shorelines are dominated by gravel, periods marked by an absence of storm, sea ice, and ice foot activity and enhanced frost weathering will result in the accumulation of more sand ("40%), and the development of more planar profiles with gentler slopes (15-20°). Placentia Bay beaches with higher proportions of sand, such as Coffin Cove, Red Land Cove, Dough Ball Cove, and Silver Bay; and the eastern shore of Northeast Arm, Trepassey Bay, show similar patterns. At Northeast Arm, the lack of sea ice in most years results in gradual accumulation of sand, which remains in the system until the beach is subjected to a severe winter storm.

Along the western shore of Belle Bay, a Class 9 shoreline has developed where South West Brook empties into Cinq Islands Bay. This embayment faces northeast and is thus sheltered from the prevailing southwesterly winds. Consequently, the beach is a low energy environment throughout most of the year. Sand and gravel is transported seaward by South West Brook. Marine transport is confined to shore-normal movement of medium to fine sand, which accumulates at the river mouth. Wave action is insufficient to remove substantial quantities of sand, and the system is dissipative. The beach has a gently to moderately concave surface profile, with a maximum slope of 15°. Sand content varies between 25% and 60%. Areas with more sand are marked by gentler slopes. Cuspate features are not present.

Another class 9 shoreline is developed on the eastern side of Cock-and-Hen Cove, St. Joseph's Cove, Bay d'Espoir. This cove is open to the south, but its position near the head of

Bay d'Espoir limits its exposure to strong southwesterly winds and high energy wave reworking. However, its more exposed nature in comparison to South West Brook Cove results in morphological differences. At Cock-and-Hen Cove, the surface profile is moderately to strongly concave, with maximum slopes of 22°. Ephemeral, poorly developed symmetrical cuspate features develop rarely. Class 9 shorelines along southern Fortune Bay, such as those at Great Dantzic Cove, Garnish, and Fox Hummocks, are similar.

The laterally restricted nature of the harbours where the majority of Class 9 beaches are located precludes most forms of anthropogenic development and modification. Extraction of sand from these beaches would probably cause initial degradation, but offshore sediment sources and/or Quaternary sediments onshore would be able to re-supply the beaches with sand. Substantial modification would only result if the sediment supplies were truncated or currents were diverted from the beach sites.

8.10 Class 10 -- Sand Beach on Wide Rock Platform

Beaches with sand concentrations in excess of 70% are uncommon along the eastern Newfoundland shore. The lithology of the bedrock units, the prevalence of frost weathering, the scarcity of fine-grained Quaternary sedimentary deposits onshore, the steep slopes, and the high energy environments (either pervasive or associated with storm activity) characteristic of much of the shoreline effectively limit the opportunities for developing sandy beaches. These factors are especially evident in locations where the bedrock comprises a substantial element of the shoreline. Consequently, examples of sand beaches associated with rock platforms or cliffs are extremely rare in Newfoundland.

The only example of a Class 10 zone observed along the coast is located along the eastern side of Lance Cove, southwest of Branch. This zone grades laterally to the south into a sandy beach on a narrower rock platform (Class 11 beach). To the west, the zone grades into an open sand flat (Class 19). The relative lateral extent of the Class 10, Class 11, and Class 19 shores shift marginally throughout the seasons, and between years, but the basic character of the rock platform supported part of Lance Cove has changed little between summer 1981 and autumn 1999.

The Class 10 zone extends for approximately 50 m along the shore, and is 30-40 m wide at low tide. The sand in this area consists of moderately sorted, medium and fine-grained, subrounded discoid clasts. Quartz, feldspar, argillite, slate, shale, hornblende, biotite, and other heavy minerals are present. The sand is derived from aeolian dome dunes that back the main sand flat to the west, and is transported to the rock platform area by beach-parallel drift, recycling from offshore areas, and rarely by northwesterly winds that rework the dunefield and move sand directly to the platform area. Minor aeolian reworking also occurs over the supratidal areas. Beach-parallel drift is the dominant process under all but strong hurricane conditions.

Sand flux is high in all seasons except mid- to late winter. Ice foot development occurred over part of the sand flat in the winters from 1990-95, and the remaining terrain was largely frozen. In milder winters, notably the El Niño year of 1997-98, an ice foot did not form. Patches of beach sediment remained unfrozen throughout the winter, facilitating reworking. The combination of milder winter conditions and enhanced storm frequency, particularly hurricanes, would result in more beach reworking and in redistribution of sediment from the dunes to the beach and nearshore. In contrast, a year with minimal hurricane frequency and substantial beach icing would minimize erosion. Observations of the beach in 1992 (following hurricane 'Bob' in summer 1991, the Hallowe'en Storm of October 1991, and substantial icing in winter 1991-92) suggest that the influence of winter icing is more important in minimizing erosion than are hurricanes in promoting it. The absence of hurricane activity in summer 1997 was followed by minimal shore ice development and inland snow cover in winter 1997-98, and erosion was evident in the following spring. Sand flux to the beach from the dunes is further enhanced by anthropogenic activity, including ATV use and sheep herding (Catto 1994c). The ongoing erosion due to sheep herding has accelerated since 1992, aided by mild winters and by the cumulative effects of degradation. Trough blowouts initially created by sheep, ATV, and human foot traffic have propagated and deepened across the dunes.

After a period of minimal erosion, the beach is marked by a gentle slope (2°-8°) with a planar to very gently concave profile. Slope angles increased to 8-12° following the winter of 1997-98, but gradually declined to 5-10° in autumn 1999, and to 4-8° in late autumn 2000. Local convex slopes below the high tide line are more common following erosional phases, but can be observed during periods of quiescence. Cuspate structures are not developed, but irregular zones of very fine swash-and-backwash scour patterns are present during calm periods, produced by minute low-energy vortex currents within the incoming and outgoing water masses. The angles between the swash and backwash features vary from 35° to 70°. Swash oriented parallel to the shore face tends to produce backwash oriented at 35–45° to the shore, and generally occurs during low to moderately low energy conditions. In contrast, very low energy conditions permit beach drift to become more effective, and the resulting backwash scours are oriented at shallower angles (50–70°) with respect to the swash. Throughout this segment of shoreline, however, the acute angles between swash and backwash indicate that transport of particles approximately normal to the shore (onshore-offshore movement) is dominant over beach-parallel drift. These features are highly ephemeral, frequently lasting only until the next large swash wave destroys the old pattern and begins designing a new one.

Ripples are also developed under low energy conditions. Characteristically, only swash produces ripples. The ripples are straight-crested, in phase, with sharp crests and distinctive stoss slopes (angles of 10-15°) and lee slopes (angles of 22-26°). Typical crest-trough heights (amplitudes) are 2-4 cm, and typical wavelengths are 8-15 cm. Wavelength/amplitude ratios (ripple index of Tanner, 1967) range between 4 and 7, representing typical values for low-energy ripples produced under essentially unidirectional water flow. The internal structures are marked by fine planar lee-side laminations defined by heavy mineral monolayers and di-layers, spaced at 0.1-0.2 cm intervals. Stoss-side structures are not preserved. Preservation of the ripples is rare. Heavy mineral segregation on the beach is common, resulting from differential entrainment and transport by swash action (Hamilton and Collins 1998).

When the beach is subject to moderate energy waves, diffuse sand sheet and grain flow activity is constant. Sedimentary structures produced during low energy events are not preserved, and the sheeting and grain flows do not generate sedimentary structures that can be discerned after activity ceases. Sediment below the surface of the beach is internally structureless, indicating that reworking during moderate energy periods is common. Bioturbation by marine organisms has not been observed on the beach surface. Disturbances by sheep, however, are evident.

8.11 Class 11 -- Sand Beach on Narrow Rock Platform

Class 11 beaches differ from those of Class 10 in that they are developed on narrow rock platforms. In addition to the beach flanking the Class 10 shore at Lance Cove, additional Class 11 shorelines are present at the westernmost extremity of Lance Cove; along the western shore of Woody Island south of Jeans Cove, Placentia Bay; along part of the north shore of Barred Island, Placentia Bay; at Three Sticks Cove, Little Lawn Harbour; and at Northern Bay Sands, Conception Bay.

The shorelines at the Placentia Bay localities differ from the Lance Cove system in that the sand is supplied primarily by beach parallel drift sediments derived from the erosion of coastal bluffs and other beach deposits, rather than being derived from aeolian sediments. Consequently, the sediments are dominantly coarse sand and granules at these localities. At Barred Island, moderately sorted coarse sand and granules dominate a gently sloping beach (2-6°), flanked laterally by sand and gravel flats (shore classes 16 and 17). The shore is marked by low energy conditions at most times, and the area serves as a temporary and permanent repository for sand following beach-parallel currents around Barred Island and across to the mainland at Land Hummock. Cuspate structures have not been observed on this beach, and the coarse sand and granule texture precludes almost all ripple development. The dominant sedimentary structures are discontinuous planar parallel sand laminae, dipping seaward at 2°-6° parallel to the beach face slope. Frequent reworking results in destruction of these laminations. Bioturbation and aeolian modification of the sediments are not apparent.

At Three Sticks Cove, the sediment varies in sorting and modal texture. Moderately sorted deposits of medium-coarse sand and granules are associated with periods following higher energy hurricane-driven waves. An increase in terrestrial sediment supply, transported by runoff, is apparent following hurricane activity. During periods of relative quiescence, sorting improves, terrestrial supply decreases, and the beach is dominated by coarse sand. Ripples and cuspate structures have not been observed.

The Class 11 beaches along the Placentia Bay shore thus undergo more seasonal and year-to-year variation than does the Class 10 beach at Lance Cove, but the beaches still maintain their essential character at all times. At Lance Cove, the Class 11 beaches have remained essentially constant in character throughout the period from July 1981 to December 2000.

Northern Bay Sands is unique among eastern Newfoundland shorelines, as an exposed sandy beach that is not fed primarily by aeolian dunes. Although aeolian sediments are present in the back-beach area, they are confined to structureless, approximately horizontal layers of sand. Sand entrapment depends upon grasses and sedges. The construction of the parking lot along the southern side of the back beach area has further reduced terrestrial sediment supply.

The sandy shoreline is gently concave in plan view, extends for 750 metres, and has a maximum width of 110 metres. At both its northern and southern margins, the beach is backed by sandstone cliffs of the Gibbett Hill Formation (Signal Hill Group), which dips northwestward (inland) at 40° (King 1988). These bedrock outcrops are susceptible to frost weathering, as spray is frequently trapped along the landward-sloping bedding bedding plane surfaces. Precipitation also is trapped along these surfaces, and is retained for longer periods here than in areas where the bedrock dips seaward. As frost wedging can occur under warmer temperatures for fresh water precipitation than for saline sea spray, the landward dip of the bedrock promotes more rapid weathering. Fractures are also present, developed parallel to the bedding planes. These cliffs thus contribute sand and granules to the beach system. Sand input also comes from the glacigenic sediment bluffs backing the central and southern segments of the shoreline (Catto 1993a).

Terrestrial material is transported seaward by fast-flowing, shallow (generally <20 cm depth), somewhat ephemeral streams characterized by seasonal development of antidunes. In the past ten years, additional sediment input has resulted as a consequence of anthropogenic disturbance of areas extending north to Caplin Cove, as a result of dredging and littoral construction. Sheep rearing has increased throughout the Conception Bay North region following the imposition of the Northern Cod Moratorium in 1992, resulting in increased erosion of coastal sediment exposures and increased input of sand to the coastal drift. The sand influx has resulted in a general textural fining along all the sand-containing systems of the northern Conception Bay coastline, and in increases in the proportion of sand in systems with mixed sediment.

Ice foot development is a major factor at Northern Bay Sands. From 1989 through 1995, ice foot development occurred in every winter, a pattern resumed in 1999-2000 and 2000-01. The ice foot developed in late December-early January, and reached a thickness of 60-70 cm by late March or early April. During the winter months, virtually no sedimentary activity occurred on the system, except for minor niveo-aeolian reworking of the backbeach areas. The subsequent spring profiles thus reflected the conditions of late autumn. Modification proceeded throughout late April, May, and early June, by which time an essentially planar surface profile had become reestablished, sloping seaward at <2°. The texture of the beach is controlled by shore-parallel transport in a southerly direction. During the late spring, following the breakup of the seasonal ice foot, the beach generally fined from granules and coarse sand in the north to fine-medium sand in the south.

Ice foot development was minimal in the winters 1995-96 and 1998-99, and nonexistent in winter 1997-98. During these winters, the amount of sediment reworking was controlled by snow cover extent on the beach. Exposed beach areas, although subjected to sub-zero temperatures, did not remain frozen throughout the winter. Consequently, enhanced erosion was possible during the winter months, especially under the El Niño influenced conditions of winter 1997-98, when snow cover was also greatly reduced. In these periods, the beach was eroded from its late autumn configuration, resulting in a marginal steepening of the beach front (maximum 8°), and an increase in sediment coarseness, with coarse sand dominant in the southern part, and granules and fine pebbles in the northern part.

Throughout the summer and autumn, Northern Bay Sands is characteristically drift-aligned, marked by longshore sediment flux from north to south. Interference by edge wave development alters the pattern of longshore transport when southerly winds are dominant, and segments of the beach show transitory swash-aligned features under these circumstances.

Summer and early fall profiles in areas undisturbed by tourist utilization are very gently concave to planar, with slopes of <1°-3°. During late autumn, the beach front is steepened through erosion by south-flowing shore-parallel currents, reaching a maximum slope of 6° and developing irregularly alternating convex-concave profiles in the intertidal and lower supratidal areas. Northeast storms accentuate the longshore tendency, accelerating profile modification but leaving the shoreline configuration unaltered. On rare occasions when southeast winds are significant (as in November 1994), the shore is eroded by shore-normal waves, and a temporary steep beach front with slopes to 10° develops. These slopes, however, are rapidly modified and lowered when the longshore currents are reestablished and drift alignment dominates.

Northern Bay Sands exhibits both periods marked by dissipative conditions, and periods where reflective conditions are dominant. Shore-parallel and shore-normal transport can both occur in association with temporary reflective and dissipative regimes. These fluctuations result in sedimentary features that are transitory and highly ephemeral, and contribute to the general featurelessness of many parts of the beach (even in undisturbed areas). Subaqueous ripples are characteristically straight-crested with low sinuosity, and have ripple indices ranging from 3 to 8 (c.f. Tanner 1967). Aeolian ripples and adhesion structures also are common. Cuspate structures are very rarely developed and are ephemeral. Swash /backwash angles on the beach range between 60° and 150°. The high degree of variation reflects the sporadic shifting between shore-normal and shore-parallel transport modes.

Hurricane winds are generally ineffective at modifying Northern Bay Sands. Precipitation maxima resulting from 'Bob', 'Opal', 'Hortense', and 'Irene' increased stream flow across the beach, resulting in the addition of coarse sand and granules to the shoreline and nearshore zones, but did not affect any long-term changes to the system. The great hurricane of 12 September 1775, however, produced waves estimated to be in excess of 10 m high along the eastern Newfoundland coastline. Strong waves swept across the beach system and resulted in casualties among residents of Northern Bay (Stevens and Staveley 1991, Stevens 1995; Ruffman 1995b, 1996). No sedimentological trace of the 1775 storm has been discovered at Northern Bay Sands, however, although further investigations are required. The configuration of Northern Bay renders it vulnerable to high storm or tsunami waves, and ongoing sea level rise poses a continuing problem.

Despite the relatively high rate of visitation (by Newfoundland standards), the anthropogenic impact on Northern Bay Sands has been much less than at other Avalon localities such as Topsail Beach and Salmon Cove, or at Frenchman's Cove, Fortune Bay. The exposed nature of the beach and the strong component of shore-parallel transport allow constant replenishment of the sands of the beach system. There are no significant impediments to transport to the north of the sands. Anthropogenic disturbance has increased erosion of more northerly areas, resulting in an enhanced sediment influx to Northern Bay.

8.12 Class 12 -- Sand Beach with Rock Cliff

Class 12 shorelines, sand beaches backed by rock cliffs, are uncommon along the eastern Newfoundland shoreline. Genesis of a Class 12 shoreline requires bedrock that either is dominantly sandstone or weathers to sand-sized particles, along with low to moderate energy conditions. Cliff heights are generally less than 15 m. In most "pocket beach" situations, focusing of wave energy during storm events results in the removal of sand-sized material, and frost weathering produces larger clasts. Terrestrial sediment input from streams is generally minimal in steep cliff areas. The Class 12 shorelines are thus much more areally restricted than are those of Classes 6 and 9.

Two examples are located along the south coast of Brunette Island, and along the northern shore of Saltwater Cove, St. John's Bay. These beaches develop where sand supply is abundant, and where the sand can be eroded and re-mobilized as a result of strong southwesterly winds and hurricanes. During the spring and autumn, generally lower energy conditions permit the sand to remain largely undisturbed and unaltered on the beaches. The absence of hurricane activity during 1997, and the limited activity from 1998-2000, has resulted in a relatively long period of quiescence on these systems, which were last significantly influenced by hurricane 'Opal' in 1995.

In the sand-dominated area of Saltwater Cove, beach slopes are 4-8°. After a period of quiescence, the beach lacks cuspate features, and has a regular planar slope without sedimentary structures. Small patches of vegetation develop where significant reworking has not occurred during the summer. The beaches would thus remain similar in character from year to year, unless subjected to a direct attack by an anomalously large storm. The hurricanes of the 1990's and 2000 have not resulted in any permanent changes to the character of these systems. At Saltwater Cove, the configuration of the coastline and the local bathymetry act to deflect waves generated by southwest winds away from the beach.

Examples of Class 12 shorelines along the Placentia Bay shore include Murphy's Cove, Little Lawn Harbour; segments of shoreline west and south of Dock Point, D'Argent Bay; and two segments of shoreline along the southern margins of Flat Island, south and west of Roche Peak. All of these shores are backed by friable rock cliffs 10 m or less in height.

The Flat Island shores are typical of those of Class 12. The beaches are exposed to storm waves during autumn gales, resulting in erosion of the cliffs by wave action and a consequent supply of coarse sand and granules for the beaches. During the spring and summer months, generally lower energy conditions (particularly in Flat Island Harbour) permit the sand to remain largely undisturbed and unaltered on the beaches. Beach slopes are low (estimated at " 5°). Aerial reconnaissance indicates that the beaches are not marked by conspicuous cuspate features, suggesting that wave reworking during the summer is generally at a minimum. Small patches of vegetation also indicate that significant reworking does not occur during the summer. The beaches would thus remain similar in character from year to year, unless subjected to a direct attack by an anomalously large storm. In most areas of Class 12 shoreline, the configuration of the coastline and the local bathymetry act to deflect wave activity away from the beaches.

At Murphy's Cove, hurricanes and winter storms modify the beach unhindered by shore ice, resulting in a steady influx of coarse and medium-grained sand. Low energy conditions are prevalent only in the spring and early summer. Sand mobility is high, and ripple forms are ephemeral. Beach slopes vary from 4° to 16°, with variations dependent on aspect, grain texture, and precipitation events. Higher slope angles form where sand is temporarily saturated by rainfall, or where sand in the supratidal zone has been saturated by storm waves. Wave reworking is constant throughout most summers, resulting in the sequential development and destruction of cuspate features. The mobility of the sand and the gentle slope of the beach preclude the development of stacked tiers of cusps.

The only example of a Class 12 shoreline along Conception Bay is located at Salmon Cove. This site, which is dominated by sand flats (Classes 19 and 20), is discussed below. Class 12 shorelines are absent from the Trinity Bay shore.

8.13 Class 13 -- Wide Gravel Flat

Wide gravel flat shores are defined as those where gravel of all grades is the dominant textural component, with less than 30% sand and fine sediments, which have maximum widths at mean low tide in excess of 30 m. A relationship exists between mean low tidal width and beach texture, with the coarsest beaches generally associated with the smallest widths. Along Fortune Bay, Bay d'Espoir, and Connaigre Bay, sand contents generally exceed 10% (typically 20-25%), and beach widths exceed 50 m. Burin Peninsula beaches along Placentia Bay resemble those of the Fortune Bay coast. Along northwestern and eastern Placentia Bay, St. Mary's Bay, and Trepassey Bay, sand contents vary from <5% to " 30%. Beaches that alternate between gravel flats and mixed sand-and-gravel flats (e.g. Biscay Bay, Portugal Cove South) tend to be wider than those with high proportions of boulder and cobble gravel (e.g. north part of Big Barasway, Placentia Bay). Class 13 gravel flats along the Southern Shore (e.g. Witless Bay Brook), Conception Bay shore (e.g. Clarke's Beach), and Trinity Bay shore (e.g. gravel-dominated areas of Bellevue Beach) tend to be dominated by coarser gravels and are less than 50 m in mean low tide width.

The Class 13 shores vary substantially in sediment texture, small- and large-scale sedimentary structures, overall morphology, and genesis. Textural assemblages range across the entire spectrum of gravel deposits, from boulder and coarse cobble-dominated assemblages, representing essentially relict sedimentary deposits formed during deglaciation (north part of Big Barasway, Placentia Bay); to those dominated by pebbles and cobbles (Ship Cove, Placentia Bay; Haystack Harbour, Placentia Bay); to pebble-dominated systems (O'Donnells, St. Mary's Bay); to assemblages dominated by fine pebbles and granules (John's Pond, St. Mary's Bay; Gooseberry Cove, Placentia Bay); to assemblages where sand and gravel are co-dominant (Saltwater Cove). Along Conception Bay, boulder and coarse cobble-dominated assemblages represent combinations of essentially relict sedimentary deposits formed during deglaciation with material deliberately added to the shoreline during railroad and road construction (parts of Clarkes Beach and Spaniards Bay assemblages). Unaltered boulder-dominated assemblages, such as that at Big Barasway on Placentia Bay (Boger 1994; Catto *et al.* 1997) are not present along Conception Bay.

Sorting varies from very good to extremely poor. On some beaches, seasonal shifts in texture are ubiquitous (Gooseberry Cove, Placentia Bay; Kings Beach, Harbour Grace; Big Barachois, St. Mary's Bay), whereas on others the textural shifts are less pronounced and less predictable (Ship Cove, Placentia Bay; Arnold's Cove, Placentia Bay), and on still others little textural change with the seasons is observed (Angel's Cove, Placentia Bay; Harricott Pond, St. Mary's Bay). Individual segments of complex, lengthy beaches such as Big Barasway, Placentia Bay, and Green Point-Point Verde-Placentia Roads show differing patterns of textural variation along their lengths, both seasonally and in response to individual storm events. Beaches also differ in texture depending on the style of sediment transportation (shore-parallel, shore-normal, or oblique), and on the relative strength and consistency of seaward sediment movement. Similar variations have been recorded on other gravel and sand beaches subject to differing energy levels (e.g. Carr *et al.* 1982; Dubois 1989; Miller *et al.* 1989; Héquette and Ruz 1990; Jennings and Smyth 1990; Thom and Wall 1991; Medina *et al.* 1994).

Textural shifts cannot be generalized between adjacent beaches, or from segment to segment of the same beach. The effect of Hurricane 'Bob' (summer 1991) on the texture of central Cape Shore beaches was negligible on Angel's Cove and the southwestern part of the Point Verde system; very limited on Patrick's Cove, most of Big Barasway, and the central and southern parts of Point Verde; evident on Gooseberry Cove, Ship Cove, and the outlet area of Big Barasway; and extremely pronounced (involving removal of almost all of the granules and medium pebbles, coupled with substantial erosion) on the eastern part of the Point Verde system. Fluctuations in the morphology of the Cape Shore beaches were evident after the Hallowe'en storm of October 1991, and storms in late December 1991 and March-April 1992, but the northeast storms of early October 1992 had virtually no impact on this shore. The 'Storm of the Century' (March 1993) had no impact on any of these systems, as most areas were still covered by seasonal ice and snow. The hyperactive hurricane season of 1995 resulted in erosion in the southern part of the Cape Shore (particularly St. Brides, Angel's Cove, and Patrick's Cove), but was less effective further north, with only Point Verde showing noticeable textural changes. The 'Saros' storm (December 1995) also modified the beaches of the southern part of the Cape Shore, but caused no significant changes to beaches to the north of Big Barasway. Hurricanes in 1996, 1998, and 1999 did not result in substantial modification of these gravel flats, but ongoing coastal erosion in the absence of sea ice and ice foot development since winter 1995 has resulted in a gradual steepening and coarsening of gravel flat profiles along the Cape Shore, as well as the erosion of coastal lagoonal sediments at Patrick's Cove, Angel's Cove, and Big Barasway. Hurricane 'Michael' resulted in local erosion along segments of beaches, but there was no significant net erosion of sediment. Sediment was laterally transferred within individual coves, but largely remained within each embayment.

Variations in overall morphology of these beaches are common. Many beaches undergo periodic cycles of erosion and deposition throughout the year, leading to changes in slope angle, development of temporary shore-parallel spits and bars, and collapse of oversteepened fronts. Variations are also evident between years. The central Cape Shore beaches generally suffered from a deficiency of sediment in 1992, leading to erosion of different magnitudes along the shore (e.g. minor at Ship Cove, moderate at Gooseberry Cove, extensive at Big Barasway). The previous two years were marked generally by a net excess of deposition over erosion. The spring of 1993 was marked by a small net deposition at most of these systems, but erosion continued at others (e.g. Patrick's Cove and parts of Big Barasway). Deposition dominated at most beach systems in 1994, but the hyperactive hurricane season of 1995 and the 'Saros' event in December 1995 triggered erosion at most sites. From winter 1995 to December 2000, the general trend has been in favour of erosion at beaches dominated by coarse pebble, cobble, or boulder gravel, and for deposition or approximately neutral sediment flux at finer sediment beaches.

Similar variations since 1966 are evident through comparison of aerial photography of many of the gravel flats throughout eastern Newfoundland. Textural variations in response to storms are most in evidence on beaches which have higher proportions of pebbles and fine cobbles, and which are not directly fed by terrestrial streams. Response to hurricanes is greatest along the eastern Placentia Bay shore and the exposed parts of the eastern St. Mary's Bay shore and Trepassey sub-peninsula, especially at Holyrood Pond Beach (Forbes 1984), Peter's River Beach (Nichols 1995), and Shoal Bay, St. Mary's Bay. Beaches along the Conception Bay shore and Trinity Bay shore (e.g. Bellevue Beach) respond most effectively to northeast gales. Class 13 shores along the South Coast generally contain more sand than those found elsewhere in eastern Newfoundland, and textural shifts following hurricanes are uncommon, although the flats are subject to erosion.

Shifts in the quantity and texture of material supplied to the beach by streams, and seasonal fluctuations in stream volume, also lead to alteration of the beach morphology. In many cases, however, variations in stream discharge are associated with high precipitation during storms. The net result on many beaches is to cancel out the effect of storm reworking, by replacing clasts moved laterally along the shore with those derived from the terrestrial hinterland. This pattern is evident at Big Barachois, St. Mary's Bay, and at Peter's River Beach and Mill Gut (Hamlyn 1995; Nichols 1995). At Big Barachois, sediment textural shifts are related more to changes in river discharge than to marine conditions. At Mill Gut and Peter's River beach, coastal processes dominate, with stream activity playing a greater role at Peter's River beach and an ephemeral role at Mill Gut.

Some wide gravel flats are associated with steep gravel beaches (shore Class 15), and the changes in slope angle throughout the seasons (or from year-to-year) are significant enough to change the designation between these two classifications. Typically, gravel beaches show modal slopes as low as 3°-4° in the late summer, especially where finer pebbles and granules are important constituents of the beach (e.g. Gooseberry Cove, Placentia Bay; Coomb's Cove; John's Pond, St. Mary's Bay). In contrast, storm activity and seasonal fluctuations may combine to produce slopes in excess of 25° during the late autumn and early winter. The beach thus varies seasonally between broad gravel flat conditions, and a complex dominated by one or more steep gravel beaches (shore Class 15). Such beaches are designated as 13/15 zones. Changes in width of the gravel flats over time (from Class 13 to Class 14) are relatively uncommon.

Sedimentary structures, both small- and large-scale, show spatial and temporal variability. Pebble, cobble, and boulder-dominated flats are too coarse to permit the formation of ripples, and the development of small-scale sedimentary structures is confined to granule and fine pebble areas during short periods of relative quiescence. Swash and backwash bar complexes, small cuspate features, and viscous grain flow cones, fans, and sheets mark granule-dominated and some fine pebble-dominated beaches during the early summer months. These features are best developed in areas where ice foot activity has been apparent in the preceding winter. Such features are ephemeral, being destroyed and reformed on a daily basis. Along coastlines exposed to the southwest, these features do not survive, even when hurricanes are absent as in 1997. Along the Conception Bay and Trinity Bay shores, years marked by autumn storms accompanied by northeast winds (1992, 1994) also result in the complete destruction and reworking of these features. In autumns without strong northeasterly gales, many features do survive in a modified form throughout the winter, if partially protected by snow and ice cover along the flat. Spring ice shove, however, results in complete destruction of these features.

Ripples are present only in granule-dominated zones (such as the lower-energy portions of Gooseberry Cove; John's Pond; Coomb's Cove; and Saltwater Cove). At all these sites, the ripples are typically in-phase forms with low sinuosity, narrow (0.5-1.0 cm) crestal platforms, stoss and lee slopes of 3-8° and 10°-20° respectively, and ripple indices (Tanner 1967) ranging between 3 and 9. The ripples formed under higher energy regimes than those evident on sandy beaches (e.g. Class 10), but the energy levels were still relatively low. They are developed by the incoming waves, and are best preserved on inter-channel 'bars' in zones marked by undulating shallow bathymetry (<1 m). Incoming waves attack the shoreline, producing ripples along their lengths. The outgoing waves are generally focused in shallow channels, especially in areas where the shore is marked by cuspate features developed during periods of higher energy. The outgoing waves succeed in destroying the ripples in the channel areas, but frequently leave the intervening bars relatively unaltered. These ripples are ephemeral, and after storms (and in some cases after high tides) the entire ripple system is destroyed.

Large-scale sedimentary structures are present on most wide gravel flats at various times during the year, and may persist throughout an entire year in some zones. Sheets and lenses of gravel, produced by rapid-flowing shallow swash and washover bores triggered by anomalously high waves or storm events, are present on some finer-grained gravel beaches, but are very ephemeral. The most common feature is the gravel cuspate structure, formed by wave activity. Gravel cusps give the beach a scalloped appearance, and are marked by bowl-like hollows open at the seaward margins, separated by sharp points of gravel. The scale of the cusps varies from minimum breadths (along shore) of <10 centimetres to maximums in excess of 10 m. Breadths in excess of 95 m have occurred at Holyrood Pond Beach (Forbes *et al.* 1995). The widths (normal to shore) range from less than 10 cm to 1.5 m, and the depths (crown to base of hollow) range from 2 cm (one clast thickness) to >1.5 m. Slope angles within the hollows may exceed 45°, but are generally between 12° and 25°.

The overall shape of the hollows varies from essentially circular, with a deep central depression, steep back slopes, and a lip at the seaward edge; to shallow depressions, with widths much less than breadths, and no seaward lip; to elongate depressions, with breadths less than or approximately equal to widths, that gradually slope landward without a seaward lip. These morphological differences reflect differing wave energy conditions, durations of wave events, the relative importance of onshore-offshore transport *versus* shore-parallel transport, and the relative energies and erosive strengths of the incoming and outgoing water. Shallow structures with breadths much greater than widths represent conditions marked by significant shore-parallel transport, whereas circular structures with strongly concave cross-sections represent very dominant onshore-offshore movement. Storm waves that successfully overtop the back-beach areas usually produce elongate, linearly-sloping depressions, with width greater than breadth, as the waves overtop the barrier and disperse landward forming washover channels, rather than returning as backwash. A seaward lip is produced where the largest materials are initially dislodged from the back wall of the cusp, but are too large to be transported seaward under wave power alone. The cobbles move to the base of the cusp under gravity, but then accumulate on the seaward lip as the water diffuses through them without being able to transport the clasts.

Where the cusps are formed by waves which strike the shore parallel to its trend, and where shore-parallel transport of sediment is negligible, the slopes bordering the depressions are symmetrical and have similar angles with respect to the trend of the shoreline. More commonly, however, the depression and slopes are asymmetrical, with the degree of skewness reflecting the angle of wave attack on the shore and the impact of some longshore transport.

The morphology and pattern of cuspate development thus is highly dependent on local, temporally-varying wave conditions. Cuspate morphology commonly differs throughout the breadth of any gravel flat, differs throughout the seasons or in response to individual storm events. Differences also are attributable to elevation above sea level, as different waves strike the shore at different elevations, and so produce different styles of cusps. Stacked sequences of cusps, reflecting different wave regimes, are common on many gravel beaches along the eastern Newfoundland shoreline, and some cusps remain unaltered for several years. These large features reflect particularly intense storms, and their presence is not a reliable guide to the most recent sedimentation history of the beach.

The degrees of variation between the shorelines grouped together within Class 13, and the spatial and temporal variations within individual wide gravel flat systems, are therefore considerable. Generalizing among Class 13 systems is difficult, and a thoroughly comprehensive approach would necessitate monitoring individual beaches over a period of several years. Wide gravel flats, and associated gravel beaches, studied and documented by researchers include Big Barasway and Ship Cove, Placentia Bay (Boger and Catto 1992, 1993a, 1993b; Boger 1994; Liverman *et al.* 1994a, 1994 b); Placentia (Forbes 1984, Shaw and Forbes 1987, Shawmont Martec 1987, Shaw 1990, Shaw *et al.* 1998); Whiffen Head (Griffiths 1999); Holyrood Pond (Forbes 1984, Liverman *et al.* 1994a, 1994b; Forbes *et al.* 1995); Mill Gut (Hamlyn 1995); Peter's River (Nichols 1995); Biscay Bay (White 1998); Portugal Cove South (Forbes 1984; Liverman *et al.* 1994a, 1994 b); and Bellevue Beach (Forbes 1984). Other examples are presented here.

Along the Bay d'Espoir-Connaigre Bay-western Fortune Bay coast, gravel beaches with less than 10% sand are very uncommon. Removal of sand occurs following hurricane events, but the sand is quickly replenished by longshore current drift on open shorelines. In more restricted coves, sand recycling occurs, with landward shore-normal transport of sand initially washed seaward during storms. In addition, large quantities of sand-sized particles are derived through frost weathering and other terrestrial processes. As a result, systems dominated exclusively by gravel are not present in this region, and the only class 13 shorelines show a temporal variation between gravel-dominated (#13) and mixed sand-and-gravel (#16) conditions. Two examples are located at Coomb's Cove and Saltwater Cove.

The class 16/13 shoreline developed along the southeastern segment of Saltwater Cove is exposed to southwesterly winds, although St. John's Island acts to partially shelter the beach. Class 13 areas are dominated by pebbles, with lesser amounts of sand (varying seasonally from 10-60%). Cuspate structures are present after strong southwesterly wave events. The cusps are greater in breadth parallel to the beach front (3-9 m) than in width (0.4-2 m), suggesting that longshore edge wave movement towards the south is involved in their formation (Allen *et al.* 1996). Strongly asymmetrical slopes indicate that the dominant direction of transport is towards the south, with sediment moving oblique to the shoreline trend at shallow angles (10°-30° azimuth). Slopes measured parallel to the axes of sediment transport are less than 6°.

These shallow, open structures indicate that longshore transport was dominant over shore normal transport during the period of their formation. Shore-parallel transport is also indicated by the presence of ephemeral small bars and spits, oriented transverse to the shoreline. Towards the northern part of the beach, the cusps display gradual changes in morphology, becoming successively wider, more symmetrical, and open to the southwest. These features are transitional to the cusps produced by shore-normal activity that characterize the northeastern segment of Saltwater Cove beach.

In contrast, along the Conception Bay coast, most Class 13 shores contain less than 10% sand-sized particles, and widths rarely exceed 50 m. Wide gravel flat areas are associated with many communities with historical roots in the fishery, although some are not currently marked by activity. Anthropogenic modification of the shorelines began upon occupation, and has continued to the present.

The gravel flat along the Spaniards Bay coast northwest of Bay Roberts is marked by moderate to high energy conditions throughout the year. Except when ice foot development precludes sediment reworking (notably during winter 1991-92), pebbles and cobbles are moved onshore by waves. The energy is expended in the offshore and beach front areas, and little outward flow is present. Structures and clast fabric patterns indicate that the beach is reflective and swash-dominated. Swash cusps characteristically have breadths (along shore) of 2-5 m (greatest in 1992; least in 1993 and 1997), widths (normal to shore) of 1 -1.5 m (little variation between 1992 and 1996, lesser widths in 1997 and 1998), and depths of 0.3-1.3 m (greatest in 1996, least in 1992). The cusps are symmetrical about their central axes, and are oriented consistently towards the northeast. The breadths are thus aligned slightly oblique (azimuth deviation 10°-15°) to the trend of the beach front. Slope angles along the cusp back walls, along the central axes, range from minimum values of 8° to maxima of 41°. The lowest slopes were recorded following overwashing associated with the severe northeast storms of October 1992. Higher slope angles are more characteristic of the cusp forms from late summer to late autumn, especially in years where storm overwashing has not occurred (e.g. 1993, 1995, 1997, 1998). During these years, maximum slope angles typically range between 25° and 35°.

A pebble gravel flat developed by shore normal transport, with conditions generally being characterized by moderate to low energy, is present along the northern segment of Clarkes Beach. The area is marked by changes in energy level throughout the summer and autumn, with occasional high energy events associated with storm activity (e.g. autumn 1992, 1994). Overwash cusps produced by storms form a series of chute-like features, generally wider (0.7-2 m) than broad (0.5-1.5 m), aligned approximately normal to the shoreline. The cusps are slightly asymmetrical in plan view, with the degree of asymmetry reflecting the obliquity of wave approach with respect to the shore face orientation. Axial orientations range from east-southeast, deviating eastward by approximately 45° from the northwest-southeast trend of the shoreline, to due north. The axes of the cusps reflect the dominant angles of attack of the waves responsible for their formation. Although many deviations exist, the cusps associated with the northwesternmost part of the beach at low elevations (<2 m asl) are most likely to be aligned towards the southeast. Cusps on the southernmost part of this shore, and those with bases more than 2 m asl, are more likely to be aligned to face the northeast or east-northeast. Cusps facing north are confined to low elevations at the southern end of the system.

The southern part of Clarkes Beach differs from the northern segment. Sediment here is generally coarse pebbles and cobbles, suggesting higher energy levels. The southern segment of Clarkes Beach faces the northeast, and thus is directly exposed to the full force of northeasterly gales in the late summer and autumn. During the storms of autumn 1992, this part of the beach was overtopped on several occasions, and marine sediment was transported over the artificial retaining wall and across the highway into the lagoon to the southwest. Under the influence of northeasterly winds, high energy shore normal transport dominates.

The cuspate structures generally present on this shore indicate that other conditions are more prevalent, however. One or two tiers of cusps have been characteristic between 1995 and late autumn 2000, although tiers are altered during northeast storms of lesser magnitude than the 1992 and 1994 events. Strongly asymmetrical slopes indicate that the dominant direction of transport is towards the southeast, with sediment moving oblique to the shoreline trend at shallow angles (10-30° azimuth). Where two tiers are present, the upper cusps are larger and less well defined than the lower set, but have similar forms and orientations. The cusps are much broader than wide, with breadths occasionally exceeding 3 m and widths rarely exceeding 30 cm. Depths are comparable to widths, and some examples are deeper than they are wide. Slopes measured parallel to the axes of sediment transport rarely exceed 12°.

These shallow, open structures indicate that longshore transport was dominant over shore normal transport during the period of their formation. Shore-parallel transport is also indicated by the presence of ephemeral small bars and spits, oriented transverse to the shoreline. Towards the northern part of the beach, the cusps display gradual changes in morphology, becoming successively wider, more symmetrical, and open to the northeast. These features are transitional to the cusps produced by shore-normal activity that characterize the northern segment of Clarkes Beach.

The southern part of Clarkes Beach differs from the northern segment because shore-parallel and oblique transport is more important and more consistent along this shoreline. Energy levels are generally higher in the southern segment of the beach. The northern segment is less affected by longshore currents, and is somewhat sheltered from the full effects of northeastern winds. An additional factor at the southern end of Clarkes Beach is the return flow seaward parallel to the southeastern shoreline, coupled with fluvial influx from South River. Prior to construction of the Conception Bay Highway, South River discharged directly into Bay de Grave, eroding the southeastern shoreline and creating a bathymetric low. This acted to funnel the outbound current along the shoreline, accelerating water movement. Construction of the modern highway and associated shoreline protective measures have diminished the effect of discharge of South River, as has the development of the aggregate pits upstream and other modifications in land use practices. Consequently, the bathymetric low is likely to gradually become infilled with sediment, reducing the return northeastward flow to Bay de Grave. Eventually, this may alter the southern part of the Clarkes Beach system, causing shore normal transport to gain in relative importance.

Kings Beach, Harbour Grace was a recurved spit, oriented approximately parallel to the shoreline. Prior to modification in conjunction with marina development in spring 1998, it had remained a prominent coastal feature for at least 200 years. The dominant texture of fine pebbles and granules indicated that this shore in general was subject to lower energy levels than are Bay Roberts or Clarkes Beach, although seasonal variations were apparent. The orientation of the spit, as well as the presence of transitory shore-normal bars and spits, suggested that shore parallel transport dominated on a consistent basis. The orientation and development of the spit also indicates the absence of significant tidal influx (c.f. Tessler and de Mahiques 1993).

Cuspate structures were rare, and when present were small, with breadths <1 m, widths <0.5 m, and depths <30 cm. Maximum slopes did not exceed 15°, and most slopes were <5°. The cusps were strongly asymmetrical, and showed a variety of axial orientations suggesting variations in the obliquity of the angles of wave attack. The shoreline was dominated by imbricated sheets of pebbles, inclined normal to the longshore current direction. The imbricated sheets sloped at shallow angles, generally <5°.

As a result of its stability and lower energy levels, Kings Beach has long been a favourite area for landing small boats and for inspecting fishing gear, as well as for other recreational activities. These activities resulted in disturbance to the natural beach morphology and pebble alignments, increasing the flatness and featurelessness of the shore. The morphology of the system was best observed immediately following a storm, but even the major event of autumn 1992 effected relatively little change to the system. The apparent low energy regime of Kings Beach thus can be assumed to represent its actual condition.

The configuration of the flat, as an attached spit oriented oblique to the shore midway along a major embayment, is unique to the Conception Bay region. The stability of the spit was due to its development on the flank of a glacigenic fan delta built into Harbour Grace at the conclusion of the Late Wisconsinan glaciation.

The degrees of variation between the shorelines grouped together within Class 13, and the spatial and temporal variations within individual Class 13 systems, are therefore considerable. Generalizing among Class 13 systems is difficult, and a thoroughly comprehensive approach would necessitate monitoring individual beaches over a period of several years. Similar variations have been recorded in gravel systems in many other areas (e.g. Finkelstein 1982, Carter and Orford 1984, Taylor *et al.* 1986, Duffy *et al.* 1989, Forbes *et al.* 1991, Orford *et al.* 1991, Medina *et al.* 1994, Forbes *et al.* 1995, Orford *et al.* 1996).

8.14 Class 14 -- Narrow Gravel Flat

Class 14 shorelines differ from Class 13 in that the width of the gravel flat is less than 30 m. These shores can develop where steep bathymetry precludes the genesis of a Class 13 shore, or where a bluff of Quaternary sediment provides an ample source of coarse material along a relatively straight, non-embayed, segment of coastline. Along Trinity Bay, an example is located at Hearts Ease Tombolo, where resistant sedimentary strata of the Musgravetown Group have formed an offshore island, as a result of erosion along a SSW-NNE trending bedding plane dipping northwestward at ± 50° (King 1988). The tombolo initially developed during the period of elevated sea level following deglaciation (Catto *et al.* 1993), and the margins were reactivated as sea level rose from the Holocene minimum. The shoreline is protected from all winds except those aligned along the SSW-NNE axis, and is further sheltered by Southeast Head and Long Island. Consequently, reworking is minimized, and the beach is dominated by terrestrial material derived through frost wedging. The clasts are dominantly coarse pebbles, subrounded to subangular. Slopes are concave, with maximum slope angles of 22-26°.

At Hodges Cove, Southwest Arm, Random Sound, a Class 14 shoreline existed prior to anthropogenic modification. This beach was dominated by pebbles, and sloped at 20-25°. Construction of marina facilities, including a large gravel pad of sediment coarser than that naturally present at the site, has resulted in an armoured anthropogenic shoreline that will not be subject to significant modification along Southwest Arm.

Narrow gravel flats exist in alternation with mixed sand-and-gravel conditions at Bellevue Beach, Trinity Bay, although sand is present on most occasions. This shoreline is discussed in more detail below (Class 16).

Along Conception Bay, several examples of narrow gravel flat shorelines have developed. Most Class 14 shores along Conception Bay are composed predominantly of coarse pebbles and cobbles. Sedimentary structures resemble those of the wider gravel flats. Typical examples are located at Holyrood, Grates Cove, and Easter Beach, Kellys Island.

The gravel flat and backing beach at Holyrood is a good example of this class of shoreline. Here, the former railway embankment acts as a back berm for the beach system, providing coarse sediment and serving as a framework element controlling onshore sediment movement and providing stability to the beach system. The surface profile at Holyrood varies from gently sloping planar (modal 4°) extending across the entire breadth of the system (after maximum summer deposition in 1993 and 1997) to strongly concave, with some slope angles in excess of 35°(after the storms of October 1992), to weakly convex with nearshore shores reaching 18° (late autumn 1994). Southwest winds associated with hurricanes can trigger countering northeast winds and waves along the water surface, resulting in enhanced erosion. This effect was particularly marked during the 1995 hurricane season ('Luis' and 'Opal'), and occurred to a lesser extent in 1999 ('Irene') and 2000 ('Michael'). During less effective hurricane events (e.g. summer 1998), the net result was to increase longshore transport of sediment towards Conception Bay South.

Holyrood beach is marked by cuspate structures, which vary in dimensions and configuration areally and temporally along the breadth of the system. At the northwestern end, cusps tend to be shallow, with breadth (parallel to the beach front) in excess of width (normal to the beach front), suggesting that longshore transport towards the southeast is the most persistent process. Cusps developed in association with northeast gales are up to 6 m in breadth, 1.5 m in width, and have depths to 1.5 m. Storm cusps are more symmetrical than those associated with less severe wind conditions. During late summer, modal cusp dimensions are 1.5-2.5 m in breadth, 0.5-1 m in width, and 0.5-1 m in depth. Movement of sediment within these cusps is controlled primarily by longshore transport and secondarily by backwash.

In the central part of the beach, the cusps are less temporally persistent, and vary from well-defined large, semi-circular, steeply sloping features with seaward lips to poorly-defined small, asymmetrical, shallow excavations. Cusps developed by longshore transport towards the southeast are associated with quiescent periods, and are typically 2-3 m in breadth, 0.2-0.5 m in width, and 0.1-0.4 m in depth. These cusps are highly ephemeral, and do not form tiers at consistent elevations across the beach front. Northeast storms generate significant shore-normal transport from the northeast, and form well-defined cusp amphitheatres, with breadths to 5 m, widths to 4 m, depths to 2 m, and frequently well-defined seaward lips up to 15 cm high. The cusps produced by the strongest storms of 1992 and 1994 were marked by flow oriented almost exactly normal to the beach front, but the forms were modified and flattened as a result of seaward flow reflected by the railway embankment.

In the southern part of Holyrood beach, cusps are rare. When present, they are poorly defined features associated with oblique flow towards the east and northeast, along the shoreline, with breadths to 2 m, widths to 0.7 m, and depths to 0.5 m. Depths are always less than widths. These cusps are best developed in association with persistent southwesterly winds, and do not survive during periods of northeast wave activity.

The shore at Easter Beach, Kellys Island, is another example of narrow gravel flat. Here, the coastline is exposed to waves from both southwest and northeast. The cuspate spit developed is thus fed by waves of differing energies, producing textural and morphological differences on each linear segment. Changes in energy and wind direction result in substantial modification of the spit. Under northeasterly winds, the northern flank of the spit is steepened, and the texture coarsens. Southwesterly winds cause similar modifications to the southwestern side. The greater fetch to the northeast, and the strength of the northeasterly gales in 1992 and 1994, resulted in the northeastern side becoming generally coarser and steeper than the southwestern side. The absence of comparably strong northeast winds throughout the period 1995-99, however, coupled with the hyperactive hurricane year of 1995 and the activity of summer 1998, autumn 1999, and autumn 2000, has reversed this trend.

The modal texture of the shore varies from fine to coarse pebbles, and the slope angles range from <5° to >35°. Cuspate structures are infrequently present along the northeastern side of the spit. Along the southwestern side, cusps are more common, and generally have breadths greater than widths, gentle slopes, and shallow depths, indicating shore-parallel transport parallel to the axis of the Bell Island Tickle.

Examples of Class 14 shorelines along the Southern Shore and St. Mary's Bay include the Ferryland area; Meadow Point, Trepassey; St Shotts; Point LaHaye; Shoal Bay Pond; O'Donnells; Big Barachois; and Branch. The steep gravel beaches and narrow gravel flats at Ferryland exhibit a wide range of texture and morphology from season to season, and among locations. Textures range from granules to boulders, but coarse pebbles and cobbles dominate in most zones during most seasons. Cuspate features are uncommon. Slopes range between 8° and 20°, with significant seasonal variability.

At St. Shotts, a narrow gravel flat has developed as terrestrial sediment deposited by the St. Shotts River has joined that eroded from coastal bluffs of Quaternary diamicton and from the grey sandstones and shales of the Trepassey Formation. The bedrock dips seaward, towards the southwest, and the cove's aspect is thus perfectly aligned to receive the full force of hurricane winds, waves, and precipitation. Sediment flux along the shoreline is high. Conditions vary from shore-normal transport during peak storm events, to shore-parallel transport towards the north during periods of swell and quiescence, to shore-parallel transport towards the southeast during northeasterly wind events. Sediment plumes directed offshore from the stream mouth have also been noted. Clast sizes span the range from silt (associated primarily with the back-barrier lagoon) to coarse cobbles. The modal grain size varies from coarse pebbles in the most exposed areas of the system (open to the southwest) to fine pebbles in more sheltered areas. Beach slopes range from 10-25° (modally # 15°). Cusps are common, with maximum breadths noted to 10 m, widths normal to the beach to 2 m, and depths to 1 m. Seaward lips are generally not present. Following strong hurricane events (particularly in 1995 and 1999), overwash chutes and associated fans developed into the back lagoon were apparent across the beach system, with individual chutes excavated to depths of 30 cm and widths of 2 m. Narrow gravel flats exposed to southwest winds at Point La Haye, Shoal Bay Pond, and O'Donnells display similar characteristics.

At Branch and Big Barachois, the gravel flats are somewhat sheltered from the full effect of southwest waves. Consequently, cusp development is less common, and the cusps are less well defined. Both beaches are marked by coarser modal textures and poorer sorting along the shoreface than in the supratidal areas.

Most Class 14 shores along Placentia Bay are composed predominantly of coarse pebbles and cobbles. Sedimentary structures resemble those of the wider gravel flats of Class 13. Typical examples are located at Little Barasway and Southern Harbour.

At Little Barasway, the gravel strand varies along its length and seasonally from 8 m to 25 m at low tide, although the modal tidal range is less than 1.5 m. The modal slope has varied from a low of 3° (after maximum summer deposition in early September 1990) to a maximum of 29° (after severe erosion resulting from the storms of late December 1992). Minimal sea ice conditions between 1995 and spring 2000 have resulted in enhanced coastal erosion and beachfront steepening, although hurricane impact was only significant during this period in summer 1995. Typically, the shore slopes seaward with a gently concave profile, with maximum slopes of 8-12°. Beach front steepening followed the impact of hurricane 'Michael' in autumn 2000, with maximum slopes of 15-20°.

Cuspate structures are infrequently present, and are generally shallow with breadth greatly in excess of width, suggesting significant shore-parallel transport. Typically, cusps are 4-6 m in breadth, less than 1 m in width, and less than 1 m deep. The lack of pronounced embayments limits the focusing of offshore waves. Texture varies with position and season, but most of the beach is composed of coarse pebbles and cobbles (slightly finer at the low tide line). Textural and morphological variations, such as cusp asymmetry (when present) indicate a northward sediment transport direction (c.f. Bartholomä *et al.* 1998).

Sediment supply to the beach is high. The beach is fed by a stream laden with sediment from the sheep-rearing area to the east. Bluff failures are common, especially during storm events, and these provide a mixed textural assemblage ranging from fine and medium sand (derived from capping loess deposits) to coarse cobbles and boulders (derived from glaciomarine diamictons and glaciofluvial gravels). Cliff recession rates locally have exceeded 1 m/a since autumn 1989, and individual blocks representing more than 1 m in depth from the cliff edge commonly fall from the bluff face. Sheep disturbance of the cliff edge sediments also contributes material to the beach. In addition, the shore-parallel current transports sediments derived from the Quaternary bluffs at the north end of Big Barasway, to the south-southwest. Consequently, Little Barasway has enjoyed a period of net sediment accretion from autumn 1989 to December 2000, although hurricane 'Michael' did result in sediment loss from the maximum accumulation in summer 2000. Characteristically, storm activity results only in short-term sediment removal, and subsequent input of new materials from the bluffs and shore-parallel currents has quickly repaired the damage. In addition, much sediment washed to sea during storms returns to the beach at later times. Chunks of terrestrial peat, derived from the Quaternary bluffs, are commonly observed arriving at the beach front from seaward for days after major storms (particularly Hurricanes 'Bob' and 'Irene').

The constancy of sediment supply allows the Little Barasway system to recover rapidly after storms, regaining its basic profile within weeks (days, after lesser storms). Class 14 shores that are less exposed, but also have a less readily available source of sediment, are both less frequently disturbed during storms and are slower to recover. The shores at Southern Harbour exhibit these effects. Recent local construction in the Southern Harbour area has disturbed some of the Quaternary sediment bluffs (by removal of vegetation), and the sediment supply to the system has increased between 1990 and 1992. This increase appears to be causing stabilization of the area, as it was not severely disturbed during any of the most recent storms, and may eventually lead to progradation and the development of a Class 13 shore in this area.

In the Coast of Bays area, the only example present is located at Otter Cove, where the shoreline varies between class #14 and #17 (mixed sand-and-gravel narrow flat), in response to prevailing wave energy conditions. The narrowness of the flat on the western side of Otter Cove, in contrast to the wider flat on the eastern shore, is the result of the combination of the initial topography with the southeasterly aspect. The partial shelter from the prevailing winds allows finer sediment (medium sand to fine pebbles) to accumulate on the western side of Otter Cove, and increases the stability of this system. On Otter Cove Point, exposed to southwesterly winds, a steep beach alternately dominated by pebble gravel (class #15) and mixed sand-and-gravel (class #18) has developed.

8.15 Class 15 -- Steep Gravel Beach

Steep gravel beaches commonly exhibit a wide range of texture and morphology from season to season, and among locations. Wide gravel flat/ steep gravel beach (Class 13/15) transitional assemblages (such as Big Barasway, Placentia Bay, and Peter's River-Holyrood Pond) are very common along the eastern Newfoundland shore. Narrow gravel flat/steep gravel beach (Class 14/15) transitional assemblages are less common, but do occur in some places, such as the southern side of Margery Cove Point, Red Island, Placentia Bay. Textures on gravel beaches range from granules to boulders. The dominant texture varies regionally throughout eastern Newfoundland. Along Trinity Bay, Conception Bay, western Placentia Bay, and eastern St. Mary's Bay, coarse pebble-dominated systems are most common. Along the Southern Shore and eastern Placentia Bay, gravel beaches are frequently cobble-dominated. Gravel beaches along western St. Mary's Bay are dominated by medium pebbles. Along Fortune Bay and the South Coast, gravel beaches are less common than elsewhere in eastern Newfoundland, and most are dominated by medium and fine pebbles. Seasonal and/or yearly variations in classification between gravel and sand-and-gravel beaches (Classes 15 and 18) occur in some areas, such as Scrape Cove, Merasheen Island; the north shore of Arnold's Cove; and Little St. Lawrence.

Many examples of steep gravel beaches exist in eastern Newfoundland, some of which are described here. The steep gravel beaches can be divided into three categories: those marked by high-energy conditions throughout most of a typical year; those marked by moderate energy conditions, punctuated by occasional higher-energy events; and those where lower energies generally prevail.

8.15.1 High Energy Class 15 Shorelines

High energy steep gravel beaches are usually reflective in nature throughout the year, although shorter periods of dissipative behaviour are evident at some locations. These shorelines are dominated by shore-normal transport and swash-aligned features, although shore-parallel and oblique transport also occurs locally. These high energy cove systems are developed along indented or embayed coastlines marked by deep bathymetry, which are aligned facing the prevailing (or storm) winds and waves: northeasterly along Conception and Trinity Bays, easterly along the Southern Shore, and southwesterly along Trepassey and Placentia Bays. These coves may undergo intense modification during storm events, followed by long periods of quiescence.

The shorelines that are most intensely affected by northeast gales are confined, deep-water coves flanked by bedrock, which act to funnel northeast winds towards the shoreline. Along Conception Bay, excellent examples are present at Bristol's Hope, Bryant's Cove, and Clement's Cove.

The beach at Bristol's Hope faces northeastward, directly fronting the maximum northeastern fetch, is exposed to all waves generated by northeasterly winds, and is strongly affected by any and all northeasterly storms. The severe storms that marked late September and early October 1992 had a major effect on Bristol's Hope. As the storms of 1993 were less potent, the structures created by the 1992 storms remained intact until high energy events in late summer-autumn 1994, which caused modifications to the lower parts of the beach but left the uppermost areas (above 4 m asl) intact. The 1992 storm features thus escaped modification, and probably would have persisted under natural circumstances until the next comparable storm. The features at Bristol's Hope, however, were destroyed in the process of the reconstruction of the beachfront road in 1994 and 1995, an anthropogenic event which substantially altered the entire system.

Wave environments, sediment transportation, and deposition show gradual transitions along the 280 metre length of the gently concave Bristol's Hope system. The southeastern margin is most exposed to shore normal transport induced by northeasterly winds and waves, and prior to 1995 was marked by strongly concave profiles with as many as six stacked tiers of gravel cusps. Storm waves led to the formation of cuspate structures on the beach, causing temporary irregularities in the profiles. The resulting profiles were made up of several superimposed concave cusps, giving a somewhat scalloped appearance to the overall concave shape. These irregularities persisted until the next major storm. In early September 1992, prior to the severe autumn storms, six tiers of gravel cusps were evident. Following the storm event, all of the cusps were destroyed, save for the uppermost structures created by the storm waves, 6-7 metres above mean sea level. Cusps created by the storm waves had breadths up to 10 m, widths in excess of 5 m, depths to 3 m, and the largest lacked seaward lips. Lower tiers of cusps were gradually been rebuilt by lesser energy waves, and four tiers existed in spring and early summer 1994.

Following road construction, only the two lowest tiers of cusps remained. Northeast winds during the autumn of 1995 were weaker than in any of the previous 4 years, precluding the re-formation of the upper tiers of cusps. In December 1995, two tiers were evident along most of the southeastern margin, with a third intermediate tier present at the southeasternmost edge of the system. The period between December 1995 and autumn 1999 was marked by an absence of strong northeast gales, and limited sea ice and ice foot activity. As a result, the beach front was gradually modified into a series of stacked tiers of small cusps. On the uppermost of three tiers present in summer 1998, at ~2.5 m asl, the cusps had maximum breadths of 3 m, widths of 1.5 m, depths of 0.7 m, and showed pronounced seaward lips. The lowermost tier, at the high tide line, had poorly formed cusps with maximum breadths of 1 m, widths of 0.5 m, depths of 0.2 m, and weak seaward lips. The upper tier of cusps persisted throughout the winter of 1998-99, and a new lower tier with similar dimensions developed at the high tide line in summer 1999.

The winters of 1999-2000 and 2000-01 have seen extensive ice foot development, coupled with minimal northeast wind activity in the preceding autumns. Consequently, the upper tiers of cusps have been gradually modified by downslope creep and surface erosion (in part due to human disturbance), but have not been subjected to wave modification. The lower tier of cusps was protected by the ice foot during winter 1999-2000, but was quickly reworked when the ice ablated, and underwent repeated modification throughout summer 2000.

The northwestern margin is most sheltered from direct impact of the storm waves, but prior to 1995 received a substantial amount of material transported parallel to and oblique to the shore from the high energy southern area during storm events. Along this segment of the beach, the net effect of storm activity was accretion, as sediment from the length of the shoreline was focused in the northwestern area. Stacked tiers of gravel cusps formed ramparts in this area, but the ramparts were generally lower (4 metres a.s.l.) and fewer tiers were evident (maximum of 3). The orientation of the cusps indicated that shore-parallel and shore-normal transport were both involved in their formation, in contrast to the exclusively shore-normal patterns evident in the southern part of the system. The fishing stage at Bristol's Hope, damaged in the 1992 storm, was located at the far northern end of the beach, within the zone marked by the lowest possible energy regime.

Road construction resulted in a reduction of the sediment available for remobilization by storm waves. The road building has lowered the crest height of the beach along its entire length, which will act to facilitate overwash of the beach during the next major storm. In addition, the northern segment of the beach now receives less sediment from the southern zone. The absence of ice foot formation in the winters 1997-98 and 1998-99 has promoted increased erosion of the southern segment, but most of this sediment has been transported away from the beach. The net result has been to leave both sides of the beach more vulnerable to the next major northeast gale.

The situation has improved somewhat as a result of ice foot development in the subsequent winters of 1999-2000 and 2000-01, but the beach remains highly vulnerable to overtopping and overwashing.

In addition to destroying the road, increased overwash activity and shore-normal transport will result in the infilling of the lagoon behind the beach, causing sediment to move inland rather than along the shore. Further storms would serve to accentuate this trend. The net result over time is likely to be a continued flattening of the beach crest, exposing the lagoon and terrain behind to storm wave activity, while inducing further erosion of the now sediment-starved northern segment.

The cusps that have developed along the southeastern and northwestern segments of the beach show morphological differences. These differences reflect differing wave energy conditions, durations of wave events, the relative importance of onshore-offshore transport *versus* shore-parallel transport, and the relative energies and erosive strengths of the incoming and outgoing water. Along the southeastern margin, the hollows between the gravel cusps along the uppermost rampart were elongate, linear depressions, with breadths less than widths, that gradually sloped landward at 3-8°. These depressions were open on the seaward side, rather than being bordered by seaward lips as is common elsewhere along the shoreline. These structures were produced during the height of the 1992 storm by washover events, as waves overtopped the barrier and dispersed landward.

The overall configuration of the hollows between the gravel cusps developed on the lower tiers of the southeastern segment prior to road construction, and those forms developed from 1995 through 2000, is essentially circular in plan view, with a deep central depression, steep back slopes, and a lip at the seaward edge. These circular structures with strongly concave cross-sections represent dominant onshore-offshore movement of water and sediment. The cusps are formed by waves that strike the shore parallel to its trend. At the southeasternmost margin, where shore-parallel transport of sediment is negligible, the slopes bordering the depressions are symmetrical and have similar angles with respect to the trend of the shoreline. Towards the central point of the beach, the depression and slopes are asymmetrical, with the degree of skewness reflecting the oblique angle of wave attack on the shore and the impact of shore-parallel transport.

Along the northwestern segment of the beach, the cusp hollows are shallow, with widths less than breadths, and with weakly developed or no seaward lips. These cusps are formed by shore-parallel transport from the southeast, combined with shore-normal transport from the northwest, and hence are intermediate in form and subject to sporadic modification. The asymmetrical nature of the structures associated with the uppermost tiers indicates that shore-parallel transport was dominant during high-energy events, reflecting the swash-backwash pattern associated with major storms. In contrast, the lower tiers of cusps are generally more symmetrical and have better-developed seaward lips, indicating that under 'normal' conditions, shore-normal transport dominates in the northwestern segment of the cove.

Bryants Cove also faces northeastward, and is exposed to the northeasterly autumn storms. The severe storms of autumn 1992 created cusps that remained intact until high energy events in 1994, which caused modifications to the lower parts of the beach but left the uppermost areas intact. The 1992 storm features thus escaped modification, and have persisted as of December 2000.

Bryants Cove is less embayed and more exposed to wave attack than is Bristol's Hope, and consequently shore parallel (northwest-southeast) and shore oblique transport are of substantial importance. Shore normal transport and reflective conditions, however, are the dominant mode. The more open coastline does not permit wave energy to be focused as effectively as at Bristol's Hope. Thus, Bryants Cove is subjected to generally higher wave energy than is Bristol's Hope, but individual strong storm events are more likely to be destructive at the latter, as was indicated by the relative effects of the storms of autumn 1992 and autumn 1994.

At Bryant's Cove, cusps developed after summer 1994 formed two to four stacked tiers (more to the south), and were generally symmetrical bowls, with seaward lips and back slopes in excess of 30°. The southeastern margin is most exposed to shore normal transport induced by northeasterly winds and waves, and until 1995 was marked by strongly concave profiles with several tiers of stacked gravel cusps. The absence of extreme northeast winds from winter 1995 to December 1999, combined with minimal ice foot formation in winter 1995-96 and none in winter 1997-98 and 1998-99, resulted in reworking of all but the uppermost parts of the beach. The beach profile slope was lowered to 20-25°, and most of the cuspate forms were destroyed. The northwestern margin, less exposed to storm attack, was characterized by poorly formed, shallow cusps prior to 1996. In March 1998, the beach front had been flattened to a slope of 20°, and flattening continued throughout 1998 and 1999. Ice foot development during winter 1999-2000 provided some protection to the lower part of the beach. During summer 2000, the beach profile slope was 20-28°.

At Clements Cove, construction of a beachfront road resulted in substantial modification to the beach. This road, damaged by the storms of autumn 1992 and 1994, was reconstructed in 1995 and 1996. Construction destroyed the upper tiers of cusps formed by the 1992 event, and the lack of comparable storm activity and limited ice foot development since 1994 has precluded formation of new high-level tiers. The crest height of the beach has been lowered by as much as 3 m since 1994, leaving it vulnerable to overwash during the next major storm. Overwash and associated shore-normal transport will result in the infilling of the lagoon behind the beach at Clements Cove, while simultaneously limiting replenishment of the northern segment of the beach.

Along the Southern Shore, examples of high-energy steep gravel beaches are present at Witless Bay, and in the Cappahayden area (Gull Pond Brook Outlet). These beaches face eastward, and hence easterly winds potentially have the greatest effect. The funnel-like nature of the steep cliffs surrounding Witless Bay, however, also act to channel countering easterly winds induced by southwesterly hurricanes into the embayment. Witless Bay is thus affected by a greater variety of wind directions than is the Cappahayden area. Considering storms influencing both sites, however, maximum storm wave heights are generally less in Witless Bay than at Cappahayden. Individual features created by storms thus persist longer at Witless Bay. Prior to anthropogenic disturbance in the mid-1990's, storm features created by a major storm event in 1966 were still visible at Witless Bay.

At Witless Bay, the beach slopes show systematic variation, both spatially and in response to storm events. During periods of quiescence, the southern side of the beach is steeper than the northern side. Typical south beach profiles are strongly concave, with maximum slopes of 25- 30° directly below the berm crest, tapering asymptotically to 3-5° at the mid-tide line. Cusps are moderately well-formed, with maximum breadths of 3 m, maximum widths of 2 m, and maximum depths of 1 m, and have seaward lips. Stacked tiers of cusps are developed during periods without significant storm activity (summer 1992, summer 1993-October 1994, early summer 1996, 1998-summer 1999), with up to four tiers present. In contrast, the northern side of the Witless Bay system is marked by more gently concave profiles, with lesser slopes at the crest (12-20°) and steeper slopes at the mid-tide line (5-8°). Cusps are present only after long periods of quiescence, and are shallow and moderately to poorly formed. The asymmetry of the cusps suggests formation by shore-oblique transport from south to north.

Following a major storm (hurricanes 'Bob', 'Opal', and 'Hortense'; the Hallowe'en Storm of 1991, the northeast gales of Octobers 1992 and 1994, the 'Storm of the Century' of 1993, the Saros storm of 1995, and the storm of 21-23 January 2000), the beach profiles are modified. The bathymetry of Witless Bay, and the headlands to the east, focus wind energy into the cove, regardless of the initial direction of the prevailing storm winds. Many hurricanes develop counterwinds along the water surface. Energy levels are higher on the southern part of the beach, generating both overtopping and overwashing. The beach crest is flattened during overwashing events, and undercutting of the steep slopes directly below the berm result in a reduction in slope following the storms. The resultant profiles are flatter, with maximum slopes of 15-20° and minimal slopes of "10° at the mid-tide line. Cusps, where present, are chute-like in form, with widths up to twice as large as breadths where overwashing has not occurred, and seaward lips are absent. All preexisting cusps below maximum storm wave height are completely destroyed. On the northern part of the beach, the profiles following the storms are steeper and more concave, with maximum crestal slopes to 22° and basal slopes as low as 4°. Cusps are semi-circular and approximately symmetrical in plan view, with maximum widths and breadths of 2-3 m, and depths of 1 m. Weakly developed seaward lips are present in some cusps at the northernmost part of the beach following some storm events.

The differences in profiles and cusp morphology can be attributed to differences in energy levels and transport patterns across the Witless Bay system. The southern end of the beach is subjected to higher energies than the northern end, regardless of the orientation of the storm track. During quiescent periods, shore-oblique transport under a reflective regime moves sediment from the southern to the northern segment, inducing local erosion of the southern margin. Sediment gradually coarsens in this area. During a storm event marked by overwashing at the southern extremity, sediment is moved inland and is lost to the beach system until returned by terrestrial processes. The presence of storm deposits from *ca.* 1966 indicates that fluvial transport is not as effective as storm waves are at mobilizing sediment. The beach crest flattens as sediment is removed by overwashing, and by backwash during lesser events. At the northern part, the storm waves are less effective at moving sediment inland, and backwash results in profile steepening. In quiescent periods, backwash continues to remove sediment from the southern margin, steepening and coarsening that part of the system over time. Shore-oblique transport moves the pebbles to the northern side of the beach, where they accrete to form the less concave profiles.

To the north of Cappahayden at Gull Pond Brook outlet, a coarse pebble beach has been developed from glaciofluvial sediments (Catto 1994a). The shoreline is not confined by headlands, and is open to the east. Under these circumstances, hurricanes are less effective agents of coastal modification, as strong countering winds are not commonly generated. The most effective waves are associated with easterly winds, and swell is also effective in intervals between storms. Reflective conditions prevail throughout the year. Two or three stacked tiers of cusps are present, with breadths up to 5 m, widths to 3 m, and depths to 1.5 m. Cusps in the upper tiers may have seaward lips. The cusps are generally symmetrical in plan view, and their morphology and the alignment of the clasts indicates that shore-normal transport is dominant. Overwash features are rarely present at the northern end of the beach, adjacent to Gull Pond Brook Outlet.

8.15.2 Moderate Energy Steep Gravel Beaches

Chapel Cove, Conception Bay, is a steep medium pebble beach marked by generally moderate energy conditions. The beach face is a moderate to steeply sloping (14-27°) system, with steeper slopes associated with ice foot development. Slope angles have steadily decreased since summer 1997. Profiles are generally planar in the late spring and early summer, gradually becoming concave as material is removed from the lower beach face during the late summer and autumn, and during winters without ice foot development. Cuspate features form up to five tiers, with the number reflecting both the amount of time elapsed since the last significant storm event and the absence of significant reworking by seasonal ice. Individual cusps in the uppermost tiers range from 1-2.5 m in breadth, 0.5-1.5 m in width, and 0.3-0.7 m in depth. In all tiers, the cusps are greater in breadth than in width, and are asymmetrical in plan view. Cusp orientations and clast fabric patterns indicate that shore normal transport is dominant, and that the beach is reflective. Offshore bars and clast monolayer lines are swash-aligned features.

Chapel Cove has been subject to considerable anthropogenic modification. The beach is backed by a retaining wall, which limits sediment resupply to the system from the land. This interruption in terrestrial sediment flux has become especially evident with continual reworking of the beach throughout the winters of 1997-98 and 1998-99. Access to the lagoon is controlled by an artificially maintained channel at the southeastern end, and the channel is dredged to seaward. The channel has acted to focus wave energy onto the southeast side of the beach, accentuating shore normal transport and causing the beach face to steepen. During periods of northeasterly winds, this acts to focus and consequently increase the wave energy affecting the southeastern part of the system, resulting in sediment transport into the artificial channel and the lagoon behind. The channel must thus be re-dredged following each major northeast storm, if access to the harbour in the lagoon is to be maintained. The prolonged hiatus in northeastern storm activity from 1996 through 2000 has resulted in gradual deepening of the channel from the lagoon seaward, with precipitation events associated with southwesterly winds being the major sources of elevated lagoon levels and increased channelization.

Another example of this style of gravel beach is located at Maddox Cove. This beach is composed primarily of coarse pebbles and cobbles. Although the overall morphology of the beach is predominantly controlled by the underlying sloping bedrock platform, sediment has gradually accumulated on this system throughout the 1990's, transforming it from a somewhat patchy veneer of gravel overlying bedrock into a well-formed gravel beach. Cusps developed in coarse pebble gravel 3-4 m asl have breadths up to 4 m, widths to 2 m, and depths to 1.3 m, with strong seaward lips. Up to three stacked tiers of cusps are present on the southern (most exposed) side of the beach.

The shift in morphology at Maddox Cove can be attributed to limited northeast gale activity and an absence of sea ice influence during the period 1995-99. Road construction, however, has also had a critical influence. The upgrading of the Petty Harbour road, accompanied by installation of large riprap along the seaward shoulder, has focused wave energy onto the beach, precluding overtopping and transport of the sediment inland. Energy is reflected from the road shoulder, resulting in strongly cyclical onshore-offshore movement of pebbles and cobbles. Coarser cobbles have accumulated on the beach, and are forming a framework for the finer cobbles and pebbles. Sediment is thus retained within the beach face more effectively, allowing accumulation. The road shoulder is acting similarly to the railroad embankments at Holyrood and Kelligrews, effectively forming an artificial elevated storm berm.

Moderate energy gravel beaches present at Cap Cove, Trinity Bay; Mall Bay and Admirals Beach, St. Mary's Bay; St. Joseph's, Placentia Bay; and Ferryland Head and Mobile, Southern Shore, show similar patterns of sedimentation and geomorphology. The system at Mobile is typical of these steep, pebble-dominated gravel beaches, and has been investigated repeatedly since 1991 (e.g. Jones 1995). In comparison to the other systems, Mobile has coarser sediment and generally higher energy levels than do Cap Cove, Mall Bay, and Admiral's Beach, but somewhat finer sediment and lower energy levels than do Ferryland Head and St. Joseph's.

At Mobile, a 160 metre long cobble gravel beach forms a concave arc at the head of Mobile Harbour (Jones 1995). Tiers of cusps are present along the 110-m long segment of the beach extending north of the mouth of Mobile Brook. The southernmost part of the beach, adjacent to Mobile Brook, is a gently sloping planar surface, with slope angles of <2° at the high tide line. In the backshore area, slopes are reversed, inland towards Mobile Brook. Overwash features, including fans, are common, and a stratigraphy of overwash fans infills the northern part of the Mobile Brook valley. The oldest of these overwash features was produced by the storm of 1966, which damaged a stage and wharf formerly located here. The ruined infrastructure was dismantled following the 1966 storm. The texture in this area is dominantly granules and fine pebbles, with coarse sand. Much of this sediment was carried to the shore as bedload by Mobile Brook. During periods of minimal flow in the brook, the beach system laterally aggrades across the outlet, partially or completely blocking it and hindering the migration of brown trout to Mobile Big Pond. During these events, fine to medium pebbles dominate this area of the beach.

The central part of the beach is marked by stacked tiers of cusps. A minimum of two tiers is always present, and up to six (partially discontinuous) tiers have been observed. The cusps vary in form along the breadth of the beach, with the largest at the southern part of the central segment being symmetrical, bowl-shaped, and having seaward lips, indicating formation by shore-normal transport in reflective environments. The breadths of the largest cusps reach 4 m, with corresponding widths of 3 m and depths of 1.2 m. Slopes in excess of the critical angle of repose, up to 51° (Jones 1995), have been noted in these coarse pebble-fine cobble cusps. Many cusp forms include disturbed kelp and rockweeds, which support the cusp until decay, and the resultant irregularities in form are commonly observed in these cusps. Smaller cusps are strongly asymmetrical, indicating longshore transport along the beach front. In the more northerly part of the central segment, all cusps tend to be asymmetrical, indicating transport towards the north. The pattern of cusp morphology, together with the grain size distribution (fining towards the north on the northern 70% of the beach) suggests that the beach sediment is moved along the shoreline to the north by local currents.

At the northernmost part of the beach, a former outlet of Mobile Brook has been impounded by storm overwash sediment. This outlet had previously been abandoned by Mobile Brook when the stream was diverted for hydroelectric power production and road construction prior to 1966. The 1966 storm infilled the former outlet with overwashed coarse pebbles and fine cobbles. Medium to coarse sand, deposited by the stream channel prior to its abandonment, has remained in the beach system, and is periodically exhumed and covered by migrating pebbles and cobbles (Jones 1995). In this area, the uppermost cusps are chute-like, indicating that overwashing has occurred, and the barrier crest is as much as 2 m lower here than along the south-central part of the system. The lower tiers of cusps are shallow and asymmetrical, indicating transport parallel to the shore, towards the northeast. Maximum slopes are 25-30°, and profiles are moderately (following storms) to gently concave (modal condition). To the north of the abandoned channel, bedrock of the Renews Head Formation (King 1988) is exposed along the shore.

Mobile beach is affected by all major storms, including southwesterly hurricanes as well as easterlies. Erosional and depositional episodes succeed each other. Thus, although the beach morphology changes subsequent to each storm, and also in response to swell and variations in the flow of Mobile Brook, the net result is that the overall character of the system remains stable.

Examples of steep gravel beaches not associated with extensive progradational beach ridge complexes or gravel flat development are present at Fox Harbour, Placentia Bay. These beaches generally exhibit a strongly concave pattern marked by one or more tiers of cuspate structures where undisturbed by anthropogenic activity (as surrounding Bottom Barasway and The Neck, in the Fox Harbour area). The slopes generally range between 10° and 22°, with significant seasonal variability. Cuspate structures are commonly present, giving the beaches a scalloped cross-section. Textures vary from pebble- to cobble-dominated.

Many tombolos are associated with this style of shoreline along Placentia Bay, including Little Gallows Harbour, St. Joseph's, Haystack Harbour, and Little St. Lawrence. The prevalence of tombolos is primarily related to the attitude of joints, faults, and planes of weakness in the bedrock, that can be exploited by frost wedging activity, rather than being related to energy differences between Placentia Bay and the other parts of the eastern Newfoundland shoreline. Tombolos occur in other locations along Trinity, Conception, St. Mary's, and Fortune bays, and along the Southern Shore.

The gravel-dominated tombolo systems of Placentia Bay were fed predominantly (e.g. Haystack Harbour) or exclusively (e.g. The Neck) by seaward progradation of individual linear barachoix or spits. Most of the gravelly tombolos are marked by well-developed steep linear beaches, with beach widths and distance across the tombolo relatively constant. Hurricane activity has little permanent effect on these tombolos. Although exceptional waves may overtop the tombolo and temporarily isolate the island from the main shore, as at The Neck and St. Joseph, no evidence of truncation or breaching of the tombolos is apparent.

The Fox Harbour beaches surrounding Bottom Barasway and The Neck, in common with most gravel beaches developed in coves under moderate energy conditions that are periodically subjected to higher energy events, exhibit a strongly concave pattern marked by one or more tiers of cuspate structures where undisturbed by human activity. The slopes generally range between 10° and 22°, with significant seasonal variability. Remnant cuspate structures are commonly present, giving the beaches a scalloped cross-section. Textures vary from pebble- to cobble-dominated.

Ferryland Head is connected to the mainland by a gravel tombolo, which has been artificially augmented and fortified throughout the twentieth century. The gravel-dominated tombolo appears to have been naturally fed predominantly by sediment derived from the land, and from the beach to the north. The tombolo developed by seaward progradation of an individual linear barachoix. Storm activity has no permanent effect on the tombolo, although exceptional waves have overtopped the tombolo and temporarily isolated Ferryland Head.

Along the South Coast, gravel-dominated steep beaches are uncommon. One example is the gravel beach at Back Cove, near Belloram, Belle Bay. Back Cove is the accumulation area for sediment derived from local frost wedging and other erosive processes of the granite surrounding the cove. The beach is dominated by fine to medium pebbles, and slopes are moderate (15-25°). The slope varies from gently to moderately concave, with slope angles increasing as material is removed from the lower beach face during the late summer and autumn. Shore normal transport is dominant, and the beach is reflective.

8.15.3 Low Energy Steep Gravel Beaches

Gravel beaches developed under low energy environments are conditioned by glacial sedimentation. In many areas, glacial deposits are exposed along the shoreline, and contain cobbles and boulders too large to be transported by wave and current activity. These large clasts accumulate to form a framework, around and over which finer pebbles, granules, and sands are deposited. During most periods, deposition occurs passively, frequently augmented by terrestrial stream flow. When these beaches are subject to storm activity, however, many of the finer particles are removed, and the sediment is remobilized to form a steeply sloping, concave coarse gravel beach. When the 'normal' low energy conditions resume, the storm deposits remain as a framework, and many stay unaltered for several years.

Dog Cove, St. Mary's Bay, is an example of this style of shore. The beach at Dog Cove extends for 800 metres along the head of the embayment, flanked by steep sandstone and red shale cliffs of the Adeyton Group to the east, and rolling uplands underlain by the shales of the Heart's Desire Formation to the west. At low tide, a flat extended a maximum of 55 metres seaward in 1992. A beach ridge of coarse pebbles, up to 6 m asl, formed a gently concave arc across the head of Dog Cove, and was flanked by a granule-fine pebble-coarse sand flat on the seaward side.

The beach was developed on a veneer of raised marine beach gravel, overlying coarse glacigenic diamicton dominated by pebbles and cobbles. Most of the sediment actively accumulating on the site has been transported seaward by two streams draining coarse glacigenic diamicton and glaciofluvial sands and gravels. Prior to 1995, the beach thus was dominated by sediment derived from terrestrial sources, ranging from silt to boulders. The gradient of the streams entering the beach, combined with the gently sloping flat area, produced a reversal of current direction during each high tide, resulting in 'reversing rapids' up to 15 cm high. These tidal currents are effective at moving fine pebbles and sands.

The sediment at Dog Cove thus was primarily glacigenic and secondarily fluvial in origin, rather than being the product of marine activity. Similar results have been noted in New Zealand beach systems (Shulmeister and Kirk 1997). The terrestrial influence, combined with the absence of extensive ice foot development, created a foreshore flat dominated by fine pebbles to medium sand. The surface slope ranged from 6-13°, and summer profiles are slightly to moderately concave. The highest berm has a maximum elevation of 6 metres above sea level.

Dog Cove was not influenced by storms between 1990 and early summer 1995, surviving hurricane 'Bob', the 'Hallowe'en Storm', the northeast gales of October 1992 and 1994, and the 'Storm of the Century' without significant geomorphic or sedimentologic change. The surface profiles were smoothly concave, without tiers of cuspate structures or subordinate berms. The entrance to Dog Cove is oriented almost due south, and the cove is unaffected by storms originating from any directions except south to southeast.

During summer 1995, however, Dog Cove was subject to hurricane activity during 'Felix', 'Luis', and 'Opal', followed by the 'Saros' event in December 1995 and hurricane 'Hortense' in 1996. These storms substantially modified Dog Cove, overtopping and breaching the highest berm, depositing overwash fans in the lagoon, eroding the peat and fluvial deposits on the surface of the raised marine sediments, and removing much of the sediment from the seaward flat. Slope angles reached maxima in excess of 35°, and the profile was strongly concave. The geomorphology of Dog Cove thus reflects the result of a single episode of enhanced storm activity, superimposed on a generally quiescent environment. The berm that had existed prior to 1995 probably developed under similar conditions.

Dog Cove was formerly the site of a small community, but no structures remain from the period of occupation. Presently, the cove is visited only occasionally by all-terrain vehicle users, and the onshore area is not utilized for fishing purposes. Consequently, the beach has developed in isolation from direct human influence for some time. The gradual encroachment of vegetation on the pastureland area may lead to a reduction of sediment influx from this area, but the abundance of fluvially transported sediment from the hinterland will serve to replenish the beach system (c.f. Shulmeister and Kirk 1997).

The beach at Caplin Cove, Conception Bay, is another example of a gravel shoreline developed under relatively low energy conditions. Here, the maximum width of 11 m is developed adjacent to the stream which discharges into the southern side of the embayment, a position coinciding with the downcurrent direction of shore-parallel transport. The sea front is moderately concave in plan view. The cove is backed and flanked by argillite and sandstone cliffs (Gibbett Hill and Bay de Verde Formations), with a thin cover of coarse Quaternary diamicton, deposited as glacial till and subsequently modified extensively by colluviation (Catto 1993a). Sediment supply to the beach is provided from the cliffs to the north, and by the stream that is reworking the glacigenic and colluvial sediment throughout the small drainage basin. Little sediment is transported southward from the cove.

Slope angles along Caplin Cove vary with the texture of the sediment and the degree of recent reworking by storm and wave activity. Slope angles are generally directly proportional to the dominant grain size involved. On the narrowest segments formed at the base of the steepest cliffs, where there is no significant channelized stream flow from land, clasts lie at or close to the critical angle of repose for dry sediment. At Caplin Cove, these areas are located along the northern part of the cove, and slope angles range from 30-38°. These segments have gently concave surface profiles, with the steepest slopes aligned perpendicular to the trend of the beach front. Accumulation of the sediment proceeds largely by mass movement, and the internal structures of the beach resemble those of terrestrial talus cones.

Storm reworking of these areas is infrequent, and most commonly results in removal of finer pebbles and cobbles, creating instabilities in the beach system and triggering small mass movements on the beach surfaces. These disturbances alter the concave profiles of the beaches, producing temporary surfaces marked by alternating zones of convex and concave slopes. Characteristically, these irregularities are gradually eliminated as further material is provided to the beach, usually within a few weeks if no subsequent storms intervene. A substantial proportion of reworking is accomplished by terrestrial sheetwash.

On the southern side of the cove, sediment influx is greater as a result of the net direction of shore-parallel transport and the stream input. Energy levels are more consistent along the southern side of the cove, as this area faces northeast. Consequently, the sediment is sorted to a greater degree, and is dominated by fine to medium pebbles, ideal for capelin spawning. During the summer and early autumn, the beach exhibits a concave profile, with the maximum angles of slope (18-22°) in the locations furthest removed from wave and river activity. The pebbles on the beach are imbricated seaward during the early summer, but are disturbed extensively during the capelin spawning season.

Cuspate structures are present during the spring and summer months. The steepest slopes tend to be aligned at sharp acute angles (70-75°) to the trend of the beach front, facing the direction of the prevalent waves. Different parts of the beach slope at different angles and trends, indicating differing wave strengths and angles of attack in consequence of the local bathymetry.

The cove is subject to modification by northeasterly wind-driven waves, resulting in erosion of the shoreline along the southern margin and a general steepening of the beach front. Severe storms, such as those that marked the fall of 1992, remove substantial quantities of fine and medium-grained pebbles from the beach front. These clasts, however, are retained in the cove system. During years when an ice foot develops, these clasts are subsequently redeposited onshore during the spring, following disintegration of the ice foot. Consequently, the beach is rebuilt texturally and geomorphologically prior to the advent of the subsequent capelin spawning season. During the winter of 1997-98, however, erosion continued throughout the winter, resulting in a coarser, steeper beach in the following spring. The coarser sediment was less stable, subject to grain flow upon disturbance, and hence was less suitable as a capelin spawning area.

Avondale, Conception Bay, is also a low energy gravel beach. Here, the widest segment of the beach is developed directly southeast of the mouth of the Avondale River, indicative of the downcurrent direction of shore-parallel transport. Sediment supply to the beach is provided from longshore transport from the north, and by the river, resulting in a beach controlled by fluvial-coastal interactions (c.f. Shulmeister and Kirk 1997). During most of the year, the system is dominated by sediment initially derived from fluvial activity, and subsequently transported to the southeast by shore-parallel currents. Sediment flux increases when river discharge is increased following precipitation events. During 1997, the absence of hurricanes resulted in diminished flow in the Avondale River. The outlet was partially obstructed by sediment transport from the northwest, hindering salmonid migration from Conception Bay inland. Simultaneously, the beach to the south of the river mouth received less sediment, and began to recede and decrease in slope. The absence of an ice foot in the subsequent winter of 1997-98 resulted in further flattening of the beach profile during the summer of 1998. Two heavy precipitation events in April 1999, however, contributed terrestrial sediment to the system. Additional terrestrial sediment resulted from runoff associated with the hurricanes of autumn 1999 and 2000.

Reworking associated with northeast storms is infrequent. Strong northeast gales result in erosion of the shoreline along the southern margin and a general flattening of the southern part of the beach front. The autumn 1992 storms lowered the beach crest up to 2 m, and reduced the modal slope from 26° to 11°. The eroded pebbles, however, were retained in the cove system, and were subsequently redeposited onshore during the spring of 1993, following disintegration of the ice foot. This pattern was replicated to a lesser extent in autumn 1994 and spring 1995. During the period summer 1995-June 1999, however, the lack of strong northeasterly storms combined with limited ice foot development and an absence of southwesterly hurricane winds in summer 1997, resulted in a flatter, lower beach profile, with greater obstruction of the Avondale River and consequent hindrance for migrating salmonids. The hurricanes of 1999 and 2000 did not impact the beach directly, but the effect of terrestrial runoff and increased discharge did result in some erosion of finer sediments, improving the Avondale River as a salmonid habitat.

Southern Shore examples of gravel beaches developed under modally low energy conditions are present at Cape Broyle River, Calvert River, Aquaforte, Port Kirwin, Brigus South, and Renews. Of these, Brigus South represents the lowest energy regime. The restricted entrance to this harbour has always limited it to small vessels, but the shelter provided from northeast winds has made it attractive as a small fishing port. As in many Newfoundland communities, the coarse gravel beach initially provided a suitable place to dry and process cod.

Brigus South Cove, marked by flanking Fermeuse Formation argillite slopes of moderate gradients surrounding the embayment, has developed a distinctive style of gravel-dominated beach. The sediment is derived from both streams and marine processes, and hence is texturally varied. Pebbles dominate throughout the year, with the relative proportions of finer and coarser materials alternating somewhat with autumn and early winter winnowing and spring deposition. At Brigus South, the predominance of stream input and reworking of upslope Quaternary materials generates a consistent supply of sediment. The beach tends to have a gentle surface slope, ranging from 8-14°, and the surface profiles are slightly concave. Storm reworking at Brigus South is extremely uncommon, and waves generally break 20 m- 50 m seaward of the opening to the harbour.

During the Late Wisconsinan glaciation, a glaciofluvial fan delta developed offshore. Water depths of less than 50 m extend off the coast for more than 1 kilometre. These inshore waters are the 'commons': the fishing grounds that have attracted European interest since the sixteenth century. Reworking and landward transport of the sand and fine gravel results in periodic infilling of the shallow harbour (maximum channel depth 3 m), and formation of mixed sand and gravel bars. This has limited the size of vessel traffic, and has also influenced stage construction (Pocius 1991; Thistle 1993).

Britannia and Burgoyne's Cove are low energy steep gravel beaches developed along Smith Sound, Trinity Bay. Both sites periodically are sand-dominated, with the modal proportion of sand generally greater at Burgoyne's Cove (~ 30%) than at Britannia (~ 15%). At Burgoyne's Cove, the beach slopes vary from a minimum of 3° to a maximum of 25°, in response to seasonal variations in wind strength and sediment supply. Ridge-and-runnel topography is common, with ridges spaced at irregular intervals and having maximum heights of 1 m. The beach is dominated by fine pebbles, granules, and coarse sand. Cusp development is rare, and the cusps are shallow and asymmetrical, indicating shore-parallel transport towards the west (head of Smith Sound). At Britannia, the beach slope is steeper (modal 15°), and the modal texture is coarse pebbles. Cusps are generally present, with maximum breadths of 1.5 m, widths of 0.5 m, and depths of 0.3 m. The modal direction of transport is easterly, towards Trinity Bay.

The low energy gravel beaches are subject to reworking at irregular intervals, as a result of anomalous storm activity. Thus, although modal energy conditions can be defined for particular shores, high energy events can and do impact any location in eastern Newfoundland. High energy shorelines can be recognized and inappropriate land uses avoided, but recognition of the dangers posed along modally low energy shores are equally if not more important.

8.16 Class 16 -- Wide Gravel & Sand Flat

Wide gravel and sand flat shorelines (Class 16) are differentiated from those of Class 13 on the basis of texture. A Class 16 shoreline is defined as a wide flat that modally contains between 30% and 70% sand, as determined either from visual estimates or *in situ* sampling. Some shorelines within this class will contain less than 30% sand under certain seasonal or meteorological conditions.

On the South Coast and Fortune Bay shore, class 16 shorelines, as exemplified by those at Big Barasway, Seal Cove, St. John's Bay, Boxey, Deadman's Bight, Great Harbour Bight, Frenchman's Cove, Doughball Barachoix, Doughball Cove, and Brown Harbour, are generally dominated by sand, granules, and fine pebbles. The sand proportion (generally coarse- and medium-grained) varies between 30% and 60%, and is preferentially concentrated in the intertidal and subtidal zones. In many areas, the sand is veneered by fine to medium pebbles, and visual inspection without field investigation may lead to an under-estimate of the sand proportion. This is particularly evident at Frenchman's Cove, Great Harbour Bight, and Big Barasway. Pebbles are concentrated in the supratidal zones.

Wide gravel and sand flats undergo textural modification over time scales from *hr*s to years. Gradations to other shoreline classes of differing slopes, widths, and textures are common. Changes in wind direction, wave energy, and sediment availability are responsible for these textural and morphological variations. At some localities, anthropogenic activity and coastal land use have also resulted in textural and morphological modifications.

The Class 16 shoreline at Big Barasway has moderate seaward slopes (10-15°) throughout the majority of the year, although after hurricane events individual slopes exceed 20°. Cusps developed in association with southwesterly winds are well to moderately developed, without seaward lips. Breadths parallel to the shore reach 15 m, whereas widths normal to the shore are commonly less than 2 m. These cusps are shallow (typically <1 m depth for the largest forms) and asymmetrical in plan view, and develop as northeastward-flowing currents strike the coastline at oblique angles ranging from 10° to 45°, generating edge waves along the shoreline. At Big Barasway, the nearshore bathymetry is shallow, allowing longshore currents to move parallel to the shoreline at moderate to low velocities, and a continuous supply of both sand and gravel is sufficient to replace sediment lost through erosion.

At Frenchman's Cove, the flat slopes seaward at 15-20°, increasing to 30° after a succession of strong hurricanes in 1995. The largest cusps are typically 5-7 in breadth, 1-2 m in width, and 1 m in depth, are asymmetrical in plan view, and are formed by northeastward flowing water. Freezing of the beach in winter 1990-91, 1991-92, and 1992-93 precluded reworking by winter storms, notably the 1993 'Storm of the Century'. In contrast, the 'Saros' storm of December 1995 resulted in steepening of the beach profile and removal of much of the sand from the beach. Similar, although less intense, effects resulted from the storm surges in January 2000.

Anthropogenic activity has influenced the sediment composition and geomorphology of Frenchman's Cove. As a result of the development of a golf course in the backbeach area, the supply of sand and granules to the flat system has decreased. The flat has responded by becoming steeper and coarser, and consequently individual storms (such as the hurricanes of 1995 and the 'Saros' storm) have been more effective at eroding the flat.

Along Placentia Bay, the flats at both Cochrane Cove and Taylor's Bay are marked by gentle seaward slopes (2-8°), with limited or no cuspate feature development. At Cochrane Cove, a river system entering from the west provides a source of medium and coarse sand, which allows the flat to maintain its relatively fine texture. The cove is sheltered, and reworking appears to be minimal. The east-facing aspect of the cove protects it from the effects of southwesterly winds, the most prevalent and effective storm winds in the Red Island area. This beach, therefore, has remained essentially quiescent from 1966 to 2000.

At Taylor's Bay, the texture of the beach is due to reworking of Quaternary sediment from the surrounding area, as well as direct river input. Taylor's Bay is more influenced by currents than is Cochrane Cove, and sediment is generally carried counter-clockwise in the bay head area (from east to west). The flats widen progressively to the west, from 5 m at the eastern extremity of the embayment head (Class 17 shore) to >70 m at some low neap tides in the central and western areas. The texture generally fines from east to west, the combined result of shore-parallel currents and the input of fine sediment from a stream which debouches into the embayment after passing through a back-barrier lagoon (and thereby loses much of its coarsest load). This pattern is repeated at other embayments along the southern Burin shore, most notably at Lansey Back Cove where river input and westward currents combine to create a westward progression from a gravel-dominated (" 70-75%) mixed sediment beach (Class 16) to a sand-dominated flat with <10% gravel (Class 19) at the western extremity.

Reworking of the Burin Peninsula systems during storm events is more extensive than is the case in Cochrane Cove. The Burin systems are open to the prevailing winds, and funneling of the waves in the embayments is common. Steep beaches form seasonally in several areas, and small segments created during storms persist in some places, especially where backed by lagoons (as at Taylor's Bay). Supply of sediment from the land, however, quickly reestablishes the textural pattern and basic morphology after storm events.

Several of the Burin Peninsula beaches, notably Taylor's Bay, were subject to tsunami attack as a result of the Grand Banks Earthquake of 18 November 1929 (Ruffman 1993, 1995; Ruffman *et al.* in preparation; Anderson *et al.* 1995). Tsunami waves are characterized by extreme wavelengths, typically in excess of 200 km in open marine waters, and may exceed 750 km/h in velocity (Tinti 1993). These waves are less subject to refraction, deflection by headlands, and bathymetric interference than are wind-driven waves. As the tsunami wave approaches the shoreline, it interacts with the bottom and responds by shortening and steepening. A tsunami wave that has a height of less than 0.3 m in deep water may thus generate waves in excess of 60 m in height, with wavelengths on the order of hundreds of metres. The arrival of tsunami wave troughs in harbours results in removal of the water, causing the harbour bottom to be exposed temporarily, until the crest of the wave arrives. Casualties resulting from this phenomenon are characteristic of many tsunami disasters (Tinti 1993).

The long wavelength, high amplitude tsunami waves thus affect many shorelines that are sheltered from normal wave, swell, and hurricane activity. This pattern has been documented for both prehistoric and historic tsunami events, which have influenced fjords, tidal flats and lagoons, and other shorelines not subject to high energy storm waves (e.g. Atwater 1987; Dawson *et al.* 1988; Atwater and Yamaguchi 1991; Clague and Bobrowsky 1994; Jacoby *et al.* 1995; Atwater and Hemphill-Haley 1996; Shennan *et al.* 1996; Bondevik *et al.* 1998; Dawson 1999). Where storm wave and tsunami deposits are preserved together, separation on textural and sedimentological criteria may be difficult (Gjevik and Röed 1976; Foster *et al.* 1991; Bondevik *et al.* 1997).

The Taylor's Bay area, and other embayments along the Burin Peninsula, were the subjects of investigations by Ruffman and his colleagues (Ruffman 1993, 1995; Ruffman *et al.* in preparation; Anderson *et al.* 1995) to recognize the sedimentological record of the 1929 tsunami event, and to determine if other tsunami events are preserved. The characteristic sediment associated with tsunami deposition, a horizontal, structureless medium sand horizon, the tsunami-laid sand (TLS), has been recognized in the sedimentary record along the Burin Peninsula by Ruffman. Although a tsunami may have affected St. Shott's in 1864 (Ruffman, personal communication), and the Lisbon Earthquake of 1 November 1755 produced tsunami deposits in the Scilly Isles off southwest Cornwall (Foster *et al.* 1991), neither event has been recognized in the deposits of the Burin Peninsula.

Along Conception Bay, mixed sediment flats are present at Kelligrews and Chamberlains, normally marked by gentle to moderate seaward slopes (2-11°). Following northeast storm events, individual slopes may exceed 25°. The Kelligrews area generally has steeper slopes than does Chamberlains. Cusps associated with non-storm periods, and those developed in association with southwesterly winds, are poorly to moderately developed, and have breadths much greater than widths. At Kelligrews, the largest cusps have breadths to 4 m, widths to 2 m, and depths to 1 m. At Chamberlains, the largest cusps are greater in breadth (to 8 m), of slightly lesser width (to 1.5 m), and less deep (to 0.5 m). These cusps are shallow and asymmetrical in plan view, and develop as northeastward-flowing currents strike the coastline at oblique angles ranging from 5° to 35°. Sediment transport directions are indicated by distinctive clasts, such as granitic materials derived from the Holyrood Intrusive Suite that crops out to the southwest (King 1988), or those clasts initially brought to the shoreline by northwestward-flowing glacial ice. Clasts from the Ordovician Bell Island Group, which crops out on Kellys and Little Bell Islands, are not present, indicating that marine transport from the northwest is not significant.

Northeast storm waves also produce cuspate features on these beaches. The cusps associated with northeasterlies are wide and broad (both dimensions may exceed 5 m), without seaward lips. Although the storm of October 1992 produced cusps that were larger than those previously present on the flats, the period since October 1994 without major northeast storm activity has resulted in the gradual development of cusps of equal or greater breadth from continuous southwesterly transport. The major differences in form are that the northeast gale-generated cusps are wider normal to the shore (in some instances, widths are greater than breadths), are less deep, are associated with chutes crossing the spine of the beach ridge, and lack seaward lips.

The strongest northeast storms (such as that of October 1992) generate overwash along the entire coast, resulting in the formation of overwash fans in the lagoons and damage to coastal infrastructure, vessels, and buildings within 50 m of the shoreline. Taylor (1994) recommended setback limits of 50 m along exposed parts of the Conception Bay South shoreline, based on susceptibility to coastal erosion and the known effects of the 1992 storms.

Sediment flux to the systems at Kelligrews and Chamberlains has changed since 1941, primarily as a result of anthropogenic activities and secondarily as a consequence of the gradual sea level rise evident along the Avalon Peninsula coastline. Study of aerial and ground level photographs taken from 1941 to 2000 indicate that textural variations, particularly involving periods when more sand was present, were more prevalent 50 years ago than has been the case from 1989-2000. Throughout this period, both shoreline areas have become narrower and steeper, but the trends differ somewhat at the two sites. At Kelligrews, changes in slope are more apparent than changes in width, whereas the reverse is true at Chamberlains.

The sand supply to these systems originates from erosion and slope failure of the Quaternary glaciofluvial deposits which flank the shoreline to the southeast (Catto 1994a, Catto and St. Croix 1997). Sand is moved offshore and towards the northeast by swash-backwash and longshore currents, gradually accumulates in the offshore areas, and is resupplied to the shoreline by wave activity associated with northeast or (less effectively) northwest winds. The sand thus undergoes a net northeast movement along the shoreline from Holyrood to Topsail, as southwesterly winds dominate, but large amounts will periodically be driven southwestward to resupply beaches at Kelligrews and Chamberlains, during northeast gales. Under natural conditions, the shores will be supplied with sand both from offshore and from the adjacent Quaternary shoreline outcrops. Shorelines to the northeast were dominated by finer sediments (greater sand: gravel ratio) and were wider than shorelines to the southwest developed under similar geomorphic conditions.

Anthropogenic activity in Conception Bay South, however, has significantly reduced the supply of sand to the shoreline. The replacement of sheep herding and agriculture with suburban development and the diversion and impoundment of rivers has reduced the erosion of inland Quaternary outcrops. Stabilization of the Quaternary bluffs and extraction of aggregate at Seal Cove also have contributed to the reduction of sediment influx from the land.

At Kelligrews, the railroad embankment isolates the shoreline from the Quaternary sediment outcrops, causing the shoreline to gradually become steeper and narrower. When the railway was active, periodic re-ballasting of the line acted as an additional source of sediment, but the cessation of operations has ended this influx. The railway embankment today serves as a retaining wall and acts as a coarse back-berm structure, limiting wave overwash and coastal erosion during storm events. This effectively reduces the sand influx available for the shores to the northeast, such as Chamberlains.

The shoreline northeast of Foxtrap, including the Chamberlains area, is not protected by a railway embankment, and hence is more susceptible to overwash during storms. Northeast winds here act to flatten the beaches, moving sediment inland and forming large overwash fans in the lagoons. The lower, narrower beaches afford less protection to coastal infrastructure surrounding the lagoons. Severe damage resulted in the Chamberlains and Manuals areas during the storms of September-October 1992, and even the lesser waves of autumn 1994 were responsible for property damage. Northwest winds are also effective agents of shoreline modification at Chamberlains, as it is not sheltered by Kellys Island (as is Manuels) and is subject to a longer fetch across Conception Bay to the northwest than is Kelligrews.

The absence of significant northeast gales from 1994-2000 has meant that the sand within the system has continued to move towards the northeast. Under this regime, Kelligrews and areas to the southwest are gradually losing sand to Chamberlains and areas to the northwest. As the sand supply entering the system at Kelligrews has been curtailed by the railway embankment, the effects are progressively more apparent at sites distal from the embankment. Thus, Topsail Beach has seen an increase in the proportion of sand from 1995-April 2001, particularly in the subtidal area. Much of this sand has been derived from erosion of the bluffs directly to the southwest. In contrast, the proportion of sand at Chamberlains has decreased, as supply from the southwest has been curtailed. The absence of northeast gales has prevented redistribution of sand from the northeast to the southwest, and thus the flat at Kelligrews has less sand in April 2001 than it did in spring 1995.

Along Trinity Bay, examples of mixed gravel-and-sand flats are present at Bellevue Beach, Dunfield, Island Cove, Port Rexton, and Champneys West. All of these sites are influenced predominantly by northeasterly waves, with sites open to the northeast (e.g. Bellevue) being marked by the coarsest gravels and largest cusps (breadths to 15 m) following strong gales. At Port Rexton and Champneys West, cusp dimensions vary directly in response to exposure to northeast fetch. At Dunfield, cusp development on the wide gravel flat is more sporadic.

The geomorphology and sediment at Bellevue Beach varies in response to the strength and persistence of northeast winds. Bellevue varies in status from a gravel-dominated system (class 13) to a mixed sediment system (class 16). Gravelly conditions, particularly in the eastern segment of the beach, develop after periods of northeasterly storm activity coupled with high discharges by the rivers entering Bellevue Lagoon. Washover structures, with fans prograding up to 15 m into the lagoon, were developed by the storms of October 1992. After periods of quiescence, particularly when ice foot activity is prevalent, the beach becomes sandier and the profiles less strongly concave. The modal transport direction is shore-oblique, with a spiral component from northwest to southeast. During summer-autumn periods marked by hurricanes, but lacking strong northeasters (e.g. 1995), the sand content of the intertidal zone in the eastern segment of the beach locally exceeds 70%. On the western side, sand content decreases during hurricane-influenced years, but increases when quiescent conditions dominate.

8.17 Class 17 -- Narrow Sand & Gravel Flat

Class 17 shores are defined as those dominated by mixed populations of sand and gravel, that are less than 30 m in width. Many Class 17 shore zones are transitional, spatially and over the short and long term, to broad sand and gravel flats (Class 16; e.g. at Boxey, Sandyville, and Long Pond Beach, Conception Bay South), to steep sand and gravel beaches (Class 18: examples include Creephole Point, Jean de Baie; the north shore of Burnt Island, Nonsuch Inlet; and Beck's Bay), to narrow gravel flats (Class 14, e.g. Saltwater Cove; Bellevue Beach, Trinity Bay), and to steep gravel beaches of Class 15 (e.g. Bittern Cove, Placentia Bay). These transitions reflect changes produced by seasonal events, shifts or temporary truncations of sediment supply, and major storms.

Along the South Coast, examples of Class 17 narrow flats are located at Rencontre East, Pool's Cove, Boxey, Mose Ambrose, Morrisville, English Harbour West, Barasway de Plate, and Seal Cove, Island Rock Point, and White Point, Fortune Bay. These shores are marked by substantial seasonal variability in texture and geomorphology. Sand proportions are generally greatest in the early summer months. In the late spring and early summer, the Class 17 shores are gently to moderately sloping (slopes 3-15°), with planar to slightly concave profiles. Seasonal reworking results in gradually steepening slopes throughout the summer, a process that is enhanced during hurricane activity. In years with numerous hurricanes (particularly 1995), slope angles reach maximum values of 20-30°. Shorelines that are subjected to strong southwesterly hurricane winds commonly develop steeper profiles, with stacked tiers of bowl-shaped cusps with seaward lips, produced by shore-normal waves. At Mose Ambrose, the largest cusps typically have breadths of 3-5 m, widths of 2-4 m, and depths to 3 m. At English Harbour West, dimensions are lesser, with breadths to 2 m, widths to 1.5 m, and depths to 1.2 m.

Along the Placentia Bay coast, two examples of Class 17 narrow flats are located at Fair Haven and Mooring Cove. Both these flats are gently to moderately sloping in the summer months (slopes 3-14°), and have little cuspate development. Slopes begin to steepen in late summer, a process that is accelerated by the autumn gales. February slopes as high as 25-30° have been observed at Mooring Cove (1992). Decline of the slope angles begins in the early spring (earlier at Mooring Cove than at Fair Haven). The Mooring Cove beach is subject to wave attack, and consequently exhibits seasonal variation in morphology.

Small-scale sedimentary structures are rare at both sites, being confined to scattered ephemeral ripples of low sinuosity with narrow crestal platforms. Sediment preserved in the flats is generally structureless and moderately to poorly sorted. The flat sediment at Fair Haven is coarser (modal 60% pebble gravel and 30% coarse sand) than that at Mooring Cove (modal 40% pebble gravel and 40-50% coarse and medium sand), but both areas have been modified somewhat by anthropogenic activity.

Examples of Class 17 narrow flats along Conception Bay are located at Coleys Point Beach (Long Pond segment) and Kettle Cove. These beaches are marked by substantial seasonal variability in texture and geomorphology. In the late spring and early summer, the Class 17 shores are gently to moderately sloping (slopes 3° -17°), with planar to slightly concave profiles. Planar profiles are more evident in beaches that are not subject to extensive ice foot development (Long Pond Conception Bay South; winters of 1993-94, 1997-98, 1998-99 along the northwest segment of Coleys Point). Areas where ice foot development has been persistent and has exceeded 30 cm in thickness during the preceding winter (Kettle Cove, northwest Coleys Point in winter 1994-95; all Conception Bay sites in winter 1999-2000 and 2000-01) are marked by concave profiles in the following spring and summer. Seasonal reworking results in gradually steepening slopes throughout the summer, a process that persists in autumns not marked by strong northeast gales. In these years, slope angles reach maximum values of 10-25°. Shorelines that are subjected to northeast winds, particularly in September and October, develop steep profiles, with stacked tiers of bowl-shaped cusps with seaward lips produced by shore-normal waves. Cusp back wall slopes can exceed 40°.

Sand proportions are generally greatest in the early summer months, reaching 40% at Coleys Point and Kettle Cove. Sand supply to Long Pond Beach has been modified due to anthropogenic activity along the Conception Bay South shoreline, and the proportion of sand in this system continues to decline on an irregular basis. All Class 17 shorelines in the Conception Bay region, however, are dominated by pebble gravel.

At New Bridge, St. Mary's Bay, a mixed sand-and-gravel flat grades laterally and seasonally into a steep mixed sediment beach (Class 18). This shoreline, however, shows relatively limited textural variability throughout the seasons, with coarser pebbles and scattered cobbles present in the autumn following active hurricane years (1991, 1995, 1996, 1999). During years without significant hurricane activity, the flat sediment becomes finer, with sheltered patches dominated by coarse to medium-grained sand. Ice foot development is rare and does not effectively modify the texture of this shore. The early summer profile is slightly concave, with a maximum slope of 6°. In hurricane years, the slope steepens, to a maximum of 14° (summer 1995). Years without hurricanes are marked by lesser changes in slope, with a tendency to develop a planar profile. Typically, cusps do not develop, unless hurricane activity is anomalously strong. In late summer 1995, two tiers of semi-circular cusps were observed, with breadths to 2 m, widths to 1.5 m, depths to 0.7 m, and weakly-formed seaward lips. The uppermost of these tiers was formed 4-5 m asl, and persisted through the winter of 1997. It was subsequently destroyed, in part due to ATV activity.

8.18 Class 18 -- Steep Gravel & Sand Beach

Steep gravel and sand beaches develop both seasonally in association with sand and gravel flats or gravel beaches, and independently. Class 18 beaches are associated with many spits and barachoix features. They also develop in association with laterally extensive bluffs of Quaternary diamictons and glaciofluvial sediments, as is evident along the Conception Bay South and Burin Peninsula shorelines.

Seasonal variability in morphology and texture is common. Slopes range from minima of <5° to maxima of >25°. Profiles are strongly concave on coarse cobble systems, moderately concave where fine cobbles and coarse pebbles dominate, and gently concave (locally and temporarily planar) where fine pebbles, granules, and sand comprise more than 40% of the textural assemblage together. Textural assemblages range from coarse cobble beaches with small amounts of coarse sand to seasonally granule-dominated systems. Cuspate structures are present on the coarsest beaches for at least some period in all years, but are only found on granule and fine pebble beaches for short periods following major storms. Stacked tiers of cusps are evident on photographs of several systems, and are routinely encountered in the field.

Along northwestern Trinity Bay, mixed gravel and sand beaches are dominated by medium pebbles to granules, with lesser amounts of coarse to medium grained sand, and few cobbles and boulders. Examples are present at Salmon Point, Champneys West, and English Harbour, Trinity Bay. At Champneys West, the modal grain size varies seasonally from fine pebbles to coarse sand-granules. Slope angles vary from 10- 20°, and the profiles are linear. Cuspate structures are not developed.

At English Harbour, the beach slope angles have varied from <5° to >20° over the previous 25 years. Textural variations generally parallel slope changes, with coarser slopes associated with coarse pebble and fine cobble cover, and lesser slopes associated with increased concentrations of medium sand. Small, poorly-formed cusps are developed when coarse pebbles are present.

At New Melbourne, Trinity Bay, the beach surface is dominated by coarse cobbles, with lesser amounts of coarse sand and granules. This high energy beach fluctuates in texture and profile in response to northeast gale frequency, the amount of surface runoff from terrestrial areas, and the extent of sea ice and ice foot activity. In years marked by strong northeast gales, high precipitation, and extensive ice foot development, the beach develops and retains a tiered succession of cusps throughout the year. The largest cusps developed in association with the October 1992 gales were in excess of 12 m breadth, 6 m width, and 3 m depth, and many had seaward lips. The beach is developed against a resistant ridge of the Big Head Formation, and thus overwash is largely precluded. The energy is thus reflected seaward during storm events. Discoid clasts moved during this storm exceeded 30 cm in diameter. Following the storm, a succession of four tiers of cusps were visible, all associated with shore-normal transport by northeast waves.

In contrast, the period 1996-99, with limited ice activity and no major northeasterly storms, saw a gradual erosion of the lower tiers of cusps through grain flow and slopewash. The beach profile became gently concave in the storm berm-upper supratidal zone. In the lower supratidal zone, wave action resulted in removal of sand, granules and fine pebbles, which were redeposited in the lower subtidal zone. The profile here was irregularly convex, with temporary slopes at the water's edge in excess of 25°. The uppermost tier of cusps suffered minor erosion through grain flow, and was also disturbed by anthropogenic activity.

The pattern at New Melbourne, repeated at other sites along the northeastern Trinity Bay shore (New Chelsea, Old Perlican, Hants Harbour, Heart's Delight), involves cuspate development primarily in response to northeasterly winds. At sites facing directly northeast, such as New Melbourne, development by shore-normal waves is intensive, resulting in the production of stacked tiers. At sites such as Heart's Delight, which are open to the northwest, cusp development is less regular, and longshore motion of waves from southwest to northeast is significant. These sites generally have more conspicuous cusp development on the southwest margins.

Along Conception Bay, additional examples of Class 18 shorelines are present at Jobs Cove, Gull Island, Broad Cove, Topsail Beach, and northeast of the Bell Island ferry terminal. Textural and geomorphic features, particularly cusp styles, indicate that wave energy regimes and transport directions differ at each site. Jobs Cove is dominated by moderate energy wave conditions, with transport predominantly aligned normal to the shoreline. Reflective conditions and extensive swash activity are the norm. Here, the pebble-dominated shoreline supports cusps with maximum breadths of 2.5 m, widths of 4 m, and depths of 1 m, with weakly defined seaward lips. These chute-like features indicate that swash activity normal to the beach face is the dominant form of transport associated with higher-energy events. During lengthy periods of quiescence, the chute cusps undergo alteration by grain flow and sheet wash, resulting in the development of a gently concave profile (maximum slope 20° at the base of the highest storm berm). The Gull Island beach is similar in character.

Broad Cove is marked by low to moderate energy, shore-parallel transport, and varies between reflective and dissipative in nature. Texture on this beach varies seasonally and in response to weather conditions and storm events. Following the northeast gales of 1992 and 1994, the beach was dominated by coarse pebbles and cobbles. Following a period of quiescence, marked by sea ice formation, the beach was dominated by granules throughout 1995. Hurricane activity generated countering northeast winds along the surface of Broad Cove, but these winds did not affect any substantial textural alteration to the beach. They did, however, result in the formation of chute-like cusps, similar to those at Jobs Cove. The absence of sea ice during the winters of 1997-98 and 1998-99 led to reworking of the beach, lowering and smoothing of the profile, and an increase in the proportion of fine and medium pebbles. Sand at this beach is predominantly coarse textured, and is concentrated in the lower intertidal and subtidal zones. The return of sea ice as a significant influence in winter 1999-2000 was accompanied by steepening of the profile, and increased concentrations of coarse and medium pebbles.

The Bell Island terminal beach is dominated by shore-parallel transport (towards the northeast), but southerly winds can generate moderate energy shore-normal swash events. Energy levels at the Bell Island site vary from low to extremely high, and anthropogenic modification of the shoreline is much in evidence. This shore is predominantly reflective in character. The dominant texture of the intertidal and subtidal zones varies from medium sand to coarse pebbles. In the supratidal zone, coarse pebbles and cobbles predominate where anthropogenic disturbance is not severe.

The steep gravel-sand system at Topsail Beach represents an example of a coastal system extensively modified by human activity, beginning from the initial settlement in 1820. Major changes in the beach have been affected by sediment mining, interruption of current flow by up-current breakwaters and groynes, changes in land-use practices, damming and regulation of the inflowing streams for hydroelectric power, and recreational usage (Catto and Thistle 1993, Prentice 1993, Catto 1994b, Catto 1995, Connors and Tuck 1999). As Topsail Beach has been discussed elsewhere, a summary is presented here.

Prior to 1940, Topsail Beach was a broad, mixed sand-and-gravel flat, with sand present in excess of gravel, and would have been described as a shoreline alternating between Class 16 (wide gravel-and-sand flat) and Class 19 (wide sand flat). The removal of aggregate during World War II, and the replacement of sheep herding by suburban development, limited the replenishment of sand to the beach system after 1950. Most of the sand had previously been derived from low bluffs of glaciofluvial and glaciomarine sediments that line the coast south to Seal Cove.

Glaciofluvial exposures along the Conception Bay coastline are subject to erosion, punctuated by enhanced removal during storms. During the October 1992 storm, as much as 1 m of bluff was eroded from the sediment bluff directly to the southwest of Topsail Beach (Topsail United Church). Further erosion resulted from the autumn 1994 storm events. The removal of sediment from the base of the bluff contributed to mass movement of the upper parts of the exposure, resulting in the systematic collapse of the cliff. Most mass movement activity, however, did not occur in direct association with the storm. Severe slope failures did not begin until spring 1995, persisted through to 1996, and have continued at reduced rates through February 2000. Although slope stability gradually increased throughout 1997 and 1998, as the disturbed material on the surface dried and compacted, the major precipitation events (70 cm each) of early and late April 1999 resulted in increased sediment mobility. Small failures of sediment at the base of the bluffs were observed following hurricanes 'Floyd', 'Gert-Harvey', and particularly 'Irene' (autumn 1999). The succession of storms from September 1999 through autumn 2000 has resulted in an increase in slope failure and coastal erosion, and destabilization of parts of the bluffs is apparent.

Along Topsail Beach, these changes have substantially modified the morphology of the beach system. Topsail is now a coarse gravel-dominated beach, with sorting varying from good to extremely poor. Seasonal shifts in texture (from coarse in late autumn to finer in early summer) are common in the southwestern part of the system, but do not occur to the northeast (in the vicinity of the outlet).

Major textural changes followed the storms of October 1992 and 1994. The 1992 storm reduced the proportion of sand in the system, and sand supply remained low throughout 1993 and summer 1994. The 1994 storms removed material from the southwestern end of the beach preferentially, but did not significantly alter the texture of the northeastern segment. After the 1994 storm season, sand in the northeastern part of the beach continued to move towards the northeast, but no sand was available from the southwest to replace this material. Consequently, the northeastern part of the system became coarser. During the summer of 1995, sand derived from the failing Quaternary bluff up-current began to replenish the southwestern and central segments of Topsail Beach, resulting in fining textures and lessening intertidal and subtidal slopes. This sand influx began to reach the northeastern part of the beach system in late autumn 1995, unhindered by northeast winds. The pattern of replenishment has continued from 1996 to April 2001.

Large gravel cusps are present at various times during the year. Cuspate morphology commonly differs throughout the length of Topsail Beach, with shore-parallel transport generally more effective at the southwestern margin, and differs throughout the seasons or in response to individual storm events. Differences also are attributable to elevation above sea level, as different waves strike the shore at different elevations, and so produce different styles of cusps.

Up to 6 stacked sequences of cusps, reflecting different wave regimes, have been observed on Topsail Beach, and two to three tiers are commonly present. All cusps were disturbed or re-formed during the October 1992 storms. During the 1994 storm event, all cusps at the southwestern end of the beach were somewhat altered, with the highest level 1992 features failing due to undercutting at their seaward margins. At the northeastern end of the beach, the highest cusps formed by the 1992 storms were not altered by the 1994 event. Many of these cusps, however, have been altered by anthropogenic activity, as the northeastern end of the beach is the most accessible and the most heavily frequented. Storm waves that successfully overtop the back-beach areas produce elongate chutes, with linear profiles of constant slope, and widths greater than breadths. The morphology is created as the waves overtop the barrier and disperse landward, rather than returning energy and sediment in association with backwash.

Along St. Mary's Bay, steep mixed sediment beaches are present at Mt. Carmel and Little Barachois. The Mt. Carmel site is influenced by high energy conditions during southwesterly storms (particularly hurricanes 'Felix', 'Opal', 'Hortense', and 'Irene'), and tends to alternate in texture between coarse pebble-fine cobble gravel-dominated (Class 15) and fine-pebble dominated with granules and coarse sand in the intertidal and subtidal zones. Cusps developed in association with southwesterly winds show chute morphology in the most exposed positions, and at sites with gentler (# 20°) slopes. Where slopes are steeper, cusps show a bowl-like morphology, with widths and breadths approximately equal, and seaward lips are prominent. Lower energy sites, and periods of quiescence (e.g. summer 1997) do not permit cusp development.

At Little Barachois, St. Marys Bay, sediment supply to the beach comes from both marine and fluvial sources. The Little Barachoix River transports granules and coarse-medium grained sand to the beach system, replenishing these grades of sediment after wave removal. Hurricane activity on this beach results in temporary seaward removal of the sand, followed by replenishment from the river swollen with precipitation. The net result is that the texture of this beach system varies less in response to hurricane activity than does the beach at Mt. Carmel.

Along Placentia Bay, steep sand and gravel beaches develop both seasonally in association with sand and gravel flats (e.g. Arnold's Cove) or gravel beaches (e.g. Hogan Cove, Merasheen Island; Scrape Cove, Merasheen), and independently (e.g. Cross Point, Merasheen Island). On Merasheen Island in particular, steep mixed-sediment beaches are associated with many tombolo, spit, and barachoix features. Profiles are strongly concave on the coarser systems, but may be almost planar on sand-dominated beaches. Textural assemblages span the range from cobble beaches with lesser amounts of coarse sand (Hogan Cove) to granule- and coarse sand-dominated systems (parts of the Cross Point shoreline). Cuspate structures have been observed on the cobble-dominated beaches in all years since 1981, but are absent from granule and coarse sand-dominated beaches at most times. Stacked tiers of cusps are evident on several Merasheen systems, but are generally absent from Cross Point and Arnold's Cove.

Tombolos associated with these beaches (such as that at Cross Point) appear to have developed primarily from seaward progradation of individual barachoix or linear spits, rather than from converging rip currents or from cuspate spits. In several cases, however, two barachoix or linear spits have prograded independently from the mainland, forming a doubly-tied island. These independently-developed tombolos usually are texturally different. At Whitesail Head, the northern tombolo system across Beckford Cove, Presque Harbour, is a mixed sediment feature, with approximately equal proportions of sand and pebble gravel. The southern tombolo at Whitesail Head, across Long Beach, is dominated by coarse pebble and cobble gravel. Evidence of overtopping is not present on most of the tombolo systems, and none appears to have been breached since 1981. Small washover channels are relatively ephemeral features, however, and hence some minor overtopping may have occurred without leaving definitive traces in the geomorphic or sedimentological record. Sea level change does not appear to have substantially modified these features.

Along Fortune Bay and the South Coast, mixed sediment steep beaches are present at Doughball Head, Great Jervais, Fox Cove, Venison Cove, Sandyville, Furby's Cove, Bill's Cove, Deadman's Bight, English Harbour Back Cove, Beck's Bay, and Man O'War Head. As elsewhere in eastern Newfoundland, seasonal variability is common, with slopes ranging from minima of $<5°$ to maxima of $>28°$. Profiles are moderately concave where fine cobbles and coarse pebbles dominate, and gently concave (locally and temporarily planar) where fine pebbles, granules, and sand comprise more than 40% of the textural assemblage together. Cuspate structures are found on granule and fine pebble beaches for short periods following major storms, but are more common and persistent on coarse pebble beaches. Stacked tiers of cusps are evident on these systems.

At Furby's Cove, the restricted entrance to the embayment precludes the development of shore-parallel edge waves. Cusps here are ephemeral, with short wavelengths, and are characteristically bowl-shaped with widths and breadths approximately equal. These forms develop by shore-normal transport. At Beck's Bay, chute-like cusps are elongate normal to the shore, with gentle, uniformly planar slopes and no seaward lips. These cusps form when southwesterly winds drive high-energy waves onto and over the beach, overtopping the sediment and depositing material in the lagoon behind the beach ridge. At English Harbour Back Cove, the cusps are intermediate in style between those of the Beck's Bay and Furby's Cove systems, indicating that this beach is less exposed than is Beck's Bay but more open than Furby's Cove.

Elongate, shallow cusps, with breadths parallel to the beach much greater than widths normal to the shore, are formed where edge waves move sediment parallel to the coast (Allen *et al.* 1996). These cusps are commonly asymmetrical in plan view, with the asymmetry reflecting the direction of sediment transport. Sandyville and Deadman's Bight display this type of cusp development. Edge-wave cusps are best developed following prolonged periods of intense wave activity, generally in association with southwesterly hurricane winds.

8.19 Class 19 -- Wide Sand Flat

Sand flats are defined here as containing less than 30% gravel of all grades, including granules. Wide sand flats have modal width normal to the shoreline of 30 m or more. Seasonal variations locally cause classifications to alternate between sand and gravel-dominated and sand-dominated zones (e.g. 16/19, Flat Island Harbour, Placentia Bay; Salt Cove, Placentia Bay). Associations of wide and narrow sand flats and steep sand beaches (Class 21) are also present.

The generally coarse texture of the Quaternary sediment, the high energy levels of most of the eastern Newfoundland shoreline, the shortness and steepness of the streams carrying sediment to the shore, the steep bathymetry, the low mesotidal to microtidal regime, and the prevalence of frost wedging all combine to limit the supply of sand to the coastline. Sand-dominated systems can only develop in a few isolated regions, where some of these factors are locally absent. Commonly, sand has accumulated in the coastal zone through other, terrestrial processes (such as aeolian activity), rather than having been carried to the sites by marine currents.

Sand flat systems are absent from the Trinity Bay shoreline, and are confined to only two locations along Conception Bay: Salmon Cove and Northern Bay Sands. The Northern Bay Sands area also contains Class 10 and 11 shorelines, and has been discussed above.

Salmon Cove differs substantially from Northern Bay Sands, as it is a confined littoral system isolated from longshore currents by bedrock headlands. Siltstones with quartz veins, assigned to the Late Proterozoic Fermeuse Formation (King 1988), dip eastward at 25-30°. The siltstones are subject to frost weathering, but the majority of the exposed beds face eastward, and sediment derived from these is swept to the south by the prevailing longshore current. Little sediment from the cliffs finds its way to the head of the cove. The Salmon Cove River was capable of transporting glaciofluvial gravel present in the valley bottom (Catto 1993a, 1994c), but highway construction and resident development has curtailed sediment input to the river. The river banks are armoured with coarse boulders, and much of the glaciofluvial deposit has been removed for aggregate, or has been built over. As a result, terrestrial sediment influx is limited to sand derived from the aeolian dunes. The sand is transported cyclically onshore and offshore by shore-normal waves, although a much lesser lateral component of motion along the beach is also present.

The cove is isolated from the prevalent southward longshore drift, and largely from the effect of northeasterly gales, but easterly storms with high wave activity result in the flushing of the cove towards the south. Sediment transport is dominantly shore-normal, and in consequence cuspate spits, rip currents, and shallow beach cusps are prevalent. A tombolo joins a bedrock island in the centre of the embayment to the mainland.

The beach is dominated by medium-grained sand throughout the year. Storm events, most recently in October 1992, can cause erosion of the base of the dunal complex, but the fine sands are swept seaward and do not form sedimentary features on the beach. In the early 1990's, clumps of beach pea acted to stabilize irregular patches of the beach area up to 1 m in diameter. Anthropogenic disturbance on the beach, however, has accelerated the decline of the beach pea. The absence of ice foot development during the winters of 1997-98 and 1998-99 also resulted in increased erosion, which has damaged the beach pea colonies. Between summer 1995 and summer 1997, beach pea growth covered <5% of the upper flat, and was absent from the lower parts of the supratidal area. In the summers of 1998 and 1999, beach pea colonies covered less than 2% of the upper flat, and were completely absent from the supratidal zone.

Swash-and-backwash structures and shallow beach cusps (breadths 20-50 cm, widths <10 cm, depths 3-10 cm) indicate that waves approach parallel to the trend of the shore throughout the active period of sedimentation. Wave ripples present on the beach are generally straight-crested, in phase, with narrow crestal platforms, and have stoss and lee slopes of 9-16° and 19-28° respectively. Typical crest-trough heights are 2-5 cm, and ripple indices (Tanner 1967) range between 3 and 8. The internal structures are marked by planar cross-laminations, with sharp but conformable bounding surfaces marked by discoid argillite and siltstone fragments, derived from clasts of the Fermeuse Formation initially incorporated within the dunes. Aeolian ripples are common in the lower supratidal zone. Diffuse medium sand sheets frequently cover the beach during higher-energy swash events, but the energy regime is typically low throughout the year. Small patches of heavy minerals develop on the beach as a result of differential entrainment and transport (Hamilton and Collins 1998).

The dune field at Salmon Cove is extremely restricted, consisting of a single line of modified parabolic and dome dunes which have coalesced into a transverse complex. The dunal complex originally extended along the length of the beach, but anthropogenic disturbance has resulted in serious degradation over the 100 m-long complex (Catto 1994c). The surfaces of the dunes are disturbed by numerous trough and saucer blowouts. Grainfall was the dominant process, and little evidence of traction or saltation load deposition is evident. Local deposition and reworking on the dune surface was controlled by short, sharp onshore wind gusts (Jungerius 1984; McFadgen and Yaldwyn 1984; Pluis 1992) and by the distribution of patches of moist sand and snow.

The coastal dunes developed during the mid-Holocene, in response to lowered sea levels and the availability of supplies of fine and medium sand. Delay in the establishment of coastal vegetation along the exposed shores allowed dune construction to progress. Destabilization of coastal environments during the incipient stages of the mid- to late Holocene transgression (Davidson-Arnott and Pyskir 1988) may have facilitated or enhanced the development of the coastal dune sequence. A fragment of *Abies* wood within the dunes that was exposed by wave erosion in October 1992 has been ^{14}C dated at 4250 ±130 B.P. (GSC-5535).

Mid-Holocene climate was milder than that of the present, retarding the development of coastal peat veneers and blankets and increasing the influx of terrestrial sediment. Under the current climate, development of aeolian dunes is hindered by the regrowth of vegetation and the blanketing of areas adjacent to the shorelines by terrestrial peat. The dunes are thus essentially relict features, and will not regenerate naturally under the present environmental conditions.

At Lance Cove, south of Branch, a wide sand flat (Class 19) shore grades laterally to the east into sand flats on wide (Class 10) and narrow (Class 11) rock platforms. Here, the sediment consists of medium to fine-grained, moderately sorted, discoid sand, accumulated from reworking of glaciofluvial deposits during early postglacial time. Following marine regression during the early and mid-Holocene, this sand was further reworked into a complex of low dome dunes, sand sheets, and patches of coarse loess. A ^{14}C date obtained from peat buried by dune material and subsequently exhumed by fluvial erosion suggests that dune building prograded to the shore area *ca.* 5380 +/- 60 B.P. (GSC-5572). The dunes are actively undergoing reworking from coastal onshore winds, fluvial erosion, storm waves, and anthropogenic-induced deflation resulting from overgrazing by sheep and disturbance from all-terrain vehicles. Sand flux to the beach, therefore, is high from early spring to mid-winter, and proceeds year-round when seasonal icing does not occur (as in winter 1997-98).

The sand flat is marked by an extremely gentle slope (<1-4°). Storm activity results in small areas of undercutting at the dune margins and along the course of the stream that crosses the beach, but these seldom exceed 0.5 m in height and are quickly smoothed by subsequent reworking. Most storm waves, including those associated with hurricanes 'Bob', 'Felix', 'Opal' 'Hortense', and 'Irene', travel over the surface of the sand flat without causing significant erosion, and the energy is focused at the dune field margin. Sediment eroded from the dunes is laid down during backwash as a thin, planar, gently dipping stratum. Repetitive swash events destroy the stratification imparted during each backwash period, and thus the storm deposits are characteristically structureless. During normal wave activity, swash-and-backwash scour patterns and low energy ripples are produced, and bioturbation is not in evidence.

The stream flowing across the beach also produces sedimentary structures. Fluctuating energy levels and water volumes in the stream allow production of various styles of ripples, planar beds (resulting from migration of small diffuse sand sheets and sediment clusters), internally structureless fan-shaped deposits (resulting from viscous grain flows induced by bank undercutting and collapse), and rarely antidunes, formed by upstream migration of oversteepened wave fronts. All of these features are small-scale structures, and all are ephemeral. Exposures of sediment in the beach show that, below the surface, sediments are generally structureless or planar-bedded, reflecting reworking during storm events.

Other wide sand flats are present along the lower reach of the Piper's Hole River, at Flat Island Cove, in the Cow Head area, and north of Red Head, Placentia Bay; and at Point May Pond. All are characterized by very gentle slopes (# 5°), and are located in areas of abundant sand supply. The character of these beaches has changed little from 1966 to 2000. Beaches such as those at Cow Head and north of Red Head, where aeolian sedimentation is less significant than fluvial input, are generally coarser than the system at Lance Cove. Cow Head is dominated by coarse-grained sand, Red Head by medium-coarse grained sand, and the Piper's Hole River shore by medium-fine grained sand. Sorting varies with modal texture, with coarser sand flats showing moderate to good sorting, whereas sand flats with finer sand are more poorly sorted. At Flat Island Cove, the sand flat is laterally transitional into a mixed sand and gravel flat, and is associated with tombolo development. Here, the textural character of some zones along the beach changes seasonally, coarsening in the late autumn and gradually acquiring finer sediments throughout spring and summer.

The only true sand flat system along the South Coast of eastern Newfoundland is located along the eastern side of Boxey Harbour, and varies in character through time from sand-dominated (shore classes 19, 20, and 21) to mixed sand-and-gravel (shore classes 16, 17, and 18). Storm events result in erosion and modification of the beach, increasing the content of pebbles and granules. Long periods of quiescence result in deposition of sand under low energy conditions.

The sand-dominated areas are located along the northeastern side of Boxey Harbour. This shore is sheltered from direct southwest (hurricane) winds by Boxey Point, which acts to deflect the strongest waves to the east, bypassing the harbour. To the south, the elevated Boxey Harbour Head also acts to shelter the beach system. Sand is derived from the friable red sandstones (Great Bay de l'Eau Formation) that flank the shore, many of which contain small caves and notches indicative of combined wave and frost erosion. This part of the coastline varies between reflective conditions (during storm events) and dissipative conditions (under calmer conditions), in contrast to the more reflective environment that prevails in the northern and western parts of the Boxey Harbour shoreline.

When sand flat development predominates, the shoreline is marked by a gentle slope (1-3°). Swash-and-backwash scour patterns, produced by low-energy vortex currents within the incoming and outgoing water masses are present during calm periods, form a cross-hatched pattern. Linear swash scours 1-2 mm deep are truncated by backwash-produced linear or very gently curved scours 2-5 mm deep. The angles between the swash and backwash features vary from 40° to 70°. Swash oriented parallel to the shore face tends to produce backwash oriented at 40-50° to the shore, and generally occurs during low to moderately low energy conditions. In contrast, very low energy conditions permit beach drift to become more effective, and the resulting backwash scours are oriented at shallower angles (50-70°) with respect to the swash. Throughout this segment of shoreline, however, the acute angles between swash and backwash indicate that transport of particles approximately perpendicular to the shore (onshore-offshore movement) is dominant over beach-parallel drift. These features are highly ephemeral, frequently lasting only until the next large swash wave destroys the old pattern and begins designing a new one.

Ripples are also formed by low-energy swash waves. The ripples are straight-crested, in phase, with sharp crests and distinctive stoss slopes (angles of 7-12°) and lee slopes (angles of 25-30°). Typical crest-trough heights (amplitudes) are 1-3 cm, and typical wavelengths are 7-12 cm. Wavelength/amplitude ratios (Tanner 1967) range between 3 and 7, representing typical values for low-energy ripples produced under essentially unidirectional water flow. Preservation of the ripples is rare.

The narrow sand flat area (class #20) resembles the broader area to the northwest in most respects. Sedimentary structures are rarely preserved. Planar laminations sloping parallel to the general slope of the beach (3-6°) are commonly intercalated vertically and laterally with structureless deposits. The steep sand beach (class 21) contains medium to coarse-grained sand. Slope angles vary from 5-10°, with most slopes approximating 6-8°. Profiles are linear to slightly concave.

Seasonal variability is less apparent on this shore than on beaches with larger concentrations of gravel (Classes 16, 17, and 18). The transition between sand-dominated and sand-and-gravel-dominated regimes on the Boxey Harbour beach is a function of local sediment supply.

8.20 Class 20- Narrow Sand Flat

Narrow sand flat systems are uncommon along the eastern Newfoundland shore. Gradation among shorelines of Classes 19, 20, and 21 is common. In addition to the areas of wide sand flats, sand flats on rock platforms, and sand beaches at cliff bases discussed above, examples of narrow sand flats occur at Swift Current; along the eastern side of Burin Bay Arm; at Lansey Back Cove; on Patricks Island, south of Oderin Island, Placentia Bay; and at the heads of elongate embayments such as Bay de l'Eau and North Harbour (Capelin Cove, Placentia Bay).

Narrow sand flats resemble the broader flats of Class 19 in most respects. Sediments are generally somewhat coarser, but much of this textural differentiation can be attributed to the available sand supply rather than to factors inherent to the flats. The narrow sand flats are all developed in regions where sediment is derived primarily from fluvial and marine processes, rather than from aeolian deposits. Consequently, the sand supplied to theses beaches is generally moderately sorted, medium- to coarse-grained discoid clasts (especially noticeable at Bay de l'Eau and Burin Bay Arm). Sedimentary structures are rarely preserved, and planar laminations sloping parallel to the general slope of the beaches (2-7°) are commonly intercalated vertically and laterally with structureless deposits. Heavy mineral segregation is evident in the nearshore areas, resulting from differential entrainment of the denser clasts by swash action (Hamilton and Collins, 1998). Variation in the texture supplied from fluvial sources has a large influence on the composition of the beach sediments (Shulmeister and Kirk 1997).

At Swift Current, the dominant texture varies from medium sand to fine granules, primarily in response to variations in fluvial input resulting from spring runoff or precipitation associated with storms. Clast shapes range from spheres to elongate blades, also reflecting fluvial transport. The flats slope at 2-5°.

8.21 Class 21-- Steep Sand Beach

Steep sand beaches develop both associated with and independently of sand flats, grading laterally (and seasonally) into mixed sand and gravel flats. Modal grain sizes are generally in the coarse sand range. Slope angles vary from <3- 15°, with most slopes approximating 5-8°. Profiles are linear to slightly concave.

Seasonal variability is less apparent on the steep sand beaches than on steep beaches with large concentrations of gravel (Classes 15 and 18). The beach front trends are gently concave to linear. Cuspate structures are not apparent at most times, but may persist for short periods following storms. Where developed, cusps are shallow and have breadths much greater than widths, with no seaward lips. Cuspate lines of sand particles, often only one or two clasts thick, form during low energy swash-and-backwash periods. Characteristically, the cuspate lines are asymmetrical, indicating the existence of shore-parallel transport. Ripples are rarely present, and are ephemeral.

At Lansey Back Cove, the sand-dominated beach is present on the down current side of the mouth of the small stream. The sandy sediment for this beach is supplied largely by the stream, and hence the down current beach is finer in texture (fine sand) than that located on the eastern, up current side of the stream mouth (medium-coarse sand). Heavy minerals are more concentrated in the up-current area. Variations in clast shape are also apparent, with sand adjacent to the river mouth having a greater proportion of elongate clasts and a lesser proportion of discoid grains. The texture is highly responsive to terrestrial runoff and precipitation events, particularly during the spring and summer. Slope angles range from 3° to 8°, increasing with grain texture and higher following storm events.

At Burin Bay Arm, the sandy beaches develop in the vicinity of the head of the arm (near Salt Pond), and grade into coarser sand and gravel beaches southward, corresponding to increased energy levels and winnowing along the seaward trend. Slope angles also increase with texture, from modal values for maximum slope of 5° in the head of the arm to 20° in gravel beaches. At both Burin Bay Arm and Lansey Back Cove, therefore, the transition between sand-dominated and sand-and-gravel-dominated beaches is evidently a function of local sediment supply, from essentially point sources.

Along the southwest Woody Island shore, the situation is somewhat more complex, with multiple sources and a serrated coast creating areas of net positive sand influx and other areas marked by deficits and erosion of sand, and coarser mixed sediment beaches. The Woody Island shorelines are thus somewhat more susceptible to seasonal and year-to-year variations than are those at Lansey Back Cove and Burin Bay Arm.

8.22 Class 22 -- Mudflat

Mudflat areas are defined as those shores with a slope <2°, little or no permanent vegetation cover, surface sediment composed of <50% total sand and gravel, and few or no boulders. The majority of the sediment may be either silt or clay, or a combination of both. Mudflats are generally associated with tidal activity in most regions of Atlantic Canada, but this is not a necessary component of the classification. Estuarine deposits formed predominantly by fluvial action, those occupied in whole or large part by any form of vegetation, and those with boulders on the surface are excluded from this classification.

The coastline of eastern Newfoundland is not suited for the development of these features. Sediment supply is limited in many areas, and coarse materials predominate. Tidal regimes are microtidal and low mesotidal, and tides are insignificant compared to waves in shaping almost all segments of the shore. The development of many tidal flats and associated salt-water marshes is related to slowly rising sea level (e.g. Allen 1990; Plater *et al.* 1999), rather than being characteristic of the relatively rapid rise evident on parts of the coast within the past 300 years. Regions where tidal flats have developed under conditions of rapidly rising sea level (e.g. Chezzatcook Inlet, Carter *et al.* 1989) are also marked by abundant sediment supply.

Only two examples of mudflats are present in the study region. An area of small mudflats is present at Black Duck Hole, along Bay d'Espoir. The mudflats are separated by shallow meandering channels, generally less than 1.5 m deep, with fine to medium grained sand deposited in the thalwegs. The mudflat slopes vary between 1-2°, and the surfaces are mantled with approximately equal proportions of sand and silt, with little clay. The Black Duck Hole mudflats appear to be aggrading under conditions of slow sea level rise and abundant sediment input, but the rate of aggradation is not known.

The other true mudflats are in the vicinity of Calmer, on Point May Pond. In this area, small mudflats are associated with sandier zones (Class 19) and lagoonal margins marked by mixed sediment and organic matter (Class 23). This region is classified as a compound shore, 23/22/19, with the order reflecting the relative importance of each shoreline type. Adjacent zones are dominated by partially vegetated lagoonal margin sand flats (23/19), and by similar flats marked by spasmodic vegetation expansion and contraction (23/19 u).

The small Calmer mudflats have maximum slopes of 2°. Sandy silt covers most of the area. Typically the surface sediment is 50%-60% silt, 35-45% sand, and <5% clay. Erosional scarps, less than 30 cm, in height, mark the edges of some flat surfaces. Successive aerial photographs indicate that the flats are eroding at a very low rate, much less than 1 m/a. This erosion may reflect rising sea levels along the southern Burin Peninsula shore, but could also be attributable solely to occasional breaches of the Point May-Calmer Point barrier system during individual hurricanes. The erosional scarps were in evidence following the hyperactive hurricane season of 1995, but are not as prominent on the 1981 videotape survey.

8.23 Class 23 -- Estuary and Fringing Lagoonal

Estuary and fringing lagoonal areas are defined as those where estuarine conditions prevail, together with marginal areas marked by organic sediments, aquatic or marsh vegetation, or near-stagnant lagoonal waters. Lagoons associated with the back-beach areas of barachoix, tombolos, and similar features are excluded from this classification. Issues involved in definition and classification of potential estuaries around the Avalon Peninsula have discussed by Catto *et al.* (1997); also see Fricker and Forbes (1988), Hume and Herdendorf (1993), and Gregory and Petrie (1994). Here, an 'estuary' is defined as an embayment marked by interchange of initially distinct populations of fresh terrestrial water with saline marine water. In a boreal climate, this definition raises the theoretical difficulty that some embayments may cease to qualify as 'estuaries' during the winter months, when stream inflow drops to such low levels that the fresh water mass fails to retain its identity. Most streams, however, flow with sufficient volume throughout the year to allow the estuary to maintain its status.

A greater climatological concern comes when trying to classify a boreal estuary. Numerous schemes have been developed for estuarine classification, but most sedimentologically- or dynamically-based attempts relate the ratio of the velocity of surface water : basal water to the ratio of surface salinity : basal salinity. Seasonal fluctuations in stream flow frequently result in major changes of character of the estuary throughout the year. In cases where surface ice develops over part of the estuary, mixing and wind shear are impeded, often resulting in changes in the near-surface salinity and velocity. Such estuaries may change in classification several times throughout the course of the year. Precise classification of an estuarine system thus requires numerous measurements of surface and basal velocity and salinity throughout the year (and preferably, for several years to eliminate weather fluctuations).

Estuarine conditions are precluded where high-energy marine shorelines are present, and where fluvial influx is ephemeral or confined to small brooks. The shorelines of Trinity Bay, most of Conception Bay, the Southern Shore, and southern Fortune Bay are not suitable for estuary development. Along the margins of Placentia Bay, estuaries are developed by many of the major streams entering the western side of the bay, such as at North Harbour, Black River, Swift Current, Cape Roger Bay, and Bay de l'Eau. Lesser streams at Salt Pond and Point May Pond have also created small estuarine/fringing marsh areas. Along the eastern shore of Placentia Bay, the steep cliffs, shallow coves, and short rivers limit the scope for estuary development. Examples are present at Ship Harbour, Northeast Brook, and Long Harbour. Modification of the sediment flux and fluvial systems entering the latter two of these estuaries by anthropogenic activity has been extensive, however (especially at Long Harbour), resulting in destabilization of the estuarine system which has of yet not been rectified. Along St. Mary's Bay, examples are present at the mouths of the Salmonier, Colinet, Rocky, and North Harbour Rivers, and at Riverhead. Along the Conception Bay shore, the only example of an estuarine system where road and railroad construction has not effectively precluded development is located at Riverhead, at the head of Harbour Grace.

In these estuarine systems, fresh water influx is low compared to the marine water mass. Fresh waters tend to rise to the surface, because of their lesser density (controlled by differential temperatures) and their relatively low sediment loads. Mixing on the surface is ubiquitous, due both to current and wind activity. The estuaries are not obstructed at their seaward margins by large moraines or bedrock sills, and over-deepening by glacially-induced erosion, a common feature of fjordal estuaries, has not occurred or is not significant in these embayments. Consequently, the most common estuarine condition would be expected to involve mixing of surface fresh water with saline waters, and hence low salinity gradients from surface to depth, coupled with high relative velocities of basal water with respect to surface water.

These estuaries, therefore, would generally be categorized by well-mixed conditions during most of the year. Salt-water wedge systems would only exist during periods of anomalously high fresh water influx (e.g. for short periods following spring break-up). Partially mixed zones develop only in the lees of bathymetric obstructions that preclude rapid flow of basal water.

Along the South Coast, the larger estuarine systems are developed in fjordal embayments that have been over-deepened by glacially-induced erosion. Influxes into these fjordal estuaries are obstructed at the seaward margins by bedrock 'sills', glacial moraines, or underflow fan-delta deposits. Marine waters that surmount the obstructions flow with reduced velocities, creating a semi-stagnant basal layer with relatively high salinity. The upper surface of this tidally-driven slow-moving saline wedge interacts with the overlying terrestrial fresh water layer, resulting in entrainment of small amounts of saline water. Caballing flow dominates, and vertical mixing along the wedge margin is minimal. Entrainment mixing proceeds at slow rates, on the order of 10^{-3} cm/s on the horizontal plane. As a result, the saline wedge front moves slowly landward.

In addition to vertical gradients induced by salinity differences, further complications result from horizontal differentiation. Transverse gradients, across the surface of the estuaries, are induced by bathymetry and Coriolis effects. This generally results in higher salinity along the eastern sides of the estuaries than along the western sides. The prevailing southwesterly winds further accentuate this gradation. Flow in estuaries with 'dog-leg' configurations, such as Bay d'Espoir, is influenced by the bathymetry, with deflections towards the centre of the estuaries as water masses flow around protruding cliffs and bends.

The degree of mixing in an estuary depends upon the tidal range, with mesotidal conditions generally resulting in enhanced mixing. The spring freshet also encourages mixing, especially in environments where the incoming water is relatively cold (less than 5°C) and contains suspended sediment. During the summer months, fresh water input develops a stratified profile in most estuaries, with the fresh and relatively warm surface layer forming a distinct seaward-moving plume, concentrated along the western side of the estuary.

Some estuaries developed in smaller embayments are not restricted at their seaward mouths. These estuaries are dominated by well-mixed conditions, with low salinity gradients from surface to depth coupled with high relative velocities of basal water with respect to surface water.

The associated fringing marsh/organic-rich zones serve as sediment traps and holding areas, primarily for sand and coarse silt. Much of the sediment impounded in these areas remains within the system, contributing to shoreline progradation. Recent rising sea levels may result in the eventual erosion and remobilization of much of this sediment.

8.24 Class 24 -- Bouldery Tidal Flat

Bouldery tidal flat areas are distinguished from mudflats (Class 22) by the presence of boulders scattered across the entire surface of the area inundated by high tides. The surface texture of bouldery tidal flats varies greatly throughout the system, but the overall sediment assemblages are dominated by sand, granules, and pebbles. Vegetated areas are commonly interspersed throughout the flat. Slopes of bouldery tidal flat areas are generally very gentle, approximately 1-2°, except where cut by tidal channels.

Several bouldery tidal flats have formed in mesotidal regimes at the heads of embayments, including The Tickle at the head of Connaigre Bay; Swanger Cove and Cribb Cove, along Bay d'Espoir; Dawson's Cove (Sandyville); and Come-by-Chance. A very small example is present at Renews. At Witless Bay, a small tidal flat existed prior to disruption of tidal influx due to road construction. All of these tidal flats display boulders on the surface that were initially transported to the sites by glaciers and which are too large to be moved by tidal action or storm waves. The tidal flats are therefore conditioned by glacial sedimentation, resulting from the surface reworking of the previously deposited glacial sediments (Catto 1991).

All of the tidal flats in the study region are marked by meandering and anastomosing tidal channels, small washover fans, bank collapse sequences, and sedimentary successions resembling those of coarse-sediment oxbow lakes in abandoned channels. Along the Coast of Bays, the rise of sea level has not resulted in significant erosion of the tidal flat complexes, and they appear to be actively aggrading. At Come-by-Chance, the tidal flat is bounded at its seaward margin by a cobble-dominated barachoix. Marine transgression here has permitted enhanced reworking of the cobble gravel barrier, and local breaching and overwashing of the barrier has led to an increase in marine energy levels, evident in the uppermost sediments of the tidal flat succession.

9. Coastal Erosion and Sensitivity to Sea Level Rise

Ongoing sea level rise along the eastern Newfoundland coast results in enhanced coastal erosion. The effects of sea level rise since the time of human occupation are evident at archaeological sites such as The Beaches, Bonavista Bay; Fort Frederick, Placentia Bay; and Ferryland. Submerged tree stumps at Mobile, Southern Shore; Biscay Bay River; Port-de-Grave; and Ship Harbour, Placentia Bay, are further indications of rising sea level (Catto *et al.* 2000). Although no evidence exists to indicate that storm frequency has increased along the Newfoundland coast, or indeed that climate warming has been significant locally (Pocklington *et al.* 1994; Pocklington 1998), sea level is rising and coastal erosion will result (Shaw *et al.* 1998).

Assessment of the sensitivity of a shoreline to sea level rise depends upon several factors. The recession rates of individual cliff faces can be measured by repetitive surveying of the escarpment using fixed reference points. This technique has been used by the Newfoundland and Labrador Department of Mines and Energy (Liverman *et al.* 1994a, 1994b; Batterson *et al.* 1999) to monitor recession rates of cliffs and changes in beach front positions at Point Verde, Placentia, Big Barasway, and Ship Cove, Placentia Bay; Topsail, Chamberlains, and Long Pond, Conception Bay; Holyrood Pond Barrier-St. Stephen's, St. Mary's Bay; Biscay Bay; and Portugal Cove South throughout the 1990's. The most susceptible cliff faces, at Topsail, Point Verde, and Holyrood Pond-St. Stephen's, are composed of glaciofluvial gravel with lesser sand lenses (Catto 1992, 1994a; Catto and Thistle 1993; Nichols 1995; Catto and St. Croix 1997), and are subjected to attack during the strongest storms.

Topsail is most severely affected by northeast gales, particularly the storms of October 1992 and 1994. During the storm of 1992, as much as 1 m of bluff surface was eroded locally, involving removal of concave segments of cliff supported by sand lenses or directly above the focal points of cusps developed at the highest storm berm. Removal of sediment at sites along the Conception Bay South shoreline, however, proceeds sporadically, with periods of minimal erosion and local deposition between major storms. The great majority of sediment removal is accomplished during the major storm events. Liverman *et al.* (1994a, 1994b) noted that a slope with spruce aged 50 to 80 years was failing through basal erosion at the shoreline, indicating that these trees had grown in an environment that was stable prior to the October 1992 event. After the second storm in October 1994, erosion continued for approximately two years. The accumulation of debris at the base of the slope since 1995, coupled with the absence of severe northeast gales since October 1994, resulted in a temporary cessation of erosion in the late 1990's. However, erosion at the base of the bluff has resumed following the hurricanes of autumn 1999 and 2000. The removal of the protective fringe of spruce through downslope failure has left the crown of the bluff vulnerable to future erosion. Similar situations are apparent along Conception Bay South wherever bluffs of gravel abut the shore, as at Carter's Lane, Cherry Lane, Burnt Island, and Chamberlains Pond.

Point Verde and Holyrood Pond-St. Stephens are affected primarily by hurricane winds from the southwest. At Point Verde, the presence of the lighthouse, and the periodic necessity for repairs resulting from undercutting of the cliff, enables long-term assessment of erosion rates. Henderson (1972) reported that the lighthouse keeper at Point Verde estimated that approximately 16 m of recession had occurred in 30 years, and suggested that in the late 1950's the recession rate was approximately 60 cm/a. Similar values were suggested for more recent erosion rates by Liverman *et al.* (1994a, 1994b), and by subsequent measurements (D. G. E. Liverman, personal communication). At Holyrood Pond-St. Stephens, Forbes (1984) estimated a retreat rate of 30 cm/a over a 20-month interval. Ongoing measurements by Forbes and Liverman, and observations by Nichols (1995; in preparation) and the author, suggest that current erosion rates (as of autumn 2000) approximate this value. At both Point Verde and St. Stephens, however, erosion does not proceed uniformly. Individual storm events (such as hurricane 'Opal' at St. Stephens, or hurricane 'Irene' at St. Brides) account for the majority of the erosion.

The strength of specific storm events, and the angle of attack of the waves produced, together dictate the amount of erosion. Although a long-term erosion rate is a useful guide to the establishment of set-back limits (Taylor 1994), and indicates where specific structures are in danger (such as the Point Verde lighthouse), it does not fully indicate the true hazard potential at a particular site. As the majority of the erosion is accomplished by individual storms, hazard assessment requires consideration of the probability of the maximum impact of a particular storm, rather than involving monitoring and dealing with incremental, infinitesimal removal of sediment on a daily basis. The Point Verde site has the longest (semi-quantitative) record of cliff erosion assessment in eastern Newfoundland, but this record does not extend to include potentially major events such as the hurricane of 1775 (Stevens and Staveley 1991; Stevens 1995; Ruffman 1995b, 1996) or the tsunamis of 1864 (suspected) and 1929 (Ruffman 1995a, 1995b). These events, or future occurrences of similar magnitude, have the potential to cause much more erosion. The hurricane of 1775 caused coastal erosion and damage to structures in localities such as Northern Bay Sands that are not generally subject to high energy events. The same is true of the 1929 tsunami in localities such as Taylor's Bay and Lansey Back Cove. The monitoring record at other sites does not extend back beyond the initial observations of Forbes (1984). The absence of long-term monitoring means that present erosional rates may not serve to indicate the magnitude of previous (or future) erosional events.

In order to assess the sensitivity of the shoreline to erosion, several variables must be considered. Study of shorelines in the eastern United States by Gornitz (1990, 1991, 1993), Gornitz and Kanciruk (1989), and Gornitz *et al.* (1991, 1993), and of Canada by Shaw *et al.*

(1998) led to the identification of parameters which can be used to assess the sensitivity of a shoreline to erosion. Shaw *et al.* (1998) list seven critical parameters:

- relief;
- rock and/or sediment type exposed along the shore;
- landform type (e.g. cliff, beach, salt marsh);
- tendency of sea-level change (amount of rise or fall per 100 years);
- shoreline displacement (laterally, expressed in m/a);
- tidal range, and
- mean annual maximum significant wave height (defined for eastern Newfoundland by Neu 1982).

Shaw *et al.* (1998) assigned each parameter an equal weight, and ranked variations within each from 1 (very low sensitivity) to 5 (very high sensitivity). Table 9-1 indicates the ranking of sensitivity index variables established by Shaw *et al.* (1998). By combining the scores for each parameter, sensitivity indices (SI) can be calculated as:

SI '% (product of scores of all 7 parameters/7)

Thus, a shore with the least sensitivity to coastal erosion would have a SI of% (1/7), or ~ 0.38, whereas the greatest value possible is% (5 x 5 x 5 x 5 x 5 x 5 x 5/7), or ~108.

Shaw *et al.* (1998) divided the coastline of Canada into three categories of SI. Coastlines with low sensitivity had SI values of # 4.9; moderately sensitive coastlines had values between 5.0 and 14.9; and highly sensitive coastlines had values in excess of 15.0. A single sensitivity index was calculated for all 2899 of the 1:50,000 map areas along the Canadian coastline. Locally, separate SI indices were calculated for map areas with two distinctly different coasts. Two examples are the Placentia map area, where values were calculated separately for the Placentia Bay and St. Marys Bay shorelines; and the Marystown Map area, with separate values for the Placentia Bay and Fortune Bay shores. Based on this analysis, the majority of the shoreline of eastern Newfoundland has a low sensitivity to coastal erosion, with scores less than 4.9. The generally high relief, resistant igneous and metamorphic bedrock, prevalence of rock cliffs, and microtidal conditions all contribute to producing low SI scores in most of the 43 coastal 1:50,000 map areas of eastern Newfoundland. Areas assessed as moderately sensitive include all or parts of the Old Perlican, Ferryland, Renews, Trepassey, St. Marys (eastern shore), St. Brides, Placentia (Placentia Bay shore), Harbour Breton, and Pass Island map-areas. The only map-areas designated as highly sensitive are Grand Bank and the Fortune Bay shore of the Marystown area.

Throughout the analysis, Shaw *et al.* (1998) caution that the regional nature of this investigation may serve to partially conceal local problem areas. The serious nature of erosion problems documented at Point Verde, Placentia town, and Holyrood Pond Barrier-St. Stephens is not diminished by the overall score for the entire 1:50,000 map area. In the Placentia area, for example, Placentia town is vulnerable to sea level rise and erosion (Forbes 1985; Shawmont Martec 1985; Shaw and Forbes 1987; Forbes *et al.* 1989; Liverman *et al.* 1994a, b), but because it is flanked by high resistant bedrock cliffs at Jerseyside and along Placentia Roads, and is subject only to microtidal conditions, the SI score for the map area as a whole is low. In contrast, areas with overall moderate sensitivity (such as St. Brides and Ferryland) will contain shoreline segments of low sensitivity (such as Cape St. Mary and Brigus Head). The St. John's map area, ranked overall as a low sensitivity region, includes the highly sensitive shoreline of Conception Bay South and the non-sensitive shoreline of Cape Spear. Even within high sensitivity areas, extremely sensitive locations (such as Frenchmans Cove) may not be sufficiently highlighted.

An investigation on a regional scale allows further subdivision of parameters, assessment of their relative importance locally, and designation of more specific areas for categorization. Although all seven variables identified nationally by Shaw *et al.* (1998) are of significance, the local environment of eastern Newfoundland provides a framework in which these can be considered further.

Relief is a critical variable, with shorelines showing high relief above sea level being relatively insensitive to erosion. Shorelines with relief less than the mean annual maximum significant wave heig ht are clearly liable to periodic inundation and erosion in consequence. Offshore of eastern Newfoundland, the mean annual significant wave height is estimated at 7 m-8 m (Neu 1982; see also Lewis and Moran 1984), with the 10-year and 100-year values estimated at 11 m and 15 m respectively. In addition, estimates of significant wave heights based on models tend to underpredict extreme storm wave heights (Bacon and Carter 1991; Cardone and Swail 1995; Cardone *et al.* 1995). These data suggest that shorelines with relief of less than 11 m are likely to be periodically inundated by storm waves, suffering erosion in consequence. If the extreme wave heights in excess of 30 m recorded during some storms (Swail 1996), and those associated with tsunami activity are considered, it is apparent that 11 m is perhaps a conservative figure for erosional risk.

A shoreline with laterally variable relief, frequently reflective of the offshore bathymetry, tends to funnel waves into low-lying areas between the cliffs. This is evident during storms at locations around eastern Newfoundland, including Shoe Cove and Middle Cove (Torbay area), Ship Cove (Placentia Bay), Mobile (Southern Shore), Bristols Hope (Conception Bay), and many others. Funneling of tsunami waves into low-lying areas has been documented elsewhere (e.g. Tinti 1993; Bondevik *et al.* 1998; Dawson 1999), as well as on the Burin Peninsula during the 1929 event (Ruffman 1995). An overall 'high relief' shoreline may actually increase the sensitivity of intervening coves and embayments to coastal erosion during storm and tsunami events. Assessment of the influence of relief must therefore include allowance for lateral variability, inducing energy focusing.

The modified ranking of sensitivity for relief is depicted in Table 9-2. Shorelines with relief less than the mean annual significant wave height offshore are considered to have a very high risk relief factor. Shorelines with relief less than the mean 10-year significant wave height are considered to have a high risk relief factor. Along shorelines with variable relief, an additional risk factor has been assigned to locations where concentration of wave energy due to offshore bathymetric conditions is anticipated, or has been observed during previous events. Many sites along the coastlines of Trinity Bay, northern Conception Bay, the Southern Shore, Placentia Bay, and northern Fortune Bay are affected in this manner.

Table 9-1 Ranking of Coastal Sensitivity Index (Shaw et al. 1998).

Variable	*Very Low (1)*	*Low (2)*	*Moderate (3)*	*High (4)*	*Very High (5)*
Relief (m)	>30	21-30	11-20	6-10	0-5
Rock Type	Plutonic rocks, high-grade metamorphic and volcanic rocks	Metamorphic Rocks	Most Sedimentary Rocks	Poorly Consolidated Sediments	Unconsolidated Sediments, Ice
Landform	Fjord, high rock cliffs, fjard	Moderate and Low Rock Cliffs	Beach, unconsolidated sediments over bedrock	Barrier, bluffs, salt marsh, peat, mudflat, delta, spit, tombolo	Ice-bonded sediment, ice-rich sediment, ice shelf, tidewater glacier
Sea-level Change (cm/100 a)	Falling more than 50 cm/100 a	Falling between 50 and 20 cm/100 a	Change between -19 and +20 cm/100a	Rising between 21 and 40 cm/100 a	Rising more than 40 cm/100 a
Shoreline Displacement (m/a)	>0.1 Accreting	0 Stable	-0.1 to –0.5 eroding	-0.6 to –1.0 eroding	Eroding more than 1.0 m/a
Tidal Range (m)	<0.50 microtidal or nontidal	0.5 to 1.9 microtidal	2.0 to 4.0 mesotidal	4.1 to 6.0 macrotidal	>6.0 strongly macrotidal
One year maximum wave height (m)	0 to 2.9	3.0 to 4.9	5.0 to 5.9	6.0 to 6.9	>6.9

Table 9-2. Modified risk relief variable.

Very low (1):	All shorelines with Relief in excess of 30 m
Low (2):	All shorelines with Relief 21 - 30 m
Moderate (3):	All shorelines with Relief 15 - 20 m Non-embayed shorelines with Relief 11 - 15 m
High (4):	Relief 11 - 15 m on embayed shorelines exposed to northeast (Conception Bay, Trinity Bay, Atlantic Southern Shore) Relief 11 - 15 m on embayed shorelines exposed to southwest (South Coast, Fortune Bay, Placentia Bay, St. Mary's Bay) All shorelines with Relief 7 - 11 m
Very High (5):	All shorelines with relief < 7 m

The rock or sediment type is also critical in determining the sensitivity to coastal erosion. Along the eastern Newfoundland shoreline, the dominant process responsible for weathering bedrock is frost action, and hence the susceptibility to erosion depends in large measure on the cliff aspect; on the orientation and number of jointing, fracture, bedding, and other planes of weakness; and on the crystal size (metamorphic and igneous) or clast size (sedimentary), as water can percolate and freeze along clast or crystal margins. The effectiveness of salt hydration pressure (Yatsu 1988; Goudie 1989) although uncertain in eastern Newfoundland, would be governed by similar considerations. Salt spray acts to depress the freezing point of water, thus inhibiting frost wedging. The few limestone outcrops along the eastern Newfoundland shoreline are also subject to coastal karst activity.

Cliffs with southerly aspects (on the north side of embayments) receive less snow and freezing rain, and are less subject to frost action than north-facing slopes. This is one reason why many communities along Conception Bay, such as Bay Roberts, Harbour Grace, and Carbonear, developed on the north sides of the embayments (Catto 1999). The bases of these cliffs are thus less susceptible to coastal erosion than are those on the southern sides of the embayments. The cliff bases on the southern sides of Conception Bay, Trinity Bay, and Southern Shore embayments are also more exposed to wave attack during northeast gales. In contrast, cliffs which face southwesterly along the hurricane-influenced shores of the South Coast, Fortune Bay, Placentia Bay, and St. Marys Bay, are more vulnerable than those with different orientations, particularly those (such as Paradise Sound and Belle Bay) along the western shores of the major bays. Southwesterly facing cliffs are also more subject to frost wedging than are those facing northward.

Jointing, fracture, and bedding plane orientation and density, and crystal and clast sizes, vary greatly within individual lithological units of eastern Newfoundland. Thus, the susceptibility of any particular cliff to erosion must be determined through on-site investigation. General tendencies based on lithology, however, are apparent. The most resistant cliffs to erosion are those composed of unjointed, unfractured, metamorphosed quartzite. Finely crystalline granitic rocks, quartz sandstones, and orthogneisses are also resistant to erosion. Moderately resistant rock types under the environmental conditions prevalent in eastern Newfoundland include unstratified rhyolite, finely crystalline diabase dykes, fine to medium-grained arkosic sandstone, paragneiss, fine to medium crystalline gabbro, and basalt. Igneous rocks with internal stratification, such as flow-banded rhyolites and trachytes, sheeted diabase (with porphyritic zones), and ignimbrite assemblages are less resistant to erosion, but generally form cliffs where planes of weakness are approximately vertically oriented. Rocks with coarse crystals, such as coarse granite and porphyries; those with diagenetically created weaker and more resistant zones, such as dolomitized and cherty limestones; and sandstones and conglomerates with coarse clasts, are more subject to erosion. However, if these rocks are unjointed and unfractured, and if they are oriented vertically or with steep dips, they can locally resist erosion.

In eastern Newfoundland, the rock units which are least resistant to erosion include argillite (particularly prone to extensive fracturing), slate, shale, pelite, phyllite, and the weakly consolidated ferruginous sediments of Bell Island. Although these lithologic units are subject to frost weathering, they may locally form cliffs, albeit ones prone to mass movement (as along the southern shore of Bell Island).

Unconsolidated sediments are more susceptible to coastal erosion than is bedrock. Along the eastern Newfoundland shoreline, these deposits include glacial, glaciofluvial, glaciomarine, aeolian, fluvial, colluvial, and organic sediments (Liverman and Taylor 1990; Catto 1992, 1993a, 1994a, 1998b; Catto and St. Croix 1997; Catto and Taylor 1999) in addition to active marine sediments and anthropogenic infills and infrastructure. Susceptibility of these sediments to erosion is a function of aspect with respect to wave activity and frost wedging, sediment texture, compaction and cementation, slope angle, and vegetation cover. Well-sorted sands (particularly aeolian deposits, including cliff-top loess, and sand lenses in glaciofluvial and glaciomarine units) are most vulnerable to erosion in the coastal zone, and organic deposits also fail readily. Fine gravel units within glaciofluvial and glaciomarine sequences are more likely to be eroded than are coarse gravel units. The deposits least likely to fail are those containing substantial amounts of fine silt and clay, such as glacial sediments derived from underlying silt-rich bedrock or (on the Burin Peninsula) from pre-existing Quaternary sediments. In local areas, groundwater activity has resulted in the formation of resistant or cemented horizons containing iron and manganese oxides (notably at Peter's River, Nichols 1995 and in preparation), which act to hinder erosion. Bluff faces with slopes in excess of the critical angle of repose are liable to failure.

The presence of vegetation has long been known to stabilize slopes, although these effects have seldom been rigorously quantified (Wu *et al.* 1979; Riestenberg and Sovonick-Dunford 1983). In eastern Newfoundland, areas with dense boreal forest vegetation are less susceptible to erosion than areas lacking any vegetation cover. However, the presence of tuckamore (krummholz) white spruce at cliff-top sites may actually accentuate erosion under conditions of rising sea level. Block failure of unconsolidated sediment bluffs, and of badly jointed bedrock, is accelerated where tuckamore killed by salt spray is present. The tuckamore roots act to wedge the substrate apart, reducing cohesion and promoting frost wedging, and the dead tree acts as a top-heavy obstruction to onshore winds. Sites with dead tuckamore cover erode more rapidly than sites covered with grass, *Empetrum* headland herb assemblages (Damman 1983; Thannheiser 1984), or boreal forests with upright trees. A similar effect is evident where a bluff-top fringe of coastal trees is subject to erosional pressure, as at Topsail United Church (Liverman *et al.* 1994a, 1994 b).

The combined effects of rock/sediment type and vegetation cover on sensitivity are summarized in Table 9-3. Shorelines with a combination of factors indicating increased sensitivity are assigned high and very high rankings (4 and 5), whereas those with a series of low sensitivity factors are assigned very low or low rankings (1 and 2). The overall ranking for any segment of shoreline thus depends on the combination of several parameters.

The ranking of sensitivity indices for landform types is illustrated in Table 9-4. Additional subdivisions have been established to link the landform classification outlined in this report (Catto *et al.* 1997, 1999a; Catto 1997) to the sensitivity criteria. Sensitivity thus varies inversely with slope normal to the shoreline. Texture also influences sensitivity, with gravel beaches being least sensitive, fine sand dominated shorelines most sensitive (due to the ability of water to readily entrain sand), and salt marshes also showing high sensitivity. Ice-bonded sediment, as occurs along periglacial shorelines, refers to permafrost terrain and is not present in eastern Newfoundland.

The tendency of sea-level change (amount of rise or fall per 100 years), and the lateral shoreline displacement (expressed in m/a) also control coastal erosion. The rankings of sensitivity indices for these factors follow those of Shaw *et al.* (1998). Tidal ranges in eastern Newfoundland lie within the microtidal and very lowest mesotidal limits, and variations in tidal range are thus less significant than along shorelines such as those of Nova Scotia and Prince Edward Island. The mean annual maximum significant wave height is also important in assessment of the sensitivity index. Along the eastern Newfoundland coastline, the significant wave height of 7-8 m (Neu 1982) establishes this parameter as having a very high sensitivity ranking. The complete table of Sensitivity Index Rankings, as modified for the shoreline of eastern Newfoundland, is illustrated as Table 9-5.

Table 9-3. Lithological and Related Factors Influencing Coastal Sensitivity to Erosion.

Factors	Sensitivity Lowest (1)	(2)	(3)	(4)	Highest (5)
Jointing	none				pervasive
Frost Activity	none				prominent
Aspect	away from prevalent storm direction				facing prevalent storm direction
Lithology	quartzite	fine granite	diabase	trachyte argillite	aeolian sand
		quartz sandstone	unstratified rhyolite	slate	glaciofluvial
		orthogneiss	arkosic sandstone	pelite	diamicton
			paragneiss ignimbrite	Quaternary	
		fine gabbro	basalt medium gabbro	silt & clay	
			coarse granite		
			feldspathic sandstone & conglomerate		
			dolomite		
			cherty limestone		
Vegetation	forest	grass-herbs	tuckamore	peat	none
	coastal barrens				

Table 9-4. Ranking of sensitivity indices for landform types, eastern Newfoundland.

Very Low (1): High Rock Cliff (Shoreline Class 3)

Low (2): Low to Moderate Rock Cliffs (Shoreline Class 3)

Low-Moderate (2.5): Rock Platforms (Shoreline Classes 1 and 2)

Moderate (3): Gravel over Rock Platform (Shoreline Classes 4 and 5)
High Energy Gravel Pocket Beach (Shoreline Class 6)
Mixed Sand and Gravel over Rock Platform (Shoreline Classes 7 and 8)
Wide Gravel Flat (Shoreline Class 13)
Bouldery Tidal Flat (Shoreline Class 24)

Moderate-High (3.5): Moderate Energy Gravel Pocket Beach (Shoreline Class 6)
Mixed Sand and Gravel Pocket Beach (Shoreline Class 9)
Sand over Rock Platform (Shoreline Classes 10 and 11)
Narrow Gravel Flat (Shoreline Class 14)
High Energy Steep Gravel Beaches not associated with lagoons (Class 15)
Mixed Sand and Gravel Flats (Shoreline Classes 16 and 17)

High (4): Sand beaches at Base of Rock Cliffs (Shoreline Class 12)
High Energy Steep Gravel Beaches associated with lagoons (Class 15)
Low and Moderate Energy Steep Gravel Beaches (Shoreline Class 15)
Steep Sand and Gravel Beaches (Shoreline Class 18)
Mudflat (Shoreline Class 22)
All gravel spits and tombolos

Very High (4.5): Sand Beaches and Flats (Shoreline Classes 19, 20, 21)
Estuarine and Fringing Lagoonal (Shoreline Class 23)

Extremely High (5): no examples in eastern Newfoundland

Table 9-5 Modified Ranking of Coastal Sensitivity Index for eastern Newfoundland *(modified from Shaw et al. 1998)*.

Variable	*Very Low (1)*	*Low (2)*	*Moderate (3)*	*High (4)*	*Very High (5)*
Relief (m)	>30	21-30	15-20 m along embayed shorelines; 11-20 m along non-embayed shorelines	7-15 m along embayed shorelines; 7-11 m along non-embayed shorelines	<7 m
Rock Type and Related Factors	Not jointed; not aligned facing prevalent storm direction; Quartzite; forest cover	Scattered joints; Fine granite; Quartz sandstone; Orthogneiss; Coastal barrens	Moderate jointing; frost action evident; diabase; rhyolite; arkosic sandstone; paragneiss; basalt; feldspathic sandstone; dolomite; grass-herb cover	Pervasive Jointing; frost action evident; trachyte; argillite; slate; pelite; ignimbrite; gabbro; coarse granite; feldspathic conglomerate; limestone; tuckamore; peat	Facing prevalent storm direction; Aeolian Sand; Glaciofluvial gravel & sand; no vegetation cover
Landform	Fjord, high rock cliffs, fjard (shoreline Class 3)	Moderate and Low Rock Cliffs (shoreline class 3); Rock Platforms (shoreline Cl. 1 & 2) assigned as 2.5	Shoreline classes 4,5, 6 (high energy), 7, 8, 13, 24; Shoreline classes 6(mod. Energy), 9, 10, 11, 14, 16, 17, and 15 (high energy but without lagoon) assigned as 3.5	Shoreline Classes 12, 15 (with lagoon; or low to moderate energy), 18, 22; also all gravel spits and tombolos Shoreline classes 19,20,21, and 23 assigned as 4.5	none
Sea-level Change (cm/100 a)	N/a	N/a	Change between 0 and +20 cm/100a (0 and 2 mm/a)	Rising between 21 and 40 cm/100 a (2.1 to 4 mm/a)	Rising more than 40 cm/100 a (>4 mm/a)
Shoreline Displacement (m/a)	>0.1 Accreting	0 Stable	-0.1 to –0.5 eroding	-0.6 to –1.0 eroding	Eroding more than 1.0 m/a
Tidal Range (m)	<0.50 microtidal or nontidal	0.5 to 1.9 microtidal	2.0 to 4.0 mesotidal	4.1 to 6.0 macrotidal	>6.0 strongly macrotidal
One year maximum wave height (m)	0 to 2.9	3.0 to 4.9	5.0 to 5.9	6.0 to 6.9	>6.9

Anthropogenic modification represents an additional complication. Building of roads across barrier beaches is particularly likely to promote coastal erosion, especially under the influence of rising sea level. Anthropogenic activities such as removal of beach sediment; construction of cliff-top buildings; construction of groynes, moles, piers, and sea walls which act to redirect or focus wave energy; and dredging, which also can focus wave energy, have affected the sensitivity of many localities to coastal erosion. Efforts to prevent erosion through the emplacement of riprap or the construction of coastal barriers are evident throughout the region. Similar effects have been achieved inadvertently in some locations, as with the construction of the railway embankment between Holyrood and Kelligrews, and the elevation of coastal roads on embankments.

Other anthropogenic activities have a more subtle effect. Compaction of beach sediment due to ATV pressure results in a surface that presents less frictional resistance to incoming waves, allowing them to extend further landward and resulting in enhanced erosion away from the mean high tide line (Anders and Leatherman 1987). This effect was apparent at Salmon Cove Sands following the northeast gale of October 1992, when the base of the aeolian dune complex was eroded (Catto 1994c). Similar effects are evident at Lance Cove (southwest of Branch), at Frenchmans Cove (Fortune Bay), and at Boxey (South Coast). ATV compaction effects on gravel beaches, although less readily apparent, have also been observed at Big Barasway (Placentia Bay), Holyrood Pond Barrier-Peters River (St. Mary's Bay), Biscay Bay, Mobile (Southern Shore), throughout Conception Bay South, and at Old Shop (Trinity Bay), among many other sites.

Anthropogenic activities which result in changes in the character of the shoreline, such as textural changes, reduction in shore width, changes in slope, changes in vegetation (particularly in dunal areas), and focusing of wave energy into specific positions, are partially accounted for in the parameters listed in Table 9-5. The chief factor not accounted for is assessment of the long-term effects of recent modification of the shore, especially road and dwelling construction. Both practices increase the vulnerability of the shoreline to erosion, and the potential for economic and human loss.

The accompanying map illustrates areas of low, moderate, and high sensitivity to coastal erosion, following the criteria outlined above in Table 9-5. The sensitivity rankings of individual localities are presented in Table 9-6.

Table 9.6. Sensitivity of Selected Communities to Sea Level Rise.

Community	Sensitivity Index	Assessment of Vulnerability
Trinity Bay: Cape Bonavista	14.5	Moderate
Lance Cove	19.0	Moderate to high
Spillers Cove	19.0	Moderate to high
Lancaster	17.8	Moderate to high
Elliston	20.3	Moderate to high
Maberly	16.8	Moderate to high
Little Catalina	24.1	Moderate to high
Catalina	31.0	Very High
Port Union	17.3	Moderate to high
Melrose	27.6	High
English Harbour	20.1	Moderate to high
Champneys	19.5	Moderate to high
Champneys West	20.1	Moderate to high
Port Rexton	20.8	Moderate to high
Trinity East	19.2	Moderate to high
Trinity	18.6	Moderate to high
Goose Cove	18.3	Moderate to high
Dunfield	29.3	High
Trouty	9.3	Low to moderate
Old Bonaventure	16.8	Moderate to high
New Bonaventure	30.0	High
Irelands Eye	14.0	Moderate
British Harbour	14.0	Moderate
Popes Harbour	14.0	Moderate
Gin Cove	16.4	Moderate to high
Somerset	16.4	Moderate to high
Harcourt	16.4	Moderate to high
Barton	14.9	Moderate
Georges Brook	16.4	Moderate to high
Milton	16.4	Moderate to high
Random Island Causeway	19.8	Moderate to high
Snooks Harbour	16.4	Moderate to high
Petley	16.4	Moderate to high
Britannia	16.4	Moderate to high
Deer Harbour Random I.	14.9	Moderate
Hickmans Harbour	16.4	Moderate to high
Burgoynes Cove	16.8	Moderate to high
Lady Cove	14.9	Moderate
Weybridge	14.9	Moderate

Table 9.6. (Cont'd.).

Community	Sensitivity Index	Assessment of Vulnerability
Elliots Cove	14.9	Moderate
Shoal Harbour	16.4	Moderate to high
Clarenville	16.4	Moderate to high
Deep Bight	15.5	Moderate to high
Adeyton	15.5	Moderate to high
St. Jones Within	15.5	Moderate to high
Hatchet Cove	15.5	Moderate to high
Hillview	15.5	Moderate to high
Northwest Brook	21.7	Moderate to high
Queens Cove	16.8	Moderate to high
Long Beach	21.7	Moderate to high
Island Cove	16.8	Moderate to high
Hodges Cove	16.8	Moderate to high
Caplin Cove	18.6	Moderate to high
Little Hearts Ease	21.7	Moderate to high
Southport	18.6	Moderate to high
Gooseberry Cove	18.6	Moderate to high
St. Jones Harbour	16.8	Moderate to high
Deer Harbour	21.1	Moderate to high
Sunnyside	21.7	Moderate to high
Little Mosquito Cove	18.6	Moderate to high
Chance Cove	22.3	Moderate to high
Bellevue Beach	17.8	Moderate to high
Bellevue	31.8	Very High
Tickle Bay	27.8	High
Thornlea	5.3	Low
Collier Bay	20.1	Moderate to high
Long Cove	11.9	Moderate
Normans Cove	13.0	Moderate
Chapel Arm	22.9	Moderate to high
Spread Eagle	21.1	Moderate to high
Old Shop	16.7	Moderate to high
Dildo South	20.2	Moderate to high
Broad Cove	15.5	Moderate to high
Dildo	22.7	Moderate to high
New Harbour	22.3	Moderate to high
Hopeall	22.9	Moderate to high
Green Harbour	23.6	Moderate to high
Whiteway Bay	22.9	Moderate to high
Cavendish	22.3	Moderate to high

Table 9.6. (Cont'd.).

Community	Sensitivity Index	Assessment of Vulnerability
Islington	22.3	Moderate to high
Hearts Delight	28.5	High
Hearts Desire	28.1	High
Seal Cove	23.6	Moderate to high
Hearts Content	28.1	High
Fitters Cove	30.0	High
New Perlican	30.0	High
Turks Cove	28.5	High
Winterton	30.0	High
Caplin Cove	21.1	Moderate to high
Hants Harbour	22.9	Moderate to high
New Chelsea	28.9	High
New Melbourne	28.9	High
Brownsdale Cove	21.7	Moderate to high
Old Perlican	22.9	Moderate to high
Cooks Cove	26.6	High
Daniels Cove	17.8	Moderate to high
Grates Cove	22.9	Moderate to High
Conception Bay: Red Head Cove	20.5	Moderate to high
Backside	19.9	Moderate to high
Bay de Verde	19.9	Moderate to high
Kettle Cove	26.6	High
Low Point	26.6	High
Caplin Cove	30.0	High
Lower Island Cove	25.1	High
Jobs Cove	24.0	Moderate to high
Long Beach	20.1	Moderate to high
Northern Bay Sands	38.0	Extremely High
Ochre Pit Cove	22.3	Moderate to high
Western Bay	28.1	High
Bradleys Cove	20.1	Moderate to high
Adams Cove	19.1	Moderate to high
Blackhead	21.2	Moderate to high
Broad Cove	23.2	Moderate to high
Kingston	20.1	Moderate to high
Perrys Cove	20.1	Moderate to high
Salmon Cove	38.0	Extremely High
Clements Cove	23.6	Moderate to high
Crockers Cove	22.9	Moderate to high

Table 9.6. (Cont'd.).

Community	Sensitivity Index	Assessment of Vulnerability
Carbonear	22.9	Moderate to high
Bristols Hope	22.9	Moderate to high
Harbour Grace	20.5	Moderate to high
Bryants Cove	21.7	Moderate to high
Upper Island Cove	19.0	Moderate to high
Bishops Cove	22.9	Moderate to high
Spaniards Bay	28.1	High
Bay Roberts	22.9	Moderate to high
South West Bay	28.9	High
Upper Back Cove	16.7	Moderate to high
Ship Cove	30.0	High
Port de Grave	22.9	Moderate to high
Clarkes Beach	22.9	Moderate to high
Cupids Cove	22.9	Moderate to high
Sharks Cove	19.1	Moderate to high
North Head	17.8	Moderate to high
Brigus	19.6	Moderate to high
Marysvale	9.5	Low to Moderate
Colliers	30.2	High
Brakes Cove	19.6	Moderate to high
Bacon Cove	22.3	Moderate to high
Kitchuses	14.7	Moderate
Conception Harbour	34.0	Very High
Middle Arm	26.0	High
Broad Cove	34.0	Very High
Avondale	31.0	Very High
Gallows Cove	21.7	Moderate to high
Harbour Main west	21.1	Moderate to high
Harbour Main east	15.3	Moderate to high
Chapel Cove	24.7	Moderate to high
North Arm	21.7	Moderate to high
Holyrood	26.0	High
Indian Pond	32.1	Very High
Seal Cove	29.0	High
Upper Gullies	29.0	High
Kelligrews	32.1	Very High
Foxtrap	32.1	Very High
Long Pond	32.1	Very High
Manuels	32.1	Very High
Chamberlains	32.1	Very High

Table 9.6. (Cont'd.).

Community	Sensitivity Index	Assessment of Vulnerability
Topsail	32.1	Very High
St. Phillips	16.3	Moderate to high
Lance Cove Bell I.	28.9	High
The Beach	28.9	High
Portugal Cove	5.9	Low to Moderate
Bauline	11.0	Moderate
Atlantic coastline: Pouch Cove	19.1	Moderate to high
Shoe Cove	13.4	Moderate
Red Head Cove	16.6	Moderate to high
Flat Rock	21.2	Moderate to high
Torbay	22.9	Moderate to high
Middle Cove	28.9	High
Outer Cove	22.9	Moderate to high
Quidi Vidi	16.8	Moderate to high
St. Johns Harbour	15.0	Moderate
Freshwater Bay	24.5	Moderate to high
Blackhead Bay	22.9	Moderate to high
Spear Bay	19.4	Moderate to high
Maddox Cove	21.7	Moderate to high
Petty Harbour	20.5	Moderate to high
Bay Bulls	22.9	Moderate to high
Witless Bay	20.5	Moderate to high
Mobile	21.2	Moderate to high
Tors Cove	17.8	Moderate to high
Burnt Cove	20.5	Moderate to high
St. Michaels	21.7	Moderate to high
Bauline East	16.4	Moderate to high
La Manche	15.2	Moderate to high
Brigus South	23.2	Moderate to high
Admirals Cove	16.0	Moderate to high
Cape Broyle	22.9	Moderate to high
Calvert	21.7	Moderate to high
Ferryland	22.6	Moderate to high
Aquaforte	18.3	Moderate to high
Port Kirwan	19.6	Moderate to high
Fermeuse	20.5	Moderate to high
Renews	20.5	Moderate to high
Cappahayden	19.0	Moderate to high
Seal Cove	18.9	Moderate to high

Table 9.6. (Cont'd.).

Community	Sensitivity Index	Assessment of Vulnerability
Shoe Cove	11.8	Moderate
Chance Cove	22.9	Moderate to high
Frenchman's Cove	8.0	Low to Moderate
Long Beach	25.2	High
Drook	15.7	Moderate to high
Portugal Cove South	27.4	High
Biscay Bay	26.6	High
Mutton Bay	23.2	Moderate to high
Trepassey	22.9	Moderate to high
Shoal Point	19.2	Moderate to high
Daniels Point	20.5	Moderate to high
St. Marys Bay: St. Shotts	20.5	Moderate to high
St Shores	16.1	Moderate to high
Peters River	22.3	Moderate to high
St. Stephens	22.9	Moderate to high
St. Vincents	23.8	Moderate to high
Gaskiers	18.4	Moderate to high
Point LaHaye	23.4	Moderate to high
St. Marys	21.2	Moderate to high
Riverhead	24.8	Moderate to high
Beachy Cove	29.1	High
Mall Bay	23.9	Moderate to high
Shoal Bay	23.1	Moderate to high
Admirals Beach	19.2	Moderate to high
O'Donnells	25.2	High
St. Josephs	19.2	Moderate to high
St. Catherines	25.5	High
Mount Carmel	26.5	High
Harricott	19.9	Moderate to high
Colinet	26.7	High
North Harbour	18.1	Moderate to high
Dog Cove	21.7	Moderate to high
Big Barachois	34.0	Very High
Little Barachois	25.8	High
Wild Cove	23.4	Moderate to high
Jigging Cove	26.8	High
Branch	22.9	Moderate to high
Gull Cove	21.1	Moderate to high
Point Lance Cove	36.1	Extremely High

Table 9.6. (Cont'd.).

Community	Sensitivity Index	Assessment of Vulnerability
Golden Bay	21.1	Moderate to high
Placentia Bay: St. Brides	22.9	Moderate to high
Cusletts Cove	22.9	Moderate to high
Angels Cove	22.3	Moderate to high
Patricks Cove	22.3	Moderate to high
Gooseberry Cove	22.3	Moderate to high
Ship Cove	22.3	Moderate to high
Big Barasway	22.3	Moderate to high
Little Barasway	22.9	Moderate to high
Point Verde	22.9	Moderate to high
Placentia	27.8	High
Jerseyside	24.5	Moderate to high
Freshwater	27.8	High
Argentia	26.0	High
Broad Cove Point	27.8	High
Fox Harbour	27.8	High
The Neck	27.8	High
Ship Harbour	21.2	Moderate to high
Long Harbour	25.2	High
Mount Arlington	21.2	Moderate to high
Fair Haven	32.0	Very High
Great Pinchgut	24.5	Moderate to high
Pumbly Cove	22.9	Moderate to high
Little Harbour	24.5	Moderate to high
La Manche	23.6	Moderate to high
Little Southern Harbour	24.5	Moderate to high
Great Southern Harbour	24.5	Moderate to high
Arnolds Cove	27.3	High
Whiffen Head	22.3	Moderate to high
Come-by-Chance	26.0	High
Goose Cove	27.8	High
North Harbour	26.0	High
Garden Cove	34.0	Very High
Black River	25.2	High
Swift Current	34.0	Very High
Woody Island Cove	34.8	Very High
Davis Cove	24.5	Moderate to high
Clattice Harbour	16.5	Moderate to high
St. Leonards	24.5	Moderate to high

Table 9.6. (Cont'd.).

Community	Sensitivity Index	Assessment of Vulnerability
St. Kyrans	24.5	Moderate to high
Little Paradise	21.5	Moderate to high
Great Paradise	21.5	Moderate to high
South East Bight	24.5	Moderate to high
Monkstown	21.5	Moderate to high
Petit Forte	27.8	High
Burnt Island	33.4	Very High
St. Josephs	31.8	Very High
Little Harbour	26.0	High
Bay de l'Eau	33.4	Very High
Brookside	34.8	Very High
Boat Harbour	32.5	Very High
Parkers Cove	32.5	Very High
Baine Harbour	34.8	Very High
Rushoon	33.4	Very High
East Broad Cove	33.4	Very High
West Broad Cove	33.4	Very High
Red Harbour	26.2	High
Jean de Baie	26.2	High
Rock Harbour	22.7	Moderate to high
Spanish Room	30.0	High
Cow Head	34.0	Very High
Cashel Cove	30.0	High
Mooring Cove	30.0	High
Marystown	30.0	High
Little Bay	30.9	High
Beau Bois	24.5	Moderate to high
Duricle Cove	24.5	Moderate to high
Fox Cove	24.5	Moderate to high
Mortier	24.5	Moderate to high
Port au Bras	28.1	High
Bulls Cove	29.2	High
Burin	22.9	Moderate to high
Collins Cove	17.9	Moderate to high
Burin Bay Arm	34.1	Very High
Salt Pond	28.5	High
Lewins Cove	24.5	Moderate to high
Bay View	24.5	Moderate to high
Salmonier	30.0	High
Wadsworth	21.2	Moderate to high

Table 9.6. (Cont'd.).

Community	Sensitivity Index	Assessment of Vulnerability
Epworth	26.0	High
Corbin	24.5	Moderate to high
Little St. Lawrence	22.9	Moderate to high
St Lawrence	24.5	Moderate to high
Little Lawn	26.6	High
Lawn	34.0	Very High
Lansey Back Cove	28.9	High
Roundabout	34.0	Very High
Pump Cove	31.8	Very High
Lords Cove	34.0	Very High
Taylors Bay	31.8	Very High
Nantes Cove	18.5	Moderate to high
Point au Gaul	30.0	High
Blow Hole Point	28.1	High
Lamaline	31.8	Very High
Allans Island	34.0	Very High
Calmer	32.3	Very High
Point May	28.1	High
Lories	30.0	High
Lannon Cove	30.0	High
Point Crewe	21.2	Moderate to high
Fortune Bay: Little Dantzic Cove	19.1	Moderate to high
Great Dantzic Cove	20.1	Moderate to high
Fortune	23.9	Moderate to high
Grand Bank	26.7	High
Kellys Cove	23.4	Moderate to high
L'Anse au Loup	30.0	High
Mollier	30.0	High
Grand Beach	31.8	High
Frenchmans Cove	30.9	High
Garnish	30.0	High
Doughball Cove	30.9	High
Point Rosie	26.8	High
St. Bernards	28.9	High
Jacques Fontaine	28.9	High
Bay L'Argent	25.0	High
Little Bay East	24.0	Moderate to high
Little Harbour East	23.8	Moderate to high
Harbour Mille	25.1	High

Table 9.6. (Cont'd.).

Community	Sensitivity Index	Assessment of Vulnerability
Terrenceville	28.1	High
Grand LaPierre	25.5	High
English Harbour East	24.1	Moderate to high
Femme	17.8	Moderate to high
Tranmer Cove	19.2	Moderate to high
Andersons Cove	13.7	Moderate
Hare Harbour	19.8	Moderate to high
Tickle Harbour	27.9	High
Rencontre East	25.9	High
Doctors Harbour	24.3	Moderate to high
Lally Cove	22.5	Moderate to high
Parsons Cove	21.1	Moderate to high
Bay du Nord	15.2	Moderate to high
Pools Cove	32.1	Very High
Corbin	23.9	Moderate to high
Belloram	24.7	Moderate to high
St Jacques	25.3	High
English Harbour West	23.9	Moderate to high
Mose Ambrose	26.7	High
Little MaJambe	23.6	Moderate to high
Boxey Back Cove	26.7	High
Boxey	30.1	High
Saltwater Cove	25.2	High
Coombs Cove	26.0	High
Blunder Cove	16.7	Moderate to high
Wreck Cove	23.2	Moderate to high
Jersey Harbour	21.2	Moderate to high
Harbour Breton	21.2	Moderate to high
Deadmans Bight	27.4	High
Dawsons Cove	27.8	High
Seal Cove	26.7	High
Beck Bay	26.7	High
Pass Island	18.4	Moderate to high
Hermitage Bay-Bay d'Espoir-Facheux Bay:		
Grole	27.4	High
Hermitage	25.6	High
Furbys Cove	25.6	High
Hardys Cove	23.9	Moderate to high
Gaultois	14.4	Moderate

Table 9.6. (Cont'd.).

Community	Sensitivity Index	Assessment of Vulnerability
Conne River	23.1	Moderate to high
Morrisville	27.6	High
Milltown	17.0	Moderate to high
Head of Bay d'Espoir	17.0	Moderate to high
St. Veronicas	24.3	Moderate to high
St. Josephs	27.6	High
Swanger Cove	27.2	High
St Albans	28.7	High
Patricks Harbour	21.1	Moderate to high
Goblin	19.9	Moderate to high
Great Jervis	12.4	Moderate
Pushthrough	16.3	Moderate to high
McCallum	21.1	Moderate to high

10. Pollution and Litter

10.1 Petroleum

Petroleum and its products represent a significant pollution hazard to the shoreline of eastern Newfoundland. Incidents and legal proceedings associated with discharge of petroleum-laden bilge by offshore vessels, and the onshore consequences (Wiese and Ryan 1999; Canadian Coast Guard 1999; F. Shahood, Newfoundland and Labrador Parks, personal communication), have been noted along shorelines from Cape Race to Facheux Bay. The potential for accidental spillage due to difficulties with tankers, offshore wells, or pipelines has increased with the development of the offshore petroleum industry. Although the fisheries in this area unfortunately have declined since initial concerns were raised (Scarlett 1983; Paine *et al.* 1988), sensitivity remains high. In addition to offshore events, accidental discharge of petroleum and gasoline at the shoreline during refinery and tanker operations (Williams *et al.* 1985, 1988), removal and disposal of waste from vessels in port (Olson 1994), and leakages from strictly terrestrial sources, are also matters of concern. Petroleum products can thus arrive at eastern Newfoundland shorelines from both offshore and onshore sources. The statistical data collected by Wiese and Ryan (1999) and the Canadian Coast Guard (1999) indicate that seabird oiling is a growing concern along the Southern Shore, St. Marys Bay, and Cape Shore coasts, particularly at Cape St. Mary's and along the Cape Shore (Shahood, personal communication).

In the wake of responses and long-term results of tanker disasters and clean-up efforts, such as those associated with the Arrow, Braer, Exxon Valdez, Irving Whale, Torrey Canyon, and many other vessels, a large body of information now exists concerning the impact of oil on marine life, its residence time in the water column and substrates under various marine conditions, and the ability of beach environments to be self-cleaned (Stolzenbach *et al.* 1977, Gundlach *et al.* 1983; Nihoul 1984; Tsouk *et al.* 1985; Spaulding 1988; Sobey 1992; Edgell 1994; Thorpe 1995; Sobey and Barker 1997; Wiese and Ryan 1999; Canadian Coast Guard 1999). The sensitivity of beaches in Canada to oil pollution has long been a concern. Owens (1977) provides a thorough review of all the factors involved in assessment of the impact of crude petroleum and petroleum products of differing viscosities under differing temperature conditions on shorelines throughout Canada. Discussions of environmental sensitivity for Canadian coastal systems (e.g. Owens 1977, 1993, 1994; Reinson 1979; Woodword-Clyde Consultants 1981; Owens and White 1982; Owens *et al.* 1982; McLaren 1980; Environment Canada 1988; Cameron *et al.* 1990; Dickins *et al.* 1990; Harper and Reimer 1991; British Columbia Ministry of the Environment 1993) have established that sand to fine gravel beaches and flats, with relatively gentle slopes, low to moderate prevailing energy conditions, and primarily dissipative regimes, are potentially at risk for long-term petroleum contamination.

A second issue involves the source of the petroleum contamination. Low energy areas such as tidal mudflats and salt marshes are less likely to be contaminated by offshore spills, as these areas are generally isolated from the prevailing pattern of current and wave motion. This is particularly true along the eastern Newfoundland shore, where microtidal conditions dominate. However, oil reaching such an environment as a result of a terrestrial-based or shoreline spill would be extremely difficult to remove. Estuarine and lagoonal areas are particularly susceptible to pollution from terrestrial sources.

Ranking of the sensitivity of the coastal environments of eastern Newfoundland to petroleum pollution thus requires consideration of the geomorphology and sedimentology of the shoreline, the dynamics and energy, the biological assemblages, and the location with respect to potential offshore and onshore sources of contamination. Aesthetic and cultural factors must also be considered, as 'sensitivity' is driven at least in part by human perceptions and values. Table 10-1 summarizes the factors involved in an assessment of the sensitivity of the eastern Newfoundland coastline to petroleum contamination.

Following the geomorphological criteria established by other studies, the shorelines most sensitive to contamination from petroleum are sand-dominated beaches assigned to shore classes 10, 11, 12, 19, 20, and 21; mixed sand-and-gravel flats with a preponderance of sand, granules, and fine pebbles (within shore classes 16 and 17); mudflats (shore class 22); estuarine systems (shore class 23); and bouldery tidal flats (shore class 24). Mixed sand-and-gravel flats dominated by pebble and coarser gravels (shore classes 16 and 17), steep mixed sediment beaches (shore class 9), and mixed sediment veneers on rock platforms (shore classes 7 and 8) are less sensitive to petroleum pollution, but local circumstances can nevertheless lead to serious situations. Steep mixed sediment beaches (shore class 18) and gravel flats (shore classes 13 and 14); steep gravel beaches (class 15); and gravel beaches developed on rock platforms (shore classes 4 and 5) are less sensitive. The sensitivity rankings are summarized in Table 10-1.

Rock shorelines are relatively insensitive to petroleum pollution, with sensitivity decreasing with slope steepness. However, biological damage can result from surface oiling and oil-laden spray, even if the oil does not remain within the shoreline system. The sensitivity of rock units also varies with lithology and fracture pattern. Fractured argillites along the eastern Newfoundland shoreline are more likely to retain oil in the shoreline environment than are unfractured, resistant granites and quartzites.

Areas of high biological productivity (Catto *et al.* 1999 b) are particularly susceptible to petroleum contamination from terrestrial and offshore sources. Although estuaries and salt marshes are obvious examples, other biologically productive areas such as capelin spawning beaches and *Ascophyllum* rockweed shorelines are present along the coastline. Vertically zoned assemblages on rock cliff faces and temporary intertidal communities are subject to periodic natural disturbances, and may regenerate following contamination, but the effects will remain within the biological communities for some time following petroleum dissipation. Retention of petroleum in porous or fractured rock units may delay recovery of some coastal rock-shore communities. The degree and persistence of contamination, and its influence on the biological community, will also depend upon the petroleum product involved. Light petroleum distillates such as gasoline may have limited effects on taxa which reside below the water surface (Williams *et al.* 1988), but the influence of heavier materials which can become admixed with the substrate will be much more pervasive.

Table 10-1. Ranking of sensitivity to Petroleum Contamination for Shoreline Classes.

Very Low (1):

Resistant Rock Cliff (within Shoreline Class 3)
Rock Platforms (Shoreline Classes 1 and 2)
Cobble Gravel over Wide Rock Platform (within Shoreline Class 4)
Gravel over Narrow Rock Platform (Shoreline Class 5)

Low (2):

Friable Rock Cliffs (within Shoreline Class 3)
High to Moderate Energy Steep Gravel Beaches (within Shoreline Class 15)
Steep Sand and Gravel Beaches with Gravel>Sand (within Shoreline Class 18)
Narrow Gravel Flat (Shoreline Class 14)
Wide Gravel Flat with Cobbles>Granules (within Shoreline Class 13)
High Energy Gravel Pocket Beach (within Shoreline Class 6)
Pebble Gravel over Wide Rock Platform (within Shoreline Class 4)

Low to Moderate (2.5):

Low Energy Steep Gravel Beaches (within Shoreline Class 15)
Steep Sand and Gravel Beaches with Sand>Gravel (within Shoreline Class 18)
Wide Gravel Flat with Pebbles>Cobbles (within Shoreline Class 13)
Moderate Energy Gravel Pocket Beach (within Shoreline Class 6)

Moderate (3):

Mixed Sand and Gravel over Rock Platform, Gravel>Sand (within Shoreline Classes 7 and 8)
Mixed Sand and Gravel Pocket Beach with Gravel >Sand (within Shoreline Class 9)
Narrow Mixed Sand and Gravel Flat with Gravel >Sand (within Shoreline Class 17)
Wide Mixed Sand and Gravel Flat, Cobble Gravel dominant (within Shoreline Class 16)
Wide Gravel Flat with Granules>>Cobbles (within Shoreline Class 13)
Low Energy Fine Gravel Pocket Beach (within Shoreline Class 6)

Moderate-High (3.5):

Narrow Mixed Sand & Gravel Flat with Sand >Gravel (within Shoreline Class 17)
Wide Mixed Sand and Gravel Flats with Gravel >Sand (within Shoreline Class 16)
Mixed Sand and Cobble Gravel Pocket Beach, Sand >Gravel (within Shoreline Class 9)
Mixed Sand and Gravel over Rock Platform, Sand>Gravel (within Shoreline Classes 7 and 8)

High (4):

Bouldery Tidal Flat (Shoreline Class 24)
Mudflat (Shoreline Class 22)
Sand over Narrow Rock Platform (Shoreline Class 11)
Sand Beaches at Base of Rock Cliffs (Shoreline Class 12)
Wide Mixed Sand & Gravel Flats with Sand>Gravel (within Shoreline Class 16)
Mixed Sand & Pebble Gravel Pocket Beach with Sand >Gravel (within Shoreline Class 9)
Narrow Mixed Sand & Pebble Gravel Flats, with Sand >Gravel (within Shoreline Class 17)

Extremely High (5):

Sand over Wide Rock Platform (Shoreline Class 10)
All Sand Beaches and Flats (Shoreline Classes 19, 20, 21)
Estuarine and Fringing Lagoonal (Shoreline Class 23)

The directions, mechanisms, and dynamics involved in water motion and sediment transport will also influence sensitivity. High energy shorelines have a greater capacity for self-cleaning than do those marked by modally low energy conditions. Shorelines that are dissipative in nature, where the energy of incoming waves is largely expended offshore, are more vulnerable than are reflective shorelines. Shorelines subject to overwashing or overtopping are more likely to retain petroleum than are those where geomorphology or anthropogenic structures preclude or limit these processes. Shore-parallel transport increases the possibility of longshore contamination from terrestrial, shoreline, or nearshore sources. In contrast, shore-normal systems are unlikely to receive contaminants from terrestrial or nearshore sources, with the exception of those in the direct vicinity. Contamination from offshore sources is more likely in shore-normal or shore-oblique systems not marked by strong, persistent returning backwash. As the direction, nature, and energy regimes of wave activity along the eastern Newfoundland shoreline change in response to meteorological conditions, the probability of any particular beach receiving contamination depends upon the wind direction prevalent at the time of petroleum spillage.

Anthropogenic modification of the shoreline environment also increases the likelihood of and the sensitivity to contamination in many instances. Along a coastline with alternating anthropogenically modified and relatively undeveloped segments, incoming waves are focused and partitioned differentially (Anthony 1994). The infrastructure has a similar effect to the natural bathymetric variations in changing local wave and transport regimes.

The variety of local circumstances, the possibility of pollution from both terrestrial and offshore sources, and the effects of different meteorological conditions, cause assessment of sensitivity to be complex. The accompanying map indicates areas of potential sensitivity, based on all the criteria discussed above.

10.2 Beach Litter

With increasing interest in ecotourism, the physical appearance of the shoreline has become a subject of concern. Although beach litter is perhaps not the most severe pollution problem facing eastern Newfoundland, and may provide habitats or shelter for some beach organisms, it is nevertheless the most visible aspect of pollution to most tourists. Accumulation of litter leaves an unfavourable impression, in addition to precluding some forms of recreational activity.

On most beaches around the world, plastic is the dominant form of litter (Ross *et al.* 1991; Lucas 1992; Coe and Rogers 1997; Frost and Cullen 1997; Walker *et al.* 1997; Willoughby *et al.* 1997; Bowman *et al.* 1998). Plastic commonly comprises more than 50% of the litter by weight and more than 70% by volume. Plastic objects originating from terrestrial sources, including those generated by both domestic and tourism-related activities, dominate the beaches near many major cities (O'Callaghan 1993; Jones 1995; Willoughby *et al.* 1997; Ribic 1998; Velander and Mocogni 1998). In areas where tourism has increased, such as Indonesia and Israel, the spread of tourist-related plastic debris is evident (Uneputty and Evans 1997; Bowman *et al.* 1998). Local variations are evident with distance from recreational beach sites (Frost and Cullen 1997; Madzena and Lasiak 1997). Areas adjacent to shipping lanes accumulate plastic jetsam (Horsman 1982; Vauk and Schrey 1987), and materials discharged by recreational boaters are also dominant locally (Whiting 1998). Plastic debris related to fishery activity, especially remnants of lines and nets, dominates in coastal sites isolated from major cities (Piatt and Nettleship 1987; Pruter 1987; Lucas 1992; Wace 1994; Walker *et al.* 1997). At sites where fishing activity offshore decreased or ceased, the proportion of fishery-related plastic debris also declined abruptly (Merrell 1984; Velander and Mocogni 1998).

Wood, excluding natural driftwood, is the second most abundant form of beach debris at most sites. Offshore islands, such as Sable Island (Lucas 1992) generally display higher proportions of plastic debris and lower proportions of wood than do sites in proximity to large cities or fishing communities. Other litter materials commonly found include glass, cloth, hemp ropes, cardboard, tar balls, beverage containers, and other metal objects. Under local circumstances, some of these items may have increased significance (Cahoon 1990; Debrot *et al.* 1995; Coles and Al-Riyami 1996). Sewage-related debris, although found on distal sites (Lucas 1992), is more abundant in proximity to large cities (Ross *et al.* 1991; Ribic 1998). In some areas, the proportion and volume of sewage-related debris has increased, even as other litter produced from domestic sources becomes both relatively and absolutely less frequent (Velander and Mocogni 1998).

The importance of quantitative assessment of beach litter, its accurate measurement by mass and volume, and the determination of its source, have been commented upon by numerous researchers (Dixon and Dixon 1981; Garrity and Levings 1993; Ribic and Ganio 1996; Willoughby *et al.* 1997; Bowman *et al.* 1998). Numerical data are important in any effort to alleviate the problem of litter, as well as to document changing patterns (Velander and Mocogni 1998). Unfortunately, quantitative study of beach litter has not been undertaken along the eastern Newfoundland coastline, although commendable efforts have been made to clean up the beaches by local residents. In the absence of rigorously quantitative study, casual observations made by the author are reported here, in the hope of stimulating research.

In common with other areas where fishery activity has been curtailed, beach litter along the northeast coast of Newfoundland has become less dominated by fishery debris since 1992, and a greater proportion of domestic debris and wood is now present. Along the Placentia Bay, St. Mary's Bay, and South Coast shorelines, fishery-related debris remains an important component of the assemblages. Variations in the quantity of debris are related to seasonal activities, with domestic debris increasing during the summer, and fishery debris fluctuating in response to the opening and closing of specific seasons. Debris volumes on the South Coast, Burin Peninsula, Placentia Bay, and St, Mary's Bay increase following hurricane events. Volumes along Trinity Bay, Conception Bay, and the Southern Shore increased following the northeast storms of October 1992 and 1994, and also tend to increase following the breakup of winter ice.

Qualitative observations reveal that differences exist in debris assemblages along the eastern Newfoundland shoreline. Immobile litter, such as automobiles, is usually found in the vicinity of communities, in locations that are readily predictable. In contrast, mobile litter may travel long distances and can arrive at the most inaccessible sites. Nearshore current patterns and the response of wave activity to meteorological conditions, however, are good guides in predicting the likely distribution of litter.

Table 10-2 indicates the qualitative differences in litter assemblages observed along some segments of the eastern Newfoundland coastline. In contrast to the general pattern of litter distribution on beaches worldwide, those of eastern Newfoundland generally have higher proportions of processed wood, and lower proportions of plastic. Plastic appears to comprise more than half the litter along the shoreline of Conception Bay South, but most other beaches have equal or greater amounts of processed wood. Fishery-related plastic debris (ropes, netting) is present in the greatest proportions along beaches adjacent to active fisheries (Cape Shore, Conception Bay North), and is proportionally less common in areas adjacent to larger population centres (such as Conception Bay South) or those where modal current activity flows from a population centre located upcurrent (such as Mobile). Plastic debris associated with recreational activity, aluminum beverage cans, and glass fragments are more common along beaches adjacent to larger centres of population. Higher energy beaches have greater proportions of metal objects, and also greater proportions of wood (especially fragments of plywood, particle board, and building framing) and glass, whereas lower energy systems have more cardboard, plastic debris, and beverage cans.

Remains of marine mammals and birds are also encountered on beaches. Whale remains are rare, whereas seal remains are more common on the beaches of Conception and Placentia Bays (Table 10-2). Although quantitative data are not available, seal remains are more common on Conception Bay beaches following winters without ice-foot development. The presence of seal and whale remains does not appear to be directly related to the energy levels of the beaches. Seabird remains representing natural mortality are more common along beaches with higher proportions of fishery-related debris, and along lower-energy shorelines. The mortality of birds resulting from marine oiling events has been the focus of recent research by Wiese and Ryan (1999) and by the Canadian Coast Guard (1999). This research has noted that chronic oil pollution poses a significant hazard to long-lived seabirds (also Hunt 1987; Burger 1992), and that the incidence of oiled birds washing ashore on beaches from Ferryland to Big Barasway has increased between 1984 and 1997. Observations conducted along the Cape Shore and at Cape St. Mary's indicate that the killing of seabirds due to oiling was an increasing problem throughout the period 1995-February 2000 (F. Shahood, Newfoundland and Labrador Parks, personal communication).

Although any litter is too much, and the persistence of litter in the environment tends to dull the sensitivity of the observer (Al-Busiady 1995), eastern Newfoundland's beaches are less littered than many of those reported in the international marine pollution literature. The lack of tourist pressure on most shorelines, the relatively small population, and the self-cleaning of many beaches during severe storms all contribute to lower the volumes of beach debris. The pattern of offshore current flow, with the Gulf Stream bypassing the South Coast and insulated from it by the Labrador Current, also reduces the volume of debris derived from distal sources and offshore vessels, in contrast to the situations along the coasts of Panama (Garrity and Levings 1993), CuraHao (Debrot *et al.* 1995), Bermuda (Gregory 1983; Smith and Knap 1985) and Sable Island (Lucas 1992). However, even though Newfoundland's beaches are relatively clean, local and governmental efforts to remove and reduce litter are still required.

Table 10-2. Relative proportions of beach litter in assemblages, eastern Newfoundland.

Litter Type	Central Cape Shore	Peters River	Becks Bay	Burin Pen.	Mobile (Placentia B)	Conception Bay South	Conception Bay North
Plastic:							
Domestic Waste	little	moderate	little	moderate	moderate	high	moderate
Tourist-Recreational	little	little	little	little	moderate	moderate	little
Rope	moderate	little	little	moderate	little	moderate	moderate
Netting, Lines	high	moderate	moderate	moderate	moderate	moderate	high
Petroleum Containers	moderate	little	little	moderate	little	moderate	moderate
Indeterminate and Other	moderate	moderate	little	moderate	moderate	moderate	moderate
Wood:							
Fishery-Related	high	moderate	little	moderate	little	moderate	high
Plywood/particle board	moderate	moderate	little	moderate	moderate	high	moderate
Framing Stock	high	high	moderate	high	high	high	high
Natural Driftwood	moderate	little	little	little	moderate	little	moderate
Indeterminate	moderate	moderate	moderate	little	moderate	moderate	moderate
Cloth	little	little	negligible	little	little	little	negligible
Glass	little	little	little	little	moderate	moderate	little
Metals:							
Beverage Cans	little	moderate	little	moderate	little	moderate	little
Other Aluminum	moderate	moderate	little	moderate	little	moderate	moderate
Steel and Iron	moderate	moderate	little	high	moderate	moderate	moderate
Copper and others	negligible	negligible	negligible	negligible	negligible	little	negligible
In situ Metal Objects	little	little	negligible	little	moderate	moderate	little
Seal Remains	occasional	none obsvd	none obsvd	none obsvd	rare	occasional	common
Whale Remains	rare	none obsvd	none obsvd	rare	none obsvd	rare	rare
Marine Bird Remains	common	rare	rare	common	occasional	occasional	common
Overall Volume of Debris	moderate-low	moderate	low	moderate	moderate	moderate	moderate

10.3 Additional Forms of Pollution

In addition to petroleum-related pollution (including congealed or partially-congealed tar balls) and solid beach litter, other fluid pollutants may occur in the eastern Newfoundland coastal environment. Terrestrial runoff from agricultural areas, bringing fertilizers and pesticides in emulsified or dissolved forms to the coastal zone, is a recognized problem (Bonde 1994). These chemicals are of greatest concern in estuarine and salt marsh regions adjacent to agricultural activity, or those adjacent to communities where domestic use for gardens and control of noxious insects is practiced. Potentially, forestry operations that involve large quantities of pesticides could also contribute pollutants to the coastal zone. The solubility of agricultural and forestry chemicals, however, means that they will only pose a problem in shoreline areas marked by low energy, dissipative or fluvially-dominated systems, where circulation with the open ocean is minimal. Thus, the only areas potentially at risk from this style of pollution are the estuarine areas (shore class 23), the mudflats (shore class 22), the lower energy areas of the bouldery tidal flats (shore class 24), and lagoons that are effectively confined by barrier beaches and are fed by streams flowing through agricultural areas. Many of the low-energy shorelines are not at risk, due to the absence of agricultural activity and commercial forestry operations in their hinterlands.

Estuarine and lagoonal systems which have agricultural regions within their catchment areas include those of northern St. Mary's Bay and southwestern Conception Bay. Along the Conception Bay shoreline from Avondale north to Harbour Grace, the estuarine system at Riverhead and the lagoonal areas at Clarkes Beach, Bay Roberts, and Spaniards Bay are potentially subject to pollution from agricultural runoff (in addition to pollution from other domestic terrestrial sources). At these sites, the dynamics of river/lagoon/harbour interaction have been altered by road construction and by the strengthening of coastal breakwater and riprap defenses. The effect has been to decrease interchange of water from lagoon to harbour (especially at The Coish and Spaniards Bay), altering the water quality in the lagoon and leaving it more vulnerable to agricultural pollution.

Lagoons that are largely isolated from ocean waters tend to be less biologically productive (Catto *et al.* 1999b). In contrast, systems where active interchange takes place are highly productive zones, with a variety of permanent biological communities, and serve as important transit points for migratory fish such as salmonids and eels. These areas are the most sensitive to pollution from terrestrial sources. In addition to reducing or strictly monitoring the application of agricultural chemicals, continuance of the interchange between lagoons and harbours through permanent channels or more transitory breaches ('guts') in barrier beaches is necessary in order to maintain water quality. The major causes of interference with interchange are decreased flow in the river systems, allowing barrier progradation (Nichols 1995), and construction of roads across the barriers, commonly with attendant breakwaters, seawalls, or riprap.

Sewage constitutes a serious form of pollution in many coastal environments. In eastern Newfoundland, plastic debris associated with domestic sewage is a common constituent of beach litter assemblages along shores adjacent to communities, particularly in low-energy environments. The occurrence of easily floatable small plastic items indicates that dispersed liquid sewage could also be present in the nearshore environment. Coves marked by reflective, modally low to moderate energy conditions, and which are located adjacent to communities, are particularly vulnerable. Examples include Salmon Cove, Conception Bay; Fox Harbour, Placentia Bay; Burgoyne's Cove, Trinity Bay; Brigus South, Southern Shore; Boxey; and the sandy shorelines of Burin Bay Arm. Planning of sewage outfall positions is critical to avoid pollution problems. At Salmon Cove, an initial proposal to discharge sewage at the head of the cove was modified to re-position the outfall away from the most sensitive, enclosed area (LeDrew, Fudge, and Associates, and Harris and Associates 1992; Harris and Associates, and Jacques Whitford Environment 1993; Jacques Whitford Environment and Harris and Associates 1994).

Shorelines marked by shore-parallel transport are less vulnerable to pollution from indigenous sources than are those dominated by shore-normal transport, although longshore drift may bring sewage from upcurrent sources. Along the shoreline of Conception Bay South, the modal direction of longshore transport is from southwest (Holyrood) to northeast (Topsail). Sewage discharged from outfall pipes will thus gradually migrate northeastward along the coast, before dispersing to the northeast of Topsail Beach. Potentially, Topsail Beach would thus be vulnerable to sewage pollution emanating from all outfalls in Conception Bay South, which could impact on efforts to develop this area as a tourist attraction.

Shorelines marked by overdeepened harbours connected to the open ocean by narrow, curved channels are also subject to pollution from sewage from coastal communities. Along the South Coast, the fjordal embayments of Bay d'Espoir and Terrenceville Harbour, among other sites, have deep basins partially isolated from the open ocean by bathymetric obstructions. The obstructions limit water circulation, thus creating slow-moving or stagnant masses of water at the bases of the water columns. Pollutants can accumulate in these areas, leading eventually to loss of water quality at the base of the fjords. At Marystown, Burin Bay Arm, and St. John's Harbour, similar problems exist, accentuated by the size of the communities.

In St. John's, the largest community in Newfoundland, water quality problems within the harbour have become obvious (Frecker 1972; Newfoundland Design Associates 1982, 1987-88; MDS Environmental Services Ltd. 1995; Oceans Limited 1996; Powell 1998), and growing public concern (Bath and Langwieder 1993; ACAP St. John's 1999) have led to several initiatives designed to alleviate the domestic pollution problem. St. John's owes its existence to its virtually ice-free harbour. Icebergs are deflected seaward at Cape St. Francis as they track southerly along the Atlantic Shore. The "dogleg" nature of the harbour entrance, which requires ships to pass westward through The Narrows past Chain Rock, and then execute a sharp turn to the southwest, also limits iceberg and brash ice penetration. The anchorage is sheltered from both southwest hurricane winds and autumn northeast gales, with only rare winter storms such as that of January 1966 able to penetrate. Although numerous other harbours are present along the Atlantic Ocean shoreline of the Avalon Peninsula, all are exposed to northeast storms. In selecting an anchorage for large sailing vessels in the 1700's and 1800's, shelter from winds was more critical than draught or harbour configuration, and the requirement for sharp turns within St. John's harbour was not seen as a disadvantage. The harbour offered ample longshore space for warehouses and anchorage for small fishing craft, facilitating trans-shipment of fish to Trans-Atlantic ships. St. John's thus represented the only suitable anchorage for ocean trade along the coast, and its attributes combined with its proximity to good fishing grounds gave its advantages over Harbour Grace and Carbonear.

The maximum water depth in the harbour is 31 m. Prior to blasting in 1998, however, both ship access and water circulation were controlled by the 14 m deep channel at The Narrows. During summers, incoming ocean waters overflow the sill and follow the northern and western shores. Outflow currents generally follow the southern and eastern side of the embayment. On calm days, the outflowing current is influenced by the Coriolis effect. On several occasions in the 1990's, this current was readily visible from Signal Hill, marked by a brown track carrying domestic sewage from the city and fish offal from the South Side Hills plant.

At depths below 20 m, the harbour waters are virtually stagnant, particularly during the winter months. The discharge of the Waterford River is insufficient to flush the embayment. As a result, most sewage that enters the harbour remains within the harbour. The deepening of the channel at The Narrows (more critical than the widening) will improve circulation within the harbour, but in itself this will not resolve the domestic sewage pollution problem. In St. John's Harbour, as at Marystown, Burin Bay Arm, St. Alban's, Terrenceville, and other harbour communities, only on-land sewage treatment can reduce the pollution problem.

11. Aquaculture and Fisheries Issues

A comprehensive discussion of the eastern Newfoundland shoreline requires extensive consideration of aquaculture activity; naturally occurring anadromous and catadromous fish; capelin, spawning on gravel shorelines; and Mollusca, Arthropoda, and Echinodermata that inhabit the nearshore zones. A detailed review of all of these species is beyond the scope of this contribution. The geomorphic, sedimentologic, and dynamic parameters of the shoreline, nearshore, and lower fluvial environments are clearly important for understanding and management of these species, however. In some instances, fish species do cause modifications to the sedimentological environment in ways not readily apparent (e.g. Johnson *et al.* 1984). Thus, some brief notes highlighting issues of importance are presented here.

Aquaculture operations have become increasingly important to the economy of eastern Newfoundland. Statistics from the Newfoundland and Labrador Department of Fisheries and Aquaculture indicate that aquaculture generated revenue of $ 8 million and employed 450 people in 1997. At that time, there were 231 licensed sites, 65 for commercial production of shellfish and 55 finfish sites. In 1998, 20 cod farming licenses were issued. The rapid development of this industry, however, has led to concerns that pollution and disease may become problems in eastern Newfoundland operations, as elsewhere. In addition to knowledge of the pathogens that can attack each aquaculture species, understanding of the circulatory patterns and coastal dynamics of the aquaculture site and its environs is necessary. The principle that fish sharing the water also share any diseases (Stewart 1998) indicates that aquaculture sites must be positioned so that potential problems relating from the spread of both pollution and disease can be minimized. The suggestions that aquaculture sites be managed on a 'single bay' or 'single area' basis, and that sites should undergo regular periods of utilization, separated by fallowing (Silvert 1992; Costello 1993; Grant and Treasurer 1993; Jarp and Karlsen 1997; Stewart 1998) can only represent partial solutions. Increased spacing between aquaculture sites would reduce the likelihood of transmission of diseases, and the spread of pollutants generated from aquaculture operations, but determination of an optimal spacing has proven difficult. Stewart (1998) reviewed spacing practices and requirements in Chile, Scotland, Ireland, Norway, and

British Columbia for salmon operations, and found that the guidelines and regulations were inadequate in all instances. The required spacing between sites cannot be determined without adequate consideration of the coastal dynamics and circulation patterns, which will differ substantially between fjords, lochs, macrotidal embayments, and the numerous other coastal environments where aquaculture is practiced (Turrell and Munro 1988; Ross *et al.* 1993a, 1993b, 1994; Stewart *et al.* 1993; Strain *et al.* 1995; Ervik *et al.* 1997; Gillibrand and Turrell 1997). Successful aquaculture management of sites in eastern Newfoundland will thus require analysis of the coastal dynamics of each locality.

Several attempts have been made to assess the suitability of coastal zones for aquaculture through general classification schemes. In Norway, the LENKA (Ibrekk *et al.* 1993; Stewart *et al.* 1993; Kryvi 1994) and MOM (Ervik *et al.* 1997) initiatives have attempted to categorize the Norwegian coastal zone for aquaculture purposes. The MOM (modelling-ongrowing fish farms-monitoring) approach is designed to study the effects of progressive aquaculture development within a single embayment or 'single area', and has been applied where several closely spaced aquaculture developments are established or proposed. This approach is suited to study of a confined embayment, particularly a fjord such as Bay d'Espoir or Paradise Sound.

The LENKA approach involves assessment of longer segments of coastline. Environmental assessment for aquaculture is divided into four categories:

- *Physical environment* (including wave dynamics, exposure to storms, water temperature and salinity, sea ice conditions and prevalence, and pollution);

- *Present utilization* (including all commercial, residential, and recreational activity, with particular concern both for resource partitioning and potential sources of pollution);

- *Infrastructure* (including roads, power supplies, and waste disposal sites, considered from the viewpoints of requirements for economic aquaculture development and potential hazards to the farm); and

- '*Special areas*' (such as parks, nature reserves, and conservation zones).

The designated 'special areas' are eliminated from further consideration for aquaculture development, as are areas that are currently utilized for other human purposes and those where pollution is pervasive. Infrastructure is considered to be necessary for establishment of the farm and marketing of the product. In eastern Newfoundland, the necessary infrastructure exists in most coastal regions, with the exception of northeastern Trinity Bay between Smith Sound and New Bonaventure and the Paradise Sound area of northwestern Placentia Bay. Existing infrastructure, however, could be readily extended to these areas.

Physical environmental factors pose significant restrictions on aquaculture activity. The LENKA classification system (Ibrekk *et al.* 1993) eliminates areas where:

- significant wave height exceeds 2 m;
- water depth is less than 20 m at low tide (except where the current is strong and unidirectional);

- water temperature remains below 0°C for at least 6 consecutive weeks;
- salinity 'occasionally' falls below 10 ppt;
- pollution is present; and
- sea ice forms statistically in at least 1 out of every 5 years.

These qualifications would preclude aquaculture development along much of the eastern Newfoundland coastline. Offshore, significant wave height is in excess of 7 m (Neu 1982), and storm waves reach much greater heights. Storm wave activity was responsible for the destruction of an aquaculture site in Bay Bulls Harbour in 1992. Ibrekk *et al.* (1993) identified wave height as the single variable most restricting aquaculture development in Norway, responsible for rejection of more than 52,600 km^2 of the coastal zone (80% of the total surface area of the Norwegian coastal zone). Along the eastern Newfoundland shoreline, this criterion would preclude aquaculture development in all areas except for restricted fjordal embayments (Bay d'Espoir, Smith Sound, Paradise Sound), resulting in the elimination of the entire length of shoreline from Bull arm southeast to Cape Race, and westward from Cape Race to Swift Current. The shoreline of the Burin Peninsula south of Rushoon, the Fortune Bay shoreline south of Terrenceville, and the South Coast shoreline with the exception of the longest and most sheltered fjords (e.g. Mal Bay, Facheux Bay) and straits (e.g. Little Passage) would all be unsuitable. This qualification, however, applies primarily to finfish aquaculture (particularly salmonids) reared in cages. Malaculture of blue mussels and other mollusca, not requiring cages, is not as restricted by wave heights, although high-energy shoreline locations must be avoided.

Within the confines of areas with low annual significant wave heights, water depth is not an important restricting factor. All of the fjordal areas are marked by depths in excess of 20 m within short distances of the mean tide line. The absence of macrotidal and high mesotidal conditions along the shoreline somewhat restricts water circulation, but also limits suspended sediment transport and turbidity.

The requirements for water temperatures greater than 0°C and the absence of sea ice potentially eliminate large expenses of the eastern Newfoundland shoreline. Seasonal water temperature variations (US Naval Oceanographic Office 1967; McManus and Wood 1991) and sea ice extent (Markham 1980; Cote 1989; Narayanan *et al.* 1995) data indicate that the coastlines of Trinity, Conception, and eastern Placentia Bays, and the open Atlantic shoreline, are all unsuitable under the LENKA criteria (Ibrekk *et al.* 1993). Areas along the margins of northwestern Placentia Bay and South Coast fjords that are also subject to winter freeze-over would also be considered unsuitable. Waters in fjord head areas are also subject to dilution during the spring freshet, which can cause salinity values to fall below the 10 ppt threshold identified by LENKA as critical. Water temperature is a critical variable throughout Atlantic Canada (Page and Robinson 1992), and in the absence of substantive regional climate change (Pocklington 1998), cold temperatures are likely to prevail.

These criteria, however, are variable, dependent upon the requirements of particular biological species. The LENKA program was designed to assess the Norwegian coastline for the purposes of finfish, primarily Atlantic salmon, aquaculture operations. Although the principles derived in Norway can be reasonably applied to the cultivation of Atlantic salmon in eastern Canada (Stewart *et al.* 1993; Stewart 1998), the specific environmental variables may not identify conditions precluding aquaculture of other species. Species such as Atlantic cod, which survive naturally in the northern North Atlantic during winter, may be more tolerant of sea ice than are Atlantic salmon. Molluscan species can also be expected to show particular environmental requirements and tolerances differing from those of salmonids.

In eastern Newfoundland, all native fish species inhabiting fresh water are either anadromous or catadromous (Scott and Crossman 1973). As saline waters surrounded Newfoundland following deglaciation (Grant 1989), and no suitable refugia for fresh water fish existed during the height of the Late Wisconsinan glaciation, all species strictly confined to fresh water were unable to reach the island. At present, migratory behaviour is exhibited by salmonids, including native *Salmo salar*, and the introduced (1884 to the Avalon Peninsula {Scott and Crossman 1973) brown trout (*Salmo trutta*) and rainbow/steelhead trout (*Salmo gairdneri*; introduced 1887 to the Avalon Peninsula {Scott and Crossman 1973) and by eel (*Anguilla rostrata*). Salmonids use the coastal zone as a transit, feeding, and resting area.

In addition to pollution, migrating salmonids face the possibility of blockage of the migration route by either artificial (e.g. dams) or natural means. Progradation of gravel barachoix has resulted in temporary closure of stream outlets at Peters River (Nichols 1995) and Mobile (Jones 1995), and other streams in eastern Newfoundland. The critical factor in maintaining an open outlet through the barachoix systems investigated in eastern Newfoundland is the amount of stream flow from the land to the lagoonal area. A strong stream flow will remove sediment from the outlet channel more rapidly than waves and currents can redeposit it. Where the outlet channel is temporarily blocked as a result of storm activity, as during the hyperactive hurricane year of 1995, the stream flow impounded in the lagoon behind the gravel barachoix will establish a gradient in hydraulic head between the lagoon and the ocean, eventually inducing barrier failure. At Peter's River, barrier failure was closely associated with enhanced stream flow fed by hurricane precipitation (Nichols 1995). Consequently, hurricane activity had the net effect of opening the channel through the barachoix, allowing salmonid migration to proceed with minimal delay. In contrast, barachoix systems tend to prograde during periods without significant storms, resulting in enhanced obstruction to migrating salmonids, as at Avondale (Catto 1999). This problem is compounded where the stream is harnessed for hydroelectricity production. Retention of the water in the reservoirs in order to provide the necessary hydraulic head for power generation can result in reduced flow to the lagoon or shoreline, allowing barachoix progradation and hindering salmonid migration.

Eels (*Anguilla rostrata*) spend more time in the coastal zone, and do not negotiate rapids as do salmon (Bertin 1956; Scott and Crossman 1973; Tesch 1977; Jessop 1984; Young and Foster 1990). Although the biology, diets, and growth rates of eels in freshwater Newfoundland environments were investigated by Gray (1969), Hudson (1974), Bouillon (1982), and Wood (1986), less is known concerning the eastern Newfoundland eel population than is the case for eels elsewhere along the margins of the North Atlantic. Investigation of the coastal zone habitats for eels requires analysis of the fluvial and estuarine geomorphology of individual systems.

Species that inhabit the nearshore and beach zones, or utilize these for spawning (particularly Capelin, *Mallotus villosus*), are important ecologically and economically. Substrate conditions and preferences for molluscan species are variable, and local assessment of the influence of coastal dynamics on sediment distribution should be conducted on a site-by-site basis. The necessity for local investigation is particularly apparent in areas that have been disturbed by adjacent dredging, or in localities where offshore or beach mining of sediments is proposed (Scott *et al.* 1990).

Capelin spawning beaches are highly productive biologically (Catto *et al.* 1999b). Along the eastern Newfoundland coastline, the beaches utilized by capelin and those where harvesting traditionally has occurred are marked by wave-dominated, exposed moderate-energy pebble and granule gravel shorelines. At sites such as Caplin Cove, Conception Bay, spawning capelin tend to concentrate on the better sorted parts of the beach, where fine to medium pebbles are dominant. Areas of the beach with gently concave or planar profiles, and seaward-imbricated pebbles, also are more favoured by the capelin. Steepening of beach fronts as a result of storms or the absence of ice-foot protection, and coarsening of sediment resulting from terrestrial mass movements or enhanced storm-driven transportation, are both less favourable for capelin spawning.

Taggart and Nakashima (1987) conducted analyses of the density of capelin eggs on spawning beaches along Conception Bay. They concluded that the maximum egg density (eggs/cm) was present on beaches facing northward and northeastward, which conforms to the directions of maximum fetch along this shore. Minimal fetch areas, although having lower modal energy conditions, are also more susceptible to terrestrial sediment input and are less likely to develop gently concave profiles dominated by well-sorted medium and fine pebbles. Analysis of the data presented by Taggart and Nakashima (1987) indicates that sites marked by modally moderate energy and wave-dominated conditions, such as Chapel Cove, Coley's Point, Broad[head] Cove, Ochre Pit Cove, and the south part of Bryants Cove, had higher densities of capelin eggs than did sites marked by modally higher energies and coarser gravel, such as Bristols Hope and Holyrood. Sites with lower energy levels, and those where terrestrial processes contributed to sorting, such as the north part of Bryants Cove, Spaniards Bay, Colliers, and Avondale, were also less productive.

In addition to substrate factors, climate has an influence on capelin spawning (Narayanan *et al.* 1995). Capelin spawning time is negatively correlative to the temperature of the uppermost 20 m of the marine water column, so colder water conditions induce spawning later in the season. If capelin spawning is delayed until the start of hurricane activity, the net result could be a loss of productivity due to modification of beach habitat. Years with prolonged sea ice cover (such as 1990, 1991, and 1992) which also were marked by effective beach reworking by hurricanes (such as hurricane 'Bob' in 1991) would tend to produce conditions less suitable for capelin spawning. Conversely, years with minimal sea ice cover and minimal hurricane activity (such as 1997) would produce suitable spawning conditions for capelin along the South Coast and Placentia Bay. However, the absence of sea ice and ice foot protection during the winter of 1997-98, and its reduced extent during the winter of 1998-99 along Conception Bay and Trinity Bay shores permitted reworking of these spawning beaches, resulting in coarser, steeper profiles less suitable as spawning areas. Along these shorelines, ice foot development in particular appears to assist preservation of suitable areas for spawning.

12. Anthropogenic Impact

Throughout the foregoing discussion, evidence of anthropogenic impact on the coastline has been apparent. In addition to concerns of a national or global nature, such as the impact of climate change in other regions of the world on sea level rise, regional and local anthropogenic impacts and modifications in the coastal zone have influenced eastern Newfoundland. Aside from pollution and fishery/aquaculture related activities, discussed above, anthropogenic modification to the coastal zone of eastern Newfoundland includes:

- deliberate construction of breakwaters, or modification of pre-existing spits and bars;
- dredging to improve navigation and access;
- construction of wharves and stages;
- construction of groynes to retard sediment erosion and beach-parallel transport;
- construction of seawalls to restrict wave erosion;
- railroad construction;
- road construction;
- construction of industrial infrastructure;
- extraction of beach aggregate, either through 'official' or regulated operations, or on a casual basis; and
- use of shoreline areas for recreation, including tourism.

Many of these impacts have been discussed above, during consideration of other classification schemes and elements.

Treatment of anthropogenic structures differs substantially amongst coastal classifications, with some authors and investigators reserving specific classification schemes for particular types of construction (Coastal and Ocean Resources 1999). The style of treatment to some extent depends upon the prevalence of anthropogenic structures in the shoreline zone, and the date of their construction, in addition to the designated purpose of the classification effort. In eastern Newfoundland, anthropogenic structures, although present, are less ubiquitous than along more densely settled coastlines, or in areas where tourist-related development is more significant (Granja 1991; Granja and Carvalho 1991; Anthony 1994). In addition, the shorelines at places where structures which have been recently constructed, such as the marina developments at Hodges Cove, Trinity Bay, and Kings Point, Harbour Grace, can be assessed using pre-construction aerial photographs and coastal videotape records.

In this report, the specific details of the influence of anthropogenic structures at local sites have been discussed in conjunction with the geomorphic classification. Classification and documentation of anthropogenic structures has been undertaken at several localities following the manual prepared by O'Brien *et al.* (1998). Discussion of shorelines from the perspective of recreation and tourism is considered in the next section.

13. Human Perceptions and Aesthetic-Socioecological Assessment

In an evaluation of 18 papers discussing coastal classification, Cooper and McLaughlin (1998) noted both the requirement for socioeconomic and socioecological information, and the difficulty of integrating this data into classifications discussing physical or biological environmental parameters. The subjective nature of much historical, cultural, and sociological information, and the problems of quantification, pose difficulties for correlation with physical scientific data (Wilson-Hodges 1978; Litton 1982; Cosgrove 1989; also see Berleant 1992).

Cultural data, particularly that involving aesthetic perceptions, involve highly personal evaluations and judgments. Ecological (or socioecological) resource assessments involving both cultural and biophysical data (e.g. Legakis *et al.* 1993; Economic and Social Commission for Asia and the Pacific 1995; Moriki *et al.* 1996; Cendrero and Fischer 1997; German Federal Agency for Nature Conservation 1997) are also subject to differences in perception and values. These difficulties, combined with problems in incorporating non-quantified data into Geographic Information Systems, have led to the exclusion or under-representation of cultural, historical, socioecologic, and aesthetic information from many coastal analyses (Lynch 1976; Bourassa 1991). Comprehensive understanding of the coastal zone, however, requires inclusion of this data, particularly where the objective is to construct a coastal resource inventory database (c.f. O'Brien *et al.* 1998; Connors and Tuck 1999; see also Whyte 1977; Sadler and Carlson 1982).

The ultimate value of coastal classification depends upon clear definition of user needs, and the incorporation of variables required for construction of a clear management strategy (Carls 1979; Cooper and McLaughlin 1998). Coastal zone management in eastern Newfoundland must be intimately connected to both 'traditional' users in fishery-based communities, and to the developing aquaculture and ecotourism interests. In eastern Newfoundland, community-based collection of some of this data is in progress, guided by the procedures outlined by O'Brien *et al.* (1998). Coastal infrastructure, and cultural-historical sites, are among the primary foci of this effort. Ecological data, including seabirds and marine mammals, is also being collected. However, the increasing economic and sociological importance of ecotourism indicates that aesthetic and socioecological data must form a component of an integrated analysis of the coastal zone.

Assessment of coastal aesthetics is by definition based on human perceptions and values. Particular users seek out particular shoreline attributes, and reject shorelines with differing characteristics. Shoreline features that have special significance and generate affection among fishers, mariners, and residents of eastern Newfoundland may not be appreciated by those unfamiliar with the coast (Lowenthal 1978). Many first-time viewers see shores without the emotions that familiarity brings, producing both more positive and more negative perceptions of aesthetic worth than are held by local residents. These differences in attitude between different user groups and stakeholders repeatedly necessitate consideration of several diverse viewpoints in coastal zone management issues where human perceptions are involved (e.g. ACERA 1998).

There is a general consensus that some anthropogenic infrastructure in the coastal zone, such as power plants, derelict industrial and port facilities, and waste disposal areas (termed 'misfits' by Leatherman 1997) are aesthetically unpleasing. Most observers also regard active industrial enterprises in the coastal zone as less aesthetically appealing, although acknowledging their economic necessity. Port facilities, however, have a particular appeal to inland residents. Predominantly, studies of aesthetic perception have concentrated largely or exclusively on visual images (e.g. Shafer *et al.* 1969; Daniel and Broster 1976; Shafer and Brush 1977; Appleton 1980; Blanco *et al.* 1982; Williams and Lavelle 1991; Rivas *et al.* 1995), without including auditory or olfactory stimuli, but it is apparent that noises and smells form major components of observers' reactions to petroleum refineries and port facilities (Dewey 1934; Sparshott 1972; Porteous 1982; Bourassa 1991). Industrial infrastructure is not uniformly aesthetically negative, however, as an 'unusual' site, such as the Bull Arm fabrication area, can become a tourist attraction.

Agreement on what constitutes an aesthetically attractive shoreline is more elusive. As with shorelines judged as aesthetically negative, smells, noises (waves, seabirds), and to some observers taste and feel of salt air and wind are involved in perception and positive evaluation. Weather conditions, always of significance in eastern Newfoundland, are involved in all on-site evaluations. Although attempts have been made to define modally suitable meteorological conditions, both daily (Peach 1975, 1984) and annually (Phillips and Crowe 1984; Robertson and Porter 1993), different coastal users may regard the weather at any given instant differently. Humans acclimatized to particular conditions may regard that climate with favour and even passion (Robertson and Porter 1993). Conversely, tourists may deliberately seek cooler, damper seacoast climate conditions, and may tend to regard a fogged-in embayment more benignly than will local mariners. Location and design of tourist facilities (Ryan 1993) and tourist promotion requires recognition of these perceptions and preferences. Differences in landscape preferences amongst tourists from different areas (Porteous 1996) are real and should also be considered.

Attempts to assess landscapes visually have generally proceeded in qualitative terms, although quantitative assessments have been attempted (Blanco *et al.* 1982; Rivas *et al.* 1995). In the guidelines proposed by the Landscape Institute (1995), visual elements include:

- balance (harmonious, balanced, discordant, chaotic)
- scale (intimate, small, medium, large)
- enclosure (confined, enclosed, open, exposed)
- texture (smooth, textured, rough, very rough)
- colour (monochrome, muted, colourful, garish)
- diversity (uniform, simple, diverse, complex)
- movement (remote, vacant, peaceful, active)
- unity (unified, interrupted, fragmented, chaotic)
- form (straight, angular, curved, sinuous)
- security (comfortable, safe, unsettling, threatening)
- stimulus (boring, bland, interesting, invigorating)
- pleasure (offensive, unpleasant, pleasant, beautiful).

In addition, evaluation includes a brief description, identification of the major landcover and landscape elements (including landforms and anthropogenic structures), an assessment of the landscape condition (e.g. managed, derelict, wild), and a suggested management strategy.

The list of criteria indicates the subjective nature of the analysis. Although there is general agreement that a 'comfortable' landscape is preferable to a 'threatening' example, definition of these terms may prove elusive. Different observers will undoubtably prefer different combinations of security and stimulation (Porteous 1996). Although some qualities, such as an absence of litter, will be seen as inherently desirable by a large majority of observers (Peterson and Neumann 1969), most will be subjectively perceived. The intensity of the perception will also be highly variable (Lowenthal 1978). Academic training in a particular discipline, be it Art History, Geomorphology, or any other field of endeavour, will affect the analysts' perceptions and evaluations as well (Carlson 1977, 1990; Bourassa 1991).

Most eastern Newfoundland coastal environments will be characterized by limited enclosure, larger scale, greater diversity, non-linear form, and at least some movement. The perceived 'colour' will vary extensively with meteorological conditions, as will the perceived degrees of security, stimulation, and pleasure. This style of classification is useful for inter-site comparisons only if all comparisons are undertaken by a single observer, or represent a consensus of common observers. Among any group of observers, evaluation of the landscape will be influenced by their experience and perspective (Lowenthal 1978; Porteous 1996).

Williams and Lavelle (1991) have discussed evaluation of photographs of coastal landscapes, and proposed methods of analysis. Attempts have been made to semi-quantitatively apply these techniques to the perceptions of groups of students in Memorial University of Newfoundland Geography courses, ranging from first-year university students to MSc candidates. Results differed little between groups at different academic levels and differing experience with the coastal environment, in accordance with the findings of Williams and Lavelle (1991). The students viewed photographs of coastal landscapes without anthropogenic infrastructure, taken under various meteorological conditions. Cliffed shores, gravel beaches, and sand beaches from eastern Newfoundland were generally perceived as aesthetically pleasing, whereas coastal wetlands and lagoonal areas were considered negatively by most students. Student tests revealed that some photographs of shorelines from distal areas were evaluated as aesthetically negative by strong majorities (e.g. mangrove coasts) or lesser majorities (macrotidal flats, tidal pools) of students. Sand beaches from both eastern Newfoundland and distal areas were uniformly perceived positively, whereas both distal and Newfoundland coastal wetlands were evaluated negatively. In one test, involving a fourth-year Coastal Geomorphology class, a photograph of the Tuktoyaktuk coast was evaluated as aesthetically pleasing by 50% of the group and strongly negative aesthetically by the other 50%. These tests, although qualitative and semi-quantitative do indicate some of the limitations of aesthetic analysis of photographs.

Fishery-related infrastructure and activity also provokes differing aesthetic reactions. Although concern is sometimes expressed in coastal communities that visitors would prefer not to see fish landings or aquaculture infrastructure, many non-residents show intense interest in fisheries and do not regard aquaculture facilities or lobster pot marker floats as aesthetically unpleasing. Most of the negative reactions are associated with industrial fish processing facilities.

The foregoing discussion has identified the subjective nature of aesthetic evaluation basal on visual means alone. Although quantitative evaluation of aesthetic values in isolation is difficult if not impossible and is of questionable value, it is clear that aesthetic considerations are one component that should be incorporated into coastal evaluation and classification.

Aesthetic analysis in the abstract has been linked to 'evaluation' of the beach environment in particular from a tourist/recreational user perspective. Although general preferences, such as clean beaches with smooth surfaces (Peterson and Neumann 1969), seem intuitive, more detailed analysis reveals both substantial differences in perceptions and preferences, and the difficulties and biases inherent in this style of evaluation.

Leatherman (1997) presented a system designed to evaluate US beaches from a tourism viewpoint. His classification scheme involves assessment on a five-point scale of fifty equally ranked factors, covering physical factors (18), biological factors (10), and human use, impacts, and physical structures (22). For any beach, the theoretical maximum score is 250, and the minimum score 50. A 'percentage' score can thus be calculated as: {raw score -50} /2. The 'best' US beaches in Hawaii score in the 80%-90% range under this scheme, whereas Pikes Beach NY, described as 'one of the worst' scored approximately 55% in 1997.

The list of categories and the ratings for each are somewhat subjective, and reflect the preferences of particular coastal users. Although not explicitly stated, it is apparent that the beaches are evaluated positively if they are suitable for swimming or surfing. Beaches that are evaluated negatively on some criteria (e.g. absence of lifeguards and coastal infrastructure such as refreshment stands) would be regarded more positively by different users. Leatherman (1997) recognizes that different water temperatures would be considered tolerable for bathing by 'northerners' and 'southerners' (his terminology), but his list of environmentally desirable conditions would not be identical to those of Robertson and Porter (1993).

The beach classification scheme of Leatherman (1997) was applied to 10 beaches in eastern Newfoundland: Beck's Bay, Boxey, Frenchman's Cove, Big Barasway (Placentia Bay), Gooseberry Cove (Placentia Bay), Topsail, Salmon Cove (Conception Bay), Northern Bay Sands, Bellevue, and Sandy Cove (Trinity Bay). These beaches were selected to be representative of shores designated for recreational purposes, as provincial parks, former provincial parks, provincial scenic attractions, or used recreationallly by local residents. For comparative purposes, two additional Newfoundland sites were evaluated: Sandbanks Provincial Park (Burgeo), and Little Sandy Cove (Bonavista Bay).

The evaluations were conducted by the author, research assistants, and students familiar with the specific beach environments. With the exception of the information presented by Leatherman (1997), no definitions of the terms were provided. The results, presented in Table 13-1, reveal that although the evaluation scheme is designed to be objective, variance exists in the perceptions and assessments of different observers. The low scores dictated by the physical environment in such categories as water temperature, beach texture, colour of sediment, and meteorological conditions, combined with a general lack of tourist infrastructure, invariably result in low overall percentage totals for eastern Newfoundland beaches. The median values for the sites ranged between 50% and 64%.

Many of the student observers commented negatively during and after the assessment process, both in terms of the difficulties in categorization and (more vehemently) in terms of the overall scores, considered to be anomalously low and 'unfair'. The differences in the perceived ideal beach environment amongst users accustomed to different surroundings (Robertson and Porter 1993; Porteous 1996) are apparent in these reactions.

Table 13-1. Evaluation using Leatherman (1997) Classification System.

Site (# of analysts)	Low	Medial	High
Beck's Bay (14)	48.5	50	55.5
Boxey (16)	53	59	64
Frenchman's Cove (22)	48	55.5	60
Big Barasway, PB (34)	50	57	63
Gooseberry Cove, PB (11)	44.5	52	58
Topsail (34)	40.5	51	58
Salmon Cove, CB (24)	54.5	60	70
Northern Bay Sands (27)	55	62	69
Bellevue (8)	44.5	50	52.5
Sandy Cove, TB (13)	53	58	66
Sandbanks, Burgeo (15)	56	64	72
Little Sandy Cove, BB (8)	54	61	64.5

A more comprehensive approach involves linkage of the visual perception data to ecological, geological, and socioeconomic information (Cendrero and Fischer 1997). Incorporation of data from both physical and cultural sources should enable formulation of a coastal management strategy more effectively than can studies based solely on bio-ecological criteria (Legakis *et al.* 1993; Moriki *et al.* 1996), or on visual perception (Blanco *et al.* 1982; Rivas *et al.* 1995), or on geological criteria alone, as discussed by Cooper and McLaughlin (1998). Application of the Cendrero and Fischer (1997) model requires assessment of:

- atmospheric quality and pollution (concentrations of pollutants, visibility, effect on vegetation, effect on humans);
- noise prevalence, intensity, and sources;
- water quality and pollution (concentrations of pollutants, microbiological assemblages, marine kill and human disease events, turbidity, floating debris);
- river influx (discharge, velocity, water quality);
- characteristics of adjacent lacustrine bodies;
- groundwater aquifer volumes, recharge/discharge, and permeability;
- precipitation type, amount, and chemistry;
- biochemistry of freshwaters;
- freshwater biology;
- type and extent of existing wetlands;
- marine biota (biomass, distribution, productivity, diversity, populations);
- seabirds and terrestrial birds;
- geomorphological and sedimentological data;
- rates of coastal erosion/deposition;
- occurrences and rates of marine and terrestrial flooding;
- storm frequencies, track directions, and wind velocities;
- wave dynamics and mechanics;

- slope instability occurrences, mechanisms, and rates;
- rates of soil erosion through overland flow and aeolian activity;
- precipitation and temperature data;
- tsunami occurrences;
- earthquake and volcanic activity;
- terrestrial resources (minerals, timber)
- marine biological resources (fish, molluscs, arthropods, echinoderms, rockweed, etc.);
- marine geological resources;
- ecotourism resources (whales, seabirds, tuckamore forests);
- visual aesthetics;
- archaeological and historical data;
- public recreation facilities;
- tourist infrastructure;
- land use, ownership, and partitioning;
- building types, densities, and functions;
- intensity of use (number of users/km^2);
- percentage of wetlands converted to anthropogenic uses;
- public health;
- educational status of the population (including the tourist population);
- unemployment and underemployment percentage;
- economic profile;
- distribution of income;
- crime rates;
- basic demographic data (population distribution by age and gender, life expectancy, etc.); and
- perception of the quality of the local environment.

Succinctly, the model requires a comprehensive knowledge of all facets of the environment of the coastal zone. Although an investigation of this magnitude is beyond the scope of this report, it is nevertheless apparent that comprehensive management of the coastal zone of eastern Newfoundland requires assessment of all of these parameters.

14. Conclusion

- This report has documented the coastal morphology of eastern Newfoundland, and has indicated the influence of climate variability on the coastline.

- The coastline of eastern Newfoundland has influenced all human occupants of the region, and will continue to do so. Changing economic conditions, differing groups of coastal residents and users, and changes in human perceptions are influencing the human view of the coastline. These changes in turn result in physical alteration of the coastal environment.

- Although all areas of the Newfoundland and Labrador coast are subject to human modifications and pressures, the population concentrated in the northeast Avalon Peninsula, along southern Conception Bay, and in other areas of eastern Newfoundland places particular stress on these segments of the coast.

- The climate of eastern Newfoundland is mid-boreal, marked by cool summers and winters. Precipitation is variable, controlled by aspect, elevation, and position with respect to the shoreline. Prevailing winds from the southwest have a substantial influence on precipitation and wave climate. Hurricanes and their associated precipitation are major elements shaping embayments along the South Coast, Burin Peninsula, Placentia Bay, and St. Mary's Bay, particularly those embayments open to the southwest. Northeast winds, particularly those associated with autumn storms, have a strong geomorphic influence along Conception Bay and Trinity Bay.

- Yearly variations in hurricane frequency and strength, in the occurrence and impact of northeast winds, and in the extent of seasonal ice cover, play a major role in shaping coastal morphology.

- Climate change and variability have influenced the coastline of Eastern Newfoundland, on scales ranging from millennia to individual storms. Climate warming is not directly evident in eastern Newfoundland at present, but does influence global sea level. Climate variability, particularly changes in storm frequency and intensity and the extent of snow and ice cover along the shorelines, does have a substantial geomorphic influence.

- The marine environment of Eastern Newfoundland is dominated by the Labrador Current, with the Gulf Stream playing a subordinate role along the South Coast. Tidal regimes are generally microtidal and semidiurnal, although mesotidal conditions exist at the heads of some embayments. The wave climate is driven by the prevalent wind systems and storm activity. The annual significant wave height approximates 7 m. The embayed nature of the coast results in reflective, moderate-to-high energy, wave-dominated shorelines in the majority of embayments.

- Biological shoreline assemblages are linked directly to geomorphic and sedimentologic environments.

- The physiography of eastern Newfoundland is largely controlled by the structural geology. Coastal morphology is linked to coastal lithology, with resistant units forming headlands and embayments developing along friable or fault-bounded geological strata. Frost wedging is the dominant weathering process, and consequently aspect also plays a role in morphological development.

- All of eastern Newfoundland was glaciated during the Late Wisconsinan episode of the Quaternary period. The most recent episodes of glaciation did not greatly alter the physiography of the terrain, but were responsible for the deposition of coarse-textured glacial diamictons and glaciofluvial gravels along the shorelines (particularly at the heads of fjordal embayments). These sediments were subsequently reworked in part by marine processes, but the coarse texture of the beaches of eastern Newfoundland is primarily a consequence of glaciation, rather than of marine energy levels. The majority of beaches of eastern Newfoundland are thus largely paraglacial.

- Sea level changes subsequent to deglaciation were produced by isostatic recovery. Initially, marine waters inundated the coastal regions which had been glacioisostatically depressed. Evidence for higher marine limits is present throughout the region, with the exception of the Southern Shore of the Avalon Peninsula. Subsequently, during the early Holocene, sea level fell below its present position, reaching a minimum value in the middle part of the Holocene Epoch (*ca.* 8,000-6,000 years ago).

- Sea level along the entire coastline of eastern Newfoundland is currently rising. The rate of sea level rise during the past 2,000 years, as estimated from ^{14}C-dated tree stumps inundated by rising marine waters, is between 2 mm/a and 6 mm/a. Limited evidence suggests that the rate of sea level rise has accelerated within the past 300 years, but additional confirming data is required.

- Classification schemes for coastal environments must attempt to serve many purposes. No single classification scheme is adequate for all users or all investigations. The geomorphic classification scheme presented here is intended to outline the available knowledge concerning the coastal geomorphology of eastern Newfoundland, and can also serve to provide supporting data for other classification efforts and investigations of the region.

- The geomorphic classification scheme considers sediment texture, coastal morphology (width and slope), and the nature of the substrate. Twenty-four categories are recognized and discussed here. Within each of these categories, local circumstances, including aspect, sediment type and flux, offshore bathymetry and onshore physiography, energy levels, and anthropogenic influences combine to produce numerous distinctive coastal geomorphic assemblages.

- Coastal erosion and sensitivity to sea-level rise are issues affecting eastern Newfoundland. Rising sea level is one factor inducing coastal erosion, but anthropogenic activity and interruptions to sediment flux also are important locally. Successful management of the coastline must take coastal erosion into account.

- Pollution and litter are unfortunately evident along many shorelines in eastern Newfoundland. Mitigation of pollution effects can be undertaken more effectively if the local geomorphic environment is considered.

- Aquaculture and fisheries are also influenced by the geomorphic environment of eastern Newfoundland. Aquacultural developments should be preceded by geomorphic analysis of the proposed sites, in addition to other investigations. The impact of coastal geomorphic processes on shellfish species, and on capelin spawning, suggests that geomorphic investigations can also aid in the management of these resources.

- Anthropogenic impacts are apparent along all sections of the eastern Newfoundland coastline. Rather than viewing such impacts as necessarily negative, or inevitable, investigations should focus on the impacts in a non-judgmental nature, and should attempt to document the effects on sediment transport and flux, energy states of the shorelines, and coastal erosion or deposition.

- Human perceptions of the coastal environment of eastern Newfoundland are changing, due to both economic changes (e.g. from the traditional fishery to other economic activities) and due to the arrival and influence of other groups and individuals (such as those involved in ecotourism). Traditionally, geomorphologists have not interacted extensively with social scientists, and have not considered socio-economic issues in their investigations. Linkages between physical science and the study of coastal aesthetics have also not been fully developed. Mutually profitable future investigations are possible throughout Atlantic Canada, and should be encouraged.

It is hoped that the observations and data presented here will serve as useful baseline information for further studies on the numerous diverse aspects of the coastal environment of eastern Newfoundland.

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