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SENSITIVITY OF THE COASTS OF CANADA TO SEA-LEVEL RISE

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FOREWORD

Change is a welcomed or feared challenge. It is welcomed when the outcome is understood and expected to be beneficial; it is feared when the outcome is unknown or expected to be deleterious. Global climate change is one of the most significant projected changes currently facing humanity; it is a feared change because so many unknowns are involved. For example, what will be the rate and level of climate change? How will global climate change be "shared" or impact on various regions? How will the complex earth ecosystems be affected? Most importantly, how will humanity cope?

One element of the global change picture that falls within the mandate of the Geological Survey of Canada is geological processes. Such processes include the various forces which act to change the Earth's surface. The forces with which we are most familiar are water and wind. These act on the surface by eroding (removing) materials from one place and depositing them in another. Because climate plays a major role in driving these processes, climatic changes will result in increases or decreases in the nature and intensity of these processes.

Through time we have gained knowledge which allows us to predict the impact of surface geological processes and hence to mitigate or avoid their harmful effects. For example, application of process knowledge has resulted in development of local practices such as construction of sea walls to protect coastal areas from erosion, and placement of current deflection structures to reduce sedimentation in navigation channels. If future global climate changes result in changes in natural process activities, it will be necessary to modify the mitigative measures. Developing and implementing new coping strategies require research, planning, and time, hence, the sooner information is gathered on what to expect, the better prepared we will be to take action when the changes occur.

The Geological Survey of Canada is studying how the common geological processes occurring in Canada might be affected by climatic change. Each of these reports shows the sensitivity to climatic change of particular processes, looks at the way in which different factors control process activity, discusses the sensitivity of the process to climate change, and considers the impact of different aspects of the process on human activity. These are not intended as research documents, predicting what might be expected in each part of the country, but as warnings to draw attention to potential "hotspots" or areas where the processes in question are likely to be most effected by global climate change. The hope is that these studies will foster and focus follow-up research which will determine potential impact more precisely and provide information for planning mitigative measures.

AVANT-PROPOS

Le changement peut s'avérer un défi souhaité ou redouté. Il est souhaité lorsqu'on connaît bien ses conséquences et qu'on les prévoit favorables; il est redouté lorsque les conséquences qui en découlent sont inconnues ou présumées nuisibles. Le changement climatique à l'échelle du Globe est le changement anticipé le plus significatif auquel doit actuellement faire face l'humanité. Le changement climatique à l'échelle du Globe est un changement redouté étant donné qu'il comporte de nombreuses inconnues. À quel rythme aura lieu le changement climatique et quelle sera son importance? Comment les effets du changement climatique à l'échelle du Globe seront-ils «répartis» ou quelles répercussions auront-ils sur les diverses régions? Comment seront affectés les écosystèmes complexes de la Terre? Encore plus important, comment réagira l'humanité?

L'un des éléments du cadre général des changements à l'échelle du Globe relevant du mandat de la Commission géologique du Canada est lié aux processus géologiques. Ces processus incluent les diverses forces qui modifient la surface de la Terre. Celles qui nous sont les plus connues sont l'eau et le vent qui agissent sur la surface de la Terre en érodant (délogeant) les matériaux à un endroit pour les déposer à un autre. Comme le climat joue un rôle important dans le déroulement de ces processus, les changements climatiques se traduiront par des modifications de la nature et de l'intensité de ceux-ci.

Avec le temps, nous avons acquis des connaissances qui nous permettent de prédire l'impact des processus géologiques actifs à la surface de la Terre et d'en atténuer ainsi les effets néfastes. Par exemple, l'application des connaissances actuelles sur les processus ont permis d'élaborer des méthodes locales comme la construction de brise-lames pour protéger les berges contre l'érosion et la mise en place de déflecteurs de courants pour réduire la sédimentation dans les chenaux navigables. Dans l'avenir, si le changement climatique à l'échelle du Globe devait modifier les processus naturels, il faudrait alors ajuster les mesures de correction en conséquence. L'élaboration et l'application de nouvelles stratégies de correction nécessitent des recherches, de la planification et du temps. C'est pourquoi en recueillant le plus rapidement possible des informations sur ce qui risque de se produire, nous serons mieux préparés à réagir aux changments lorsqu'ils surviendront.

La Commission géologique du Canada étudie actuellement de quelle manière les processus géologiques les plus courants actifs au Canada pourraient être modifiés par les changements à l'échelle du Globe. Chacun des rapports de la présente série traite de la sensibilité de processus particuliers au changement climatique, de la façon dont les différents facteurs agissent sur les processus et des répercussions des différents aspects des processus sur l'activité humaine. Ce ne sont pas des documents de recherche qui contiennent des prévisions sur les changements qui pourraient toucher chaque région du pays; ils visent plutôt à attirer l'attention sur les «points chauds» ou les régions où les processus en question sont le plus susceptibles d'être affectés par le changement climatique à l'échelle du Globe. Nous espérons que ces études favoriseront un suivi des recherches qui permettra d'établir les répercussions potentielles de façon plus précise et fournira des informations utiles pour la planification de mesures correctrices.

This report looks at the sensitivity of Canadian coasts to changes in sea level. Global climate change causes sea-level change by modifying the proportion of water stored on land (largely in glaciers) compared to that in the oceans, and by causing thermal expansion or contraction of sea water. Change of sea level will impact on human activity by changing the rate of coastal retreat, causing inundation or shoaling, and by generally changing coastal currents and processes. In this Bulletin Canadian coasts are classified in terms of an index of sensitivity which is derived by relating a number of variables, such as, relief, lithology, landform, and wave energy. This index assesses the relative sensitivity of Canadian coasts to changes in sea level and identifies the coastal areas that are most vulnerable. Critical regions are highlighted where studies will have to be conducted to outline the probable local impact of global change and to develop the best coping mechanisms. Only through studies such as this, which provides knowledge of the possible impact of global change, will our fear of facing the unknown be reduced.

The other reports published in this series are: Sensitivity of eolian processes to climate change in Canada (GSC Bulletin 421) and Geomorphological processes in alpine areas in Canada: the effects of climate change and their impact on human activities (GSC Bulletin 524).

R.J. Fulton,
Co-ordinator,

Impact of Global Climate Change on Geological Processes Project

Le présent rapport se penche sur la sensibilité des régions côtières du Canada aux changements du niveau de la mer. Un changement climatique à l'échelle du Globe se répercutera sur le niveau de la mer en modifiant la proportion d'eau stockée sur les continents (surtout dans les glaciers) par rapport à la quantité contenue dans les océans et en causant l'expansion ou la contraction thermique de l'eau de mer. Les changements du niveau de la mer ont des incidences sur les activités anthropiques du fait qu'ils font varier la vitesse de recul des côtes, qu'ils entraînent des inondations ou l'émergence de hauts-fonds et qu'ils modifient les courants et les processus côtiers. Dans le présent bulletin, les côtes canadiennes sont classifiées en fonction d'un indice de sensibilité qui est obtenu en mettant en relation un certain nombre de variables, comme le relief, la lithologie, les formes de relief et l'énergie des vagues. Cet indice évalue la sensibilité relative des côtes canadiennes aux changements du niveau de la mer et permet de délimiter les secteurs côtiers les plus vulnérables. Des régions à sensibilité critique sont également délimitées là où l'on considère que des études doivent être menées pour déterminer les répercussions locales probables des changements à l'échelle du Globe et pour élaborer les mécanismes de défense les mieux adaptés. Ce n'est que par des études de ce type, qui fournissent des données sur les répercussions possibles des changements à l'échelle du Globe, que notre peur de l'inconnu pourra être mieux maîtrisée.

Les autres rapports publiés dans cette série sont : *Sensitivity of eolian processes to climate change in Canada* (CGC, Bulletin 421) et *Geomorphological processes in alpine areas in Canada : the effects of climate change and their impact on human activities* (CGC, Bulletin 524).

R.J. Fulton
Coordonnateur

Projet d'étude sur les répercussions du changement climatique à l'échelle du Globe sur les processus géologiques

PREFACE

This is the second overview in the Geological Survey of Canada's project: "Impact of Global Climate Change on Geological Processes". These overviews provide the information on the possible impacts of global change and the potential magnitude of the problem.

This report looks at the sensitivity of Canada's coasts to sea-level rise. The link with global climate change comes through the connection between climate and sea level. There is an inverse relationship between the volume of water in glaciers and that in oceans (e.g. warmer climate will reduce glacier size with the meltwater ending up in the oceans). In addition, the warming or cooling of the oceans results in a rise or fall of sea level because of the thermal expansion or contraction of the volume of ocean water.

This report describes coastal and related geological processes, discusses how predicted global climate change could result in changes in sea level and modification of rates of coastal erosion, and uses information drawn from several sources to derive a system for rating the sensitivity of Canadian coasts to changes in sea level. Segments of Canada's coasts that are most sensitive to changes in sea level are identified. Critical regions where detailed studies should be conducted are discussed to determine the probable local impact of sea-level change and the development of the best mitigative measures.

This report was prepared under the auspices of the Global Change Program of the Geological Survey of Canada with the principal support of the Canada Green Plan Fund.

M.D. Everell
Assistant Deputy Minister
Earth Sciences Sector

PRÉFACE

La présente étude est la deuxième à présenter une vue d'ensemble dans le cadre du projet de la Commission géologique portant sur les répercussions du changement climatique à l'échelle du Globe sur les processus géologiques. Ces rapports colligent des données sur les répercussions possibles des changements à l'échelle du Globe et nous fournissent une vue d'ensemble nous permettant d'avoir un aperçu de l'ampleur possible du problème.

La présente étude porte sur la sensibilité des côtes du Canada à une hausse du niveau de la mer. Le lien au changement climatique à l'échelle du Globe tient aux rapports qui existent entre le climat et le niveau de la mer. Il existe une relation inverse entre le volume d'eau contenu dans les glaciers et celui contenu dans les océans (p. ex. un réchauffement du climat réduira la taille des glaciers et les eaux de fonte aboutiront à la mer). De plus, le réchauffement ou le refroidissement des océans cause une élévation ou un abaissement de leur niveau par suite d'une expansion ou d'une contraction thermique du volume d'eau qu'ils contiennent.

La présente étude décrit les processus géologiques côtiers et ceux qui leur sont associés, traite de la façon dont le changement climatique anticipé à l'échelle du Globe modifiera le niveau de la mer et les vitesses d'érosion des côtes et utilise les informations tirées de plusieurs sources pour établir un système de pondération de la sensibilité des côtes canadiennes aux changements du niveau de la mer. Les segments des côtes canadiennes qui sont les plus sensibles aux changements du niveau de la mer sont identifiés. Les régions à sensibilité critique où il faudrait mener des études détaillées du phénomène font l'objet d'une attention spéciale afin de déterminer les répercussions locales probables du changement du niveau de la mer et d'élaborer les mesures correctrices appropriées.

La présente étude a été préparée sous les auspices du Programme des changements à l'échelle du Globe de la Commission géologique du Canada avec l'appui du fonds du Plan vert du Canada.

M.D. Everell
Sous-ministre adjoint
Secteur des sciences de la Terre

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SENSITIVITY OF THE COASTS OF CANADA TO SEA-LEVEL RISE

Abstract

An objective method is used to evaluate the sensitivity of Canadian coasts to a rise in sea level of 0.65 m by the end of next century. Based on the assumption that the intensity of impact is related to seven quantifiable variables – relief, geology, coastal landform, coastal retreat rate, sea-level trend, wave energy, and tidal range – a dimensionless index is determined for each of 2899 NTS map sheets (1:50 000 scale) that include parts of Canada's coast. Scores range from 0.8 to 57, with a mean of 5.1, and a strong mode between 2 and 4. Areas of low sensitivity (scores below 5) constitute 67% of the total, of moderate sensitivity (scores of 5 - 15) make up 30%, and of high sensitivity, only 3%. No large areas are susceptible to catastrophic inundation by the sea but any sea-level rise would cause an increase in the rates of change.

The most sensitive region includes much of the coasts of Nova Scotia, Prince Edward Island, and New Brunswick. The major impacts would be higher rates of coastal erosion and retreat. Only small parts of the coast would be permanently submerged. Salt marshes would be subject to more frequent inundation but would accrete sufficiently to keep pace with sea-level rise. New spits, beaches, and barriers could form in places. Many small settlements are in sensitive locations but impacts on the largest urban areas would be small.

The Pacific coast has low sensitivity overall, mainly due to a preponderance of high, rocky fiord and skerry shorelines. Areas of high sensitivity include the urbanized Fraser Delta and parts of Graham Island.

Most of the Arctic coast has low sensitivity. An increase in extent and duration of open water in summer would have a greater impact than sea-level rise. On the other hand, the coast of the Beaufort Sea in the Yukon and Northwest Territories is highly sensitive. Here anticipated impacts include more rapid coastal retreat and an acceleration in the rate at which coastal freshwater lakes are breached and converted into brackish or saline coastal embayments. Accretion of marsh surfaces in the Beaufort Sea region may not keep pace with sea-level rise.

Due to simplifications in the methodology, numerous small areas of higher sensitivity are overlooked by the scoring system. Small- and medium-sized deltas, particularly in the Arctic, outside of regions of rapidly falling sea level, and strand plains and small salt marshes fall into this category.

Résumé

Pour évaluer la sensibilité des côtes canadiennes à une hausse du niveau de la mer de l'ordre de 0,65 m d'ici la fin du prochain siècle, une méthode objective a été utilisée. En se basant sur l'hypothèse selon laquelle l'intensité des répercussions est liée à sept variables quantifiables (relief, géologie, formes côtières, vitesse de recul de la côte, tendance à la variation du niveau de la mer, énergie des vagues et amplitude de la marée), un indice sans dimension a été établi pour chacune des 2 899 cartes du SNRC (échelle de 1/50 000) figurant une partie des côtes du Canada. Les valeurs de cet indice s'échellonnent de 0,8 à 57, affichent une moyenne de 5,1 et montrent un mode très prononcé se situant entre 2 et 4. Les secteurs de faible sensibilité (valeurs plus basses que 5) constituent 67 % de l'ensemble des côtes, ceux de sensibilité moyenne (valeurs entre 5 et 15) correspondent à 30 % de ce même ensemble, et les secteurs de forte sensibilité n'en constituent que 3 %. Aucun grand secteur n'est susceptible de subir une inondation catastrophique par la mer mais toute hausse du niveau de la mer pourrait causer une accélération des processus de changement.

La région la plus sensible inclut la majeure partie des côtes de la Nouvelle-Écosse, du l'île-du-Prince-Édouard et du Nouveau-Brunswick. Les principaux impacts seraient une érosion et un recul plus rapides des côtes. De petites parties seulement de ces côtes seraient submergées en permanence. Les marais salés seraient plus fréquemment inondés, mais leur accrétion serait suffisante pour s'adapter à la hausse du niveau de la mer. De nouvelles formes sédimentaires – flèches, plages et bancs – s'édifieraient par endroits. De nombreuses petites agglomérations sont situées dans les zones sensibles, mais les grandes régions urbaines dans la même situation sont rares.

La côte du Pacifique affiche dans l'ensemble une faible sensibilité, du fait que le littoral y est surtout constitué de fjords rocheux élevés et d'écueils. Les secteurs montrant une forte sensibilité se rencontrent notamment dans la région urbanisée du delta du Fraser et dans certaines parties de l'île Graham.

Presque tout la côte arctique affiche une faible sensibilité. Un accroissement de l'étendue et de la durée des eaux libres de glaces durant l'été aurait des répercussions plus importantes qu'une élévation du niveau de la mer. Par contre, la côte bordant la mer de Beaufort au Yukon et dans les Territoires du Nord-Ouest est très sensible. Parmi les effets possibles, mentionnons un recul plus rapide de la côte et une accélération de la vitesse d'érosion des lacs d'eau douce littoraux et de leur transformation en baies d'eau saumâtre ou saline. L'accrétion de la surface des marais dans la région de la mer de Beaufort pourrait ne pas se produire à une vitesse suffisante pour contrer la hausse du niveau de la mer.

En raison des simplifications intrinsèques associées à la méthode utilisée, de nombreux secteurs affichant une forte sensibilité n'ont pas été identifiés à l'aide du système de pondération. Dans cette catégorie, on trouve les deltas de petite et de moyenne tailles, en particulier dans l'Arctique, à l'extérieur des régions de baisse rapide du niveau de la mer et les estrans et les petits marais salés.

SUMMARY

The purpose of this publication is to assess the impacts of a global rise in sea level (such as might be caused by climate warming) on Canadian coasts. This involves an examination of the nature and extent of coastal features which would be sensitive to such change. By sensitivity we mean the degree to which a rise in sea level would initiate or accelerate geomorphological changes such as coastal retreat and beach erosion. To assess the sensitivity of the Canadian coastline we have used a method adapted from that of Gornitz and Kanciruk (1989), Gornitz (1990, 1991), and Gornitz et al. (1991) who used a "coastal vulnerability index" which combined data on seven variables. *Relief* and *vertical land movements* were considered indicators of inundation risk; *lithology* and *coastal landform* were associated with resistance to erosion; *rates of erosion* were considered indicators of sensitivity to coastal processes, and *wave energy* was related to the capacity for erosion. It was argued that *tidal range* was linked to both inundation and erosion hazards.

A coast with a high sensitivity index, for example, would be in a region of low relief and unconsolidated sediments, with barrier islands, high tidal range, high wave-energy levels, where relative sea level is already rising rapidly. Under current conditions such a coast would be subject to landward migration of barrier islands, and retreat of shorelines but with rising sea level, barrier migration and destruction would be accelerated and the coastal area behind the barrier would be subject to inundation. A coast with a low sensitivity index, on the other hand, would have high relief, a rocky shore with resistant, noneroding bedrock, falling sea level, low tidal range, and low wave energy. Such a coast is not subject to significant retreat under current conditions and would remain stable even if sea level rises at predicted rates.

The sensitivity index method of classifying coasts accommodates not just sea-level trends but also the potential of other factors to render the coast more or less sensitive to change. The resulting numerical assignment cannot be directly equated with particular physical effects, however. Figure 2 highlights those regions where the various effects of

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Le but de la présente publication est d'évaluer les conséquences sur les côtes canadiennes d'une hausse du niveau de la mer à l'échelle planétaire (comme le réchauffement du climat pourrait en causer une). Cette évaluation passe par l'étude de la nature et de la répartition des caractéristiques des côtes qui pourraient être sensibles à ce changement. La sensibilité correspond au degré auquel une hausse du niveau de la mer entraînerait ou accélérerait les processus géomorphologiques tels que le recul de la côte et l'érosion du littoral. Une adaptation de la méthode de Gornitz et Kanciruk (1989), Gornitz (1990 et 1991), ainsi que Gornitz et al. (1991) a donc servi à évaluer la sensibilité des côtes canadiennes à une hausse du niveau de la mer. Selon cette nouvelle méthode, «l'indice de sensibilité d'une zone côtière», constitue une synthèse de sept variables : *le relief* et *l'ampleur des mouvements de terrain verticaux* (indicateurs des risques d'inondation), *la lithologie* et *la morphologie de la zone côtière* (résistance à l'érosion), *le taux d'érosion* (sensibilité aux processus côtiers), *l'énergie des vagues* (capacité d'érosion) et *l'amplitude de la marée*; après discussion, cette dernière caractéristique a été liée aux risques d'inondation et d'érosion.

Une zone côtière à fort indice de sensibilité serait, par exemple, une région au relief peu élevé, où l'on pourrait observer des sédiments non consolidés, des îles-barrières, une marée à grande amplitude et des vagues à forte énergie et où le niveau relatif de la mer serait déjà à la hausse. Dans les conditions actuelles, cette zone serait soumise à une migration des îles-barrières vers la côte et à une régression du rivage. Une hausse du niveau de la mer ferait cependant en sorte que la migration et la destruction des îles-barrières seraient accélérées et que la zone côtière serait inondable. À l'opposé, une zone côtière à faible indice de sensibilité serait une région au relief élevé, où le rivage rocheux serait composé de lithologies du substratum résistantes à l'érosion, où le niveau de la mer serait en baisse et où l'amplitude des marées et l'énergie des vagues seraient faibles. Dans les conditions actuelles, cette zone ne serait pas soumise à une forte régression. Et même si le niveau de la mer s'élevait comme il l'est prévu, la côte resterait stable.

La classification des côtes selon l'indice de sensibilité concilie non seulement les tendances du niveau de la mer mais aussi la capacité d'autres facteurs de rendre les côtes plus ou moins sensibles au changement. Les chiffres obtenus ne peuvent pas être mis directement en équation avec des effets physiques précis. Toutefois, la figure 2 fait ressortir les régions où les diverses sea-level rise probably will be greatest. The possible impacts in various regions are discussed in the report, and we have also tried to assess other effects of global climate change, such as an increase in the extent and duration of open water.

conséquences d'une hausse du niveau de la mer seraient les plus importantes. Le présent bulletin traite des répercussions attendues dans diverses régions mais donne aussi une évaluation provisoire d'autres effets du changement climatique à l'échelle du globe, comme l'accroissement de l'étendue des eaux libres de glaces et la durée de leur existence.

Because of the large extent of the coast, the rudimentary and fragmentary knowledge of some of the variables, and our poor grasp of how they could influence outcomes, Figure 2 must be considered as a generalized depiction of coastal sensitivity. As is pointed out in the report, the Canadian coastline commonly has highly contrasting coastal environments juxtaposed to form a complex mosaic whose reaction to rising sea level is difficult to predict. Also, due to the gross simplifications inherent in the method used to assess sensitivity over such a lengthy coastline, numerous small, highly sensitivity sites are overlooked. Typical small but sensitive sites which generally have been grouped with larger, less sensitive areas are small and moderate-sized deltas, pocket beaches, low beach-ridge plains, and small salt marshes.

Compte tenu de la grande étendue des côtes, de la connaissance rudimentaire et fragmentaire de certaines variables et de la mauvaise compréhension de l'influence de ces variables sur les conséquences d'une hausse du niveau de la mer, la figure 2 doit être prise comme une représentation généralisée de la sensibilité des côtes. Comme il l'est souligné dans le bulletin, les divers environnements des côtes canadiennes sont extrêmement contrastés et se juxtaposent pour former une mosaïque complexe pour laquelle il est difficile de prévoir la réaction à la hausse du niveau de la mer. De plus, en raison des simplifications intrinsèques associées à la méthode retenue pour évaluer la sensibilité d'un aussi vaste ensemble de côtes, de nombreux petits sites très sensibles sont nécessairement ignorés. Ces derniers sont généralement regroupés avec de plus grandes zones moins sensibles. Typiquement, ce sont des deltas de petite et de moyenne tailles, des petites plages abritées, des levées de plage à faible altitude et de petits marais salés.

Stress is placed on the role of glacial deposits which, when they are eroded by waves and currents, supply sediment to the littoral system. Fine sediment released by coastal erosion commonly finds its way into estuaries, resulting in the growth of salt marshes. The release of coarser material into the littoral system usually results in the formation and growth of sand and gravel beaches.

In several places coastal processes that are currently occurring are contrary to what would be expected from the direction of present sea-level change. For example, in Atlantic Canada, some gravel beaches have accreted to form extensive strand plains in the last several thousand years, despite rising sea level, and in some parts of eastern Hudson Bay, rapid coastal erosion is occurring despite falling of sea level. This indicates that we do not fully understand the forces driving coastal processes and that predictions of the effects of sea-level change must be considered as regional generalizations which are not necessarily accurate at the site level.

L'accent est mis sur le rôle des dépôts glaciaires dont l'érosion par les vagues et les courants constitue un apport de sédiments au système côtier. Les sédiments à grain fin libérés par l'érosion côtière aboutissent normalement dans les estuaires et donnent naissance aux marais salés. La libération de matériaux à grain plus grossier dans le système côtier provoque généralement la formation et la croissance de plages de sable et de gravier.

À plusieurs endroits, les processus côtiers en cours sont en contradiction avec les prédictions faites quant à la tendance actuelle du niveau marin (à la hausse ou à la baisse). D'une part, sur les côtes atlantiques canadiennes, certaines plages de gravier se sont formées en dépit de la hausse du niveau de la mer et sont devenues de grandes plaines côtières au cours des quelque derniers milliers d'années. D'autre part, dans certaines zones de la partie est de la baie d'Hudson, les côtes s'érodent rapidement malgré une baisse du niveau de la mer. Ces phénomènes indiquent que notre compréhension des processus côtiers n'est pas entière et que les prévisions quant aux conséquences du changement du niveau de la mer doivent être considérées comme des généralisations applicables à l'échelle régionale et non nécessairement à l'échelle d'un site.

After identifying and considering some of the more important factors that play a role in changing the Canadian coast, we feel that the main impact of an acceleration in the rate of sea-level rise would be an intensification of the destructive processes which presently occur at the coast. In other words, the processes which we observe today, such as beach erosion and retreat, bluff erosion, and landward migration of barrier islands will continue, but will take place more rapidly and more extensively. The sensitivity of the Canadian coast to a modest global sea-level rise caused by anthropogenically induced global warming, which is discussed in detail in the report, is summarized in the following accounts covering the three principal maritime regions of Canada.

Après avoir identifié et pris en compte quelques-uns des principaux facteurs qui jouent un rôle dans la modification des côtes canadiennes, les auteurs considèrent que la principale conséquence de l'accélération de la hausse du niveau de la mer serait une intensification des processus destructeurs qui érodent actuellement les côtes. En d'autres termes, les processus observés actuellement, comme l'érosion et le recul des plages de même que l'érosion des falaises et la migration des îles-barrières vers la côte vont se poursuivre, mais de plus en plus rapidement et sur de plus grandes étendues. Le présent bulletin passe à la loupe la sensibilité des côtes canadiennes à une légère hausse du niveau de la mer à l'échelle du globe dérivant du réchauffement planétaire d'origine anthropique. Les paragraphes qui suivent constituent un bref exposé du problème dans les trois principales régions côtières du Canada.

Atlantic coasts

Atlantic Canada includes the largest extent of highly sensitive coast. The sensitive area includes much of the coasts of Nova Scotia, Prince Edward Island, and New Brunswick. The impacts of sea-level rise will include: 1) increased rates of bluff erosion (the mean rate of bluff-top retreat today ranges from 0.1-5.4 m per year); 2) higher rates of beach erosion and retreat; 3) more frequent overwashing of beaches; and 4) destabilization of coastal dunes. Small parts of the coast will be permanently submerged. Salt marshes will be subject to more frequent inundation but may accrete sufficiently to keep pace with sea-level rise. New spits, beaches, and barriers could form in places.

Communication links in some areas may be vulnerable, for example, on the Tantramar Marsh (New Brunswick/Nova Scotia border) or along the Gaspésie coast (eastern Québec). A number of small settlements in sensitive locations could have problems. A good example is the town of Placentia, in Newfoundland, which has expanded in recent years onto a low, gravel beach-ridge plain, susceptible to flooding. As a rule, however, impacts on the largest urban areas will be small. In some places, such as at Saint John (New Brunswick) and Charlottetown (Prince Edward Island), these impacts have already been assessed in detail (Martec Ltd., 1987; and P. Lane and Associates Ltd., 1988); elsewhere, detailed local studies are required to gauge the impact with greater precision.

Pacific coasts

The Pacific coasts of Canada have low sensitivity overall, mainly due to a preponderance of high, rocky, fiord and skerry coasts, and great variation in existing sea-level trends. The small areas of high sensitivity include the important urbanized Fraser Delta near Vancouver, where the impacts of further sea-level rise could be dyke-breaching, flooding, and erosion of salt marshes. In addition, instabilities on the submarine prodelta slope present a hazard to the urban coastline and port facilities situated on the delta front. Erosion of unconsolidated cliffs at Vancouver, some sites on Vancouver Island, and along the northeastern coast of Graham Island (in the highly active Rose Spit region) may accelerate under higher sea levels. It is conceivable that other climatic effects such as changes in precipitation might have important implications for sediment delivery to the coast and the stability of some shorelines, particularly in the Fraser River area and in many small fiord-head delta settings. The latter are generally sites of urban and industrial development, such as the community of Squamish, at the head of Howe Sound. Although too small to influence the regional sensitivity index scores, these low-lying delta shores may be susceptible to climate-change sensitive impacts from both land and sea.

Les côtes de l'Atlantique

La région atlantique du Canada constitue le plus vaste ensemble de côtes extrêmement sensibles au pays. Le territoire inclut la majeure partie des côtes de la Nouvelle-Écosse, de l'Île-du-Prince-Édouard et du Nouveau-Brunswick. Parmi les incidences d'une hausse du niveau de la mer, il y aurait les suivantes : 1) rythme accéléré d'érosion des falaises (le taux moyen de la régression des falaises supérieures varie actuellement de 0,1 à 5,4 mètres par année); 2) taux plus élevé d'érosion et de recul des plages; 3) inondation plus fréquente des plages; 4) déstabilisation des dunes côtières. De petites parties des côtes seraient submergées en permanence. Les marais salés seraient plus souvent inondés, mais l'accrétion de leur surface serait suffisante pour s'adapter à la hausse du niveau de la mer. De nouvelles formes sédimentaires - flèches, plages et bancs - s'édifieraient par endroits.

Les liens de communication pourraient devenir vulnérables dans certaines régions, notamment dans celles du marais de Tantramar (à la frontière entre le Nouveau-Brunswick et la Nouvelle Écosse) ou de la côte de la Gaspésie (dans l'est du Québec). Bon nombre de petites localités situées dans des endroits sensibles pourraient être confrontées à des problèmes. La ville de Placentia (Terre-Neuve), qui s'est agrandie ces dernières années sur une plaine de levées de gravier sujette aux inondations, en est un bon exemple. Cependant, les incidences sur les plus grands centres urbains seront généralement très limitées. Localement, comme à Saint John (Nouveau-Brunswick) et à Charlottetown (Île-du-Prince-Édouard), on en a fait une évaluation détaillée (Martec Ltd., 1987, P. Lane and Associates Ltd., 1988). Ailleurs, il serait nécessaire d'effectuer des études détaillées à l'échelle locale pour évaluer ces effets avec plus de précision.

Les côtes du Pacifique

En bordure du Pacifique, les côtes affichent dans l'ensemble une faible sensibilité à une hausse du niveau de la mer, principalement du fait qu'elles sont surtout constituées de fjords aux parois rocheuses élevées et d'écueils, mais aussi que, actuellement, le niveau de la mer y est très variable. Les petits secteurs de forte sensibilité comprennent la grande région urbanisée du delta du Fraser, près de Vancouver, où une hausse plus importante du niveau de la mer pourrait provoquer l'ouverture de brèches dans des digues, des inondations et l'érosion de marais salés. De plus, l'instabilité du talus prodeltaïque sous-marin présente un danger pour les côtes en zone urbaine et les installations portuaires situées sur le front du delta. L'érosion des falaises non consolidées à Vancouver, à certains sites sur l'île de Vancouver et le long de la côte nord-est de l'île Graham (dans la région très active de la flèche Rose) pourrait s'accélérer si le niveau de la mer augmentait. D'autres phénomènes climatiques, tels des changements dans les précipitations, pourraient aussi avoir des conséquences considérables sur l'apport de sédiments sur la côte et sur la stabilité de certains rivages, en particulier dans la région du fleuve Fraser et dans les environs de nombreux petits deltas à l'extrémité amont des fjords. Ces derniers sont généralement des sites de développement urbain et industriel; la communauté de Squamish, au fond de la baie Howe, en est un exemple. Même si ces rivages deltaïques à faible altitude sont trop petits pour influer sur l'indice de sensibilité à l'échelle régionale, ils sont vulnérables aux incidences du changement climatique tant côté terre que côté mer.

Arctic coasts

The impact of a global sea-level rise on Arctic coastlines will be less than in Atlantic Canada generally, mainly because of the large extent of the region over which sea level is currently falling as a result of crustal rebound. The impact due to sea-level rise could be less than that which might result from an increase in the extent and duration of open water in summer due to global warming. In this case, beaches would be reworked by waves for longer periods of time, and the greater fetch over more extensive open water would allow storms to cause correspondingly more damage at the coast than today.

The Beaufort Sea coast of the Yukon and Northwest Territories is the largest area of high sensitivity in the Arctic. This is because submergence is currently occurring along much of this coast and foreshore areas generally are low with coastal marshes, lagoons, spits and barrier islands, and extensive permafrost. Sea-level rise augmented by global warming would subject beaches, barrier islands, and coastal bluffs to more rapid landward retreat. One of the major settlements in the region, Tuktoyaktuk, is already threatened by coastal erosion. The rate at which coastal freshwater lakes are breached and converted into brackish or saline coastal embayments would be accelerated. Warmer air and water temperatures would lead to accelerated thaw consolidation from melting ice, thus exacerbating erosion due to waves.

Les côtes de l'Arctique

Les répercussions d'une hausse du niveau de la mer à l'échelle planétaire seraient généralement moins considérables sur les côtes canadiennes de l'Arctique que sur celles de l'Atlantique, principalement parce que le niveau de la mer est actuellement en train de baisser sur une bonne partie de cette région par suite du relèvement isostatique de la croûte. Ces répercussions pourraient être moindres que celles résultant d'un accroissement au cours de l'été de l'étendue des eaux libres de glaces et de la durée de leur existence, en raison du réchauffement de la planète. Dans ce cas, les plages seraient remaniées par les vagues pendant de plus longues périodes; en outre, la plus longue course du vent sur une plus grande superficie d'eaux libres de glaces permettrait aux tempêtes d'endommager davantage les côtes qu'aujourd'hui.

La côte bordant la mer de Beaufort au Yukon et dans les Territoires du Nord-Ouest est la zone de forte sensibilité la plus vaste de l'Arctique. Cette situation résulte du fait que presque toute la côte est en voie d'être submergée et que les zones d'avant-plage sont généralement basses et comprennent des marais côtiers, des lagons, des flèches, des îles-barrières et de grandes étendues de pergélisol. Une plus grande hausse du niveau de la mer en raison du réchauffement de la planète soumettrait les plages, les îles-barrières et les falaises côtières à un recul plus rapide. Une des principales localités de la région, Tuktoyaktuk, est déjà menacée par l'érosion du littoral. Un autre effet possible est l'accélération de la vitesse à laquelle les lacs d'eau douce de la côte seraient ébréchés et transformés en baies d'eau saumâtre ou saline. Une augmentation des températures de l'air et de l'eau activerait le tassement par dégel lié à la fusion de la glace, ce qui amplifierait l'érosion par les vagues.

INTRODUCTION: THE THREAT OF RISING SEA LEVEL

One predicted aspect of global climate change is a rise in sea level. The purpose of this study is to assess the impacts of a global rise in sea level on Canadian coasts, using an objective method to compare the sensitivity of all coastal regions throughout Canada. By sensitivity we mean the degree to which a rise in sea level, in combination with local coastal conditions and coupled perhaps with other effects of global climate change such as increases in mean annual temperatures, would initiate or accelerate geomorphological changes at the coast.

Our concern with sea-level change arises from the idea that a radical adjustment of global climate may be occurring due to greenhouse gas emissions into the atmosphere. It is worthwhile noting that a universal consensus on this hypothesis does not exist (cf. Pocklington, 1991). However, if we accept the view of the Intergovernmental Panel on Climate Change (IPCC) (Houghton et al., 1990), then by the year 2025 the global mean temperature will have risen 1°C above the present level. Similarly, a 3°C increase will occur before 2100. If the postulated greenhouse effect occurs, climatic conditions on Earth may approach those attained during the climatic optimum of the Pliocene, 4.4 to 3.3 Ma ago, when carbon dioxide levels were twice those of today (Bowen, 1991).

The increase in global mean temperature will likely cause a rise in mean sea level because of thermal expansion of the oceans (Gornitz et al., 1982), melting of glaciers (various sources cited in National Research Council, 1987), and a variety of other effects. For example, Revelle's (1983) prediction of a 0.7 m rise by 2085 was based on contributions from Greenland glaciers (0.12 m), mountain glaciers (0.12 m), thermal expansion (0.30 m), and other factors (0.16 m). Peltier and Tushingham (1989) speculated that a globally coherent signal of rising sea level, observed in tide-gauge data from various parts of the world, is an indication that the sea-level rise due to the greenhouse effect is already occurring.

The wide range of predictions (Houghton et al., 1990) results from the use of differing estimates of future global temperatures, and from the use of differing contributions from the various sources. Mikolajewicz et al. (1990) added further complexity to prediction by showing that the increase due to thermal expansion would be distributed differentially around the globe. For example, their ocean circulation model showed that mean global sea-level rise from thermal expansion alone will be 0.19 m by 2040. However, this will vary spatially, so that a 0.40 m increase is predicted for the North Atlantic, and only 0.20 m for Atlantic Canada. Notwithstanding these complexities, our analysis is based on the prediction of the Intergovernmental Panel on Climate Change (Houghton et al., 1990). Based on the "Business as Usual" scenario of these authors, sea-level rise that is due mainly to thermal expansion of the oceans and the melting of some land ice will amount to 0.20 m by 2030 and 0.65 m by the end of the next century (Fig. 1a). After completion of this study, Houghton et al. (1996) published a revised estimate of 0.49 m for sea-level rise by 2100 A.D. This does not substancially alter the qualitative conclusions of the study.

Impacts of sea-level rise on the coast

The potential impacts of rising sea level have been examined elsewhere (cf. National Research Council, 1987; Bijlsma et al., 1992). It is unnecessary to reiterate the arguments in detail, but it is important to summarize some of them before examining impacts on the Canadian coastline.

Increasing tidal levels

An increase in mean water level would increase the flooding frequency of high intertidal environments and cause flooding in areas presently above astronomical high tide levels. The most sensitive coastal environments in this respect are: 1) salt marshes, which occur throughout Canada in estuaries, deltas, and backbarrier settings, and have their greatest extent in the Bay of Fundy; and 2) coastal freshwater marshes, such as

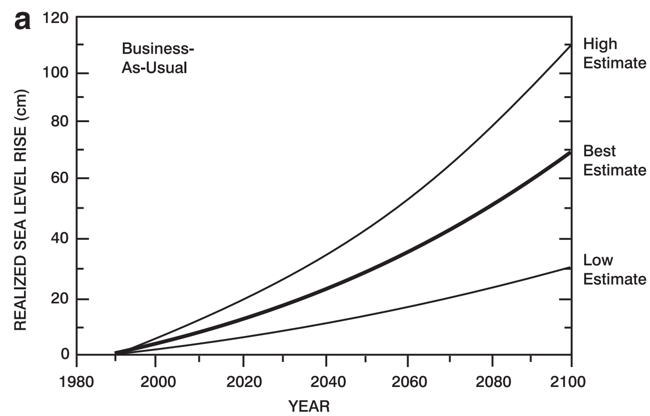

Figure 1a. *Sea-level rise predicted to result from Business-as-Usual emissions, from Houghton et al. (1990).*

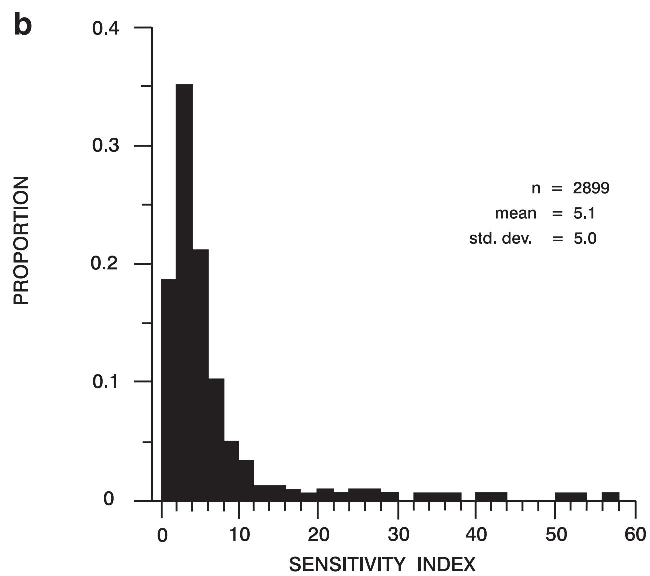

Figure 1b. *Histogram showing the distribution of sensitivity scores. The strong modal peak is in the 2-4 interval.*

those on the east coast of New Brunswick. Deltas commonly contain both saltwater and freshwater wetlands and constitute large sensitive areas. The largest deltas in Canada are those of the Mackenzie River (Beaufort Sea) and the Fraser River (Strait of Georgia). There are, in addition, many thousands of smaller deltas along the Canadian coast, generally providing distinctive wetland and intertidal habitats on otherwise rocky coasts. Because the magnitude of sea-level rise being considered here is rather small, we have not calculated the area that would be permanently inundated. The threat of permanent inundation of large areas of Canada due to sea-level rise is of little consequence compared with other regions (e.g. eastern England, the Netherlands, Bangladesh). Other, less direct effects (e.g. changes in rates of marsh accretion, increased frequency of storm and surge damage) are more important in Canada.

Flooding due to surges

The highest water levels experienced on Canadian coasts are typically caused when astronomical high tides are augmented by storm surges (elevated water levels caused by wind and pressure changes during storms). Galbraith (1979) gave statistics for surges between 1940 and 1975 in Atlantic Canada. The mean annual frequency of surges greater than 0.6 m was 2.7 per year at Halifax, 7.2 per year at St. John's, and 2.6 per year at Yarmouth. The highest surges recorded at these locations were 1.1 m, 2.0 m, and 0.9 m respectively. In the microtidal Beaufort Sea, positive storm surges of up to 2.4 m have been documented (Harper et al., 1988). Higher mean sea level may increase the probability of extreme water levels associated with surges, although on an idealized continental shelf the wind-stress component of surges would decrease (see National Research Council, 1987, p. 35). Determination of the future frequency and magnitude of extreme water levels in each region is beyond the scope of this study; it is best ascertained by local studies such as the Charlottetown and Saint John studies (Martec Ltd., 1987; P. Lane and Associates, Ltd., 1988).

Coastal retreat due to sea-level rise

Sea-level rise causes an upward shift in the reach of coastal processes, and generally tends to result in coastal retreat. The link between sea-level rise and coastal retreat, for sandy coasts at least, was quantified by Bruun (1962, 1983), who related the amount of shoreline erosion to sea-level rise and profile width and depth. Using this approach, Titus et al. (1985) concluded that a 0.3 m sea-level rise would cause about 30 m of erosion on most U.S. beaches. It is reasonable to conclude that a future sea-level rise would initiate or accelerate coastal retreat in many parts of Canada.

Barrier beaches are particularly susceptible to accelerated retreat, due to their low height and narrow width. Their landward migration in response to rising sea level has been exhaustively investigated, particularly in the United States (cf. Leatherman 1979, 1982), and occurs as a result of the following processes: 1) overwashing during storms; 2) the formation of new inlets during storms (allowing landward transfer of sediment into flood deltas); 3) landward migration of dunes across barriers; and 4) erosion of beachface exposures of backbarrier freshwater and salt-marsh deposits.

Many barriers in Canadian waters, principally those on the Atlantic coast of Nova Scotia, the Beaufort Sea coast, and the gulf coasts of New Brunswick and Prince Edward Island, behave similarly (Armon, 1979; Rosen, 1979), except that shorefast ice and pack ice generally curtail wave activity for part of the year. Because migration rates will accelerate with rising sea-level, it is possible that warmer climates would increase the duration of ice-free conditions, or result in thinner, more mobile ice. This would cause more rapid rates of coastal change than otherwise.

Coastal bluffs commonly retreat as rapidly as beaches and barriers. In Canada they typically consist of unconsolidated glaciogenic sediments such as glacial diamict, ice-proximal sand and gravel, or glaciomarine muds, commonly capped by Holocene peat and rarely bonded by ice. High rates of retreat occur on the Beaufort Sea coast, locally in British Columbia, and in the Atlantic Provinces. Shaw et al. (1992, 1993) summarized rates in Nova Scotia, where values are typically 0.2 to 0.4 $m \cdot a^{-1}$ but are locally much higher (up to 7.6 $m \cdot a^{-1}$). Recession rates greater than 10 $m \cdot a^{-1}$ (during a 4 month open-water season) are documented for the Beaufort Sea coast. Although increased rates of bluff retreat may result from sea-level rise, we must be careful when simply extrapolating retreat rates because erosion may be temporarily halted by the accumulation of coarse debris at the base of cliffs (see below).

Bedrock coasts erode more slowly than other types and, as a rule, would suffer commensurately few problems due to accelerated sea-level rise. However, cliffs in poorly consolidated rocks such as the sandstone of Prince Edward Island can be expected to show increased erosion. Other areas with a soft rock coast include the gulf coasts of New Brunswick and Nova Scotia, parts of Vancouver Island, and islands in the western portion of the Canadian Arctic Archipelago.

Response of complex coasts to sea-level rise

On the Canadian coastline, highly contrasting coastal environments are commonly juxtaposed to form a complex mosaic whose reaction to rising sea level is more difficult to predict. Eroding glacial deposits supply heterogeneous sediment to the littoral system, often resulting in a predominance of gravel beaches. The response of such beaches to sea-level change is poorly understood (Forbes and Taylor, 1987; Carter et al., 1987, 1989, 1990a, b; Forbes et al., 1989, 1991b; Orford et al., 1991a, b, 1992). Their sediment supply is typically intermittent and cyclic, as local glaciogenic sources are successively exposed, eroded, and exhausted. In Atlantic Canada we can observe partly or wholly submerged, prograded gravel strand plains which formed in the last several thousand years, despite rising sea level. It has been argued (Shaw et al., 1990) that these formed when a sediment excess occurred in the littoral system, either because of erosion of glacial deposits or due to breakdown of earlier barrier systems. The implication is that, with rising sea level in the future, we might expect coastal progradation to occur, at least in some areas (Forbes and Shaw, 1992; Forbes and Syvitski, 1994).

An important assumption of the foregoing argument is that coastal evolution during the past several thousand years has been forced by steadily rising sea level. In the case of Atlantic Nova Scotia this has occurred at a long-term rate of ~ 2 mm·a^{-1} since 5000 BP (cf. Shaw et al., 1992, 1993). However, rates of sea-level rise indicated in tide-gauge records of the past century are well in excess of this figure (Carrera and Vaníček, 1988), from which it must be inferred that rates can vary. There is evidence from elsewhere that this is so. For example, four phases of "transgression" or, more precisely, periods of high storm flood frequency, occurred on the Friesland (Netherlands) barrier coast in the past two millennia (Bakker, 1981). Also, van de Plassche (1991) argued that during the late Holocene transgression in Connecticut, U.S.A., intervals of rapid and slow mean high water (MHW) rise were interspersed, and rapid transgression occurred five times in the past 2000 years (the latest phase began 200 years ago). In another study, Tanner (1992) claimed to have found evidence in the Gulf of Mexico of three drops and two rises of sea level in the past 3.5-3.0 ka, with amplitudes of 1-2 m. He wrote that the most recent oscillation corresponded with the Little Ice Age and that the current sea-level rise is the recovery from a lowstand during that period.

Is there evidence of comparable sea-level fluctuations in Canada? Grant (1980, 1985) argued that during the past 3000 years the Holocene transgression was interrupted at least four times by regressions on the Tantramar Marsh, on the New Brunswick-Nova Scotia border. If the transgression along the Atlantic coast of Nova Scotia was episodic, then perhaps the coast prograded in some areas during pauses in the transgression, forming strand plains. From this it follows that with accelerated sea-level rise, erosion and coastal retreat may become pervasive.

To see the response of a complex, glaciated coast to sea-level rise, some of the processes occurring in the present transgressive phase on the Atlantic coast of Nova Scotia must be noted. Relative sea level in this area has been rising during this century at a rate approaching 4 mm·a^{-1}. At Chezzetcook Inlet, a large estuary 30 km east of Halifax, barrier beaches in the outer estuary have been migrating landward at a rate up to 8 m.a^{-1}, while adjacent headlands have been retreating up to 7 m·a^{-1} (Carter et al., 1990a, b; Forbes et al., 1990, 1991b; Orford et al., 1991a; Shaw et al., 1992, 1993). Nevertheless, expanding flood deltas have enabled estuary infilling to keep pace with sea-level rise, transforming *Zostera* mud flats into *Spartina* marshes in the middle estuary zone (Jennings et al., 1993). It is evident, therefore, that in many cases sea-level rise will probably result not just in more erosion, inundation, and beach migration, but also in other mitigating effects. However, it is important to note that this estuary is now at a critical phase in its development. The outer barrier, Story Head Beach, is about to disintegrate. If this happens, the estuary will experience a catastrophic reorganization: high wave energy may reach into formerly quiescent areas, and gravel from the old barrier may form the nucleus of a new barrier system farther landward.

Assessing the sensitivity of the Canadian coast to sea-level rise

How is the sensitivity of the entire coast to sea-level rise best assessed? Before answering this question, we must make it clear that by sensitivity we mean the likelihood that physical changes will result. This contrasts with the views expressed in the report by the Coastal Zone Management Subgroup of the Intergovernmental Panel on Climate Change (Luitzen et al., 1992) which lists susceptibility to physical changes as one of three aspects of the sensitivity of a nation's or region's coastline to accelerated sea-level rise. The other aspects are the impacts of physical changes on socio-economic and ecological systems, and the capability of a region or country to manage or alleviate impacts.

The usual approach to this kind of question is to examine what has been done. We studied some of the works completed in the past decade. Many have been local in scale, including, for example, those by Titus and Barth (1984) of the Galveston and Charleston areas, or Titus at al. (1985) on Ocean City, Maryland. Environment Canada has published reports (e.g. P. Lane and Associates, 1988) on the impact of a 1 m sea-level rise at several cities in eastern Canada, and Stokoe et al. (1990) forecast impacts on coastal communities in the Atlantic Provinces. Other local studies are cited in Gornitz (1991).

Studies on a regional scale include the document by Boorman et al. (1989) who considered the effects of a rapid 0.8 to 1.65 m sea-level rise on the coastline of Great Britain. The impacts included changes in mud-flat and salt-marsh vegetation, in bird populations, and in beaches and dunes. The areas thought to be most sensitive were defined primarily by relief; they comprised the low-lying coastal wetlands and adjacent 'paramaritime' zones such as the Norfolk Broads. For Canada, Egginton and Andrews (1989) mapped those parts of the coast which are submerging, and those which would submerge with rates of 0.4 and 0.6 m per century added to present trends. Forbes et al. (1989) examined possible impacts in eastern Canada and showed that on a glaciated coast the factor of sediment supply has to be considered because sediment added to the littoral system due to erosion can counteract coastal retreat due to rising sea level.

An example of a more systematic approach is that used by Carter (1990) who, on 1:260 000 scale survey maps, identified those parts of the coast of Ireland which were at risk from flooding, erosion, ecological change, and storm damage. He compiled a coastal database containing information on attributes such as shoreface slope, coastal features, coastal structures, access, and land use, and used it to calculate a coastal sensitivity index. This arguably is the best way in which to map the sensitivity to sea-level rise of a coastline as large as that of Canada. We have adopted this kind of approach.

Sensitivity index

To assess objectively the sensitivity of the Canadian coastline to inundation, erosion, and other processes which might result from accelerated sea-level rise, we use a method adapted from that of Gornitz and Kanciruk (1989), Gornitz (1990, 1991), and Gornitz et al. (1991). These authors used a "coastal vulnerability index" which combined data on seven variables as follows: *relief* and *vertical land movements* were considered indicators of inundation risk; *lithology* and *coastal landform* were associated with resistance to erosion; *rates of erosion* were considered indicators of sensitivity to coastal processes; and *wave energy* was related to the capacity for erosion. It was argued that *tidal range* was linked to both inundation and erosion hazards. In general, a region of low relief and unconsolidated sediments, where a barrier coast is exposed to high tidal range and high wave-energy levels, and where relative sea level is already rising rapidly, will yield a high sensitivity index. A low index will result where relief is high, bedrock is hard, the coast is rocky and non-eroding, sea level is falling, tidal range is low, and wave energy is at a minimum.

This method yields numerical data which cannot be directly equated with particular physical effects. We would argue, however, that it does highlight those regions where the various effects of sea-level rise may be greatest. The map of sensitivity levels, when augmented with supporting text, can offer an overview of the nature and extent of problems that will result from a relative sea-level change of the predicted magnitude.

Calculating the sensitivity index

The sensitivity index (SI) incorporates seven variables, each of which is assigned a value in the range 1 to 5 (Table 1). The variables are calculated for individual 1:50 000 scale NTS sheets. Each map sheet covers an area which has a north-south length equivalent to 0.25 degrees of latitude. However, the east-west width of each map sheet is 0.50 degrees of longitude south of 68°N, 1.0 degree of longitude between 68°N and 80°N, and 2.0 degrees of longitude north of 80°N.

$$SI = \sqrt{((a_1 \times a_2 \times a_3 \times a_4 \times a_5 \times a_6 \times a_7)/7)}.$$

The variables, each allocated a score of 1-5 (Table 1) are listed as follows:

a_1 = relief
a_2 = rock type
a_3 = coastal landform
a_4 = sea-level tendency
a_5 = shoreline displacement rate
a_6 = mean tidal range (higher tides)
a_7 = mean annual maximum significant wave height

To avoid confusion with the coastal vulnerability index (CVI) of Gornitz and co-workers, which results from a slightly different method of scoring some variables, we use the term sensitivity index (SI).

A relief score was obtained by calculating the average elevation of points at a three minute latitude-longitude grid spacing, obtained from the ETOPO-5 Gridded World Elevations data file, aggregated into cells corresponding with NTS sheets that contain coastline. Scores between 1 and 5 were allocated, with areas of mean elevation above 30 m scored as 1 and <5 m as 5 (Table 1). This is an unsatisfactory method, for several reasons but was used because the database was available. NTS map sheets vary in longitudinal extent. Thus, the maximum number of grid points used to calculate average elevation can be 65, 125, and 245 respectively. Also, the mean elevation generally increases with the amount of land in the NTS sheet, and does not truly reflect relief close to the coast.

Bedrock lithology influences the risk of erosion in coastal areas (Gornitz and Kanciruk, 1989; Gornitz, 1990, 1991). At one end of the scale (score 1) are hard granites, gneisses, and volcanic rocks. Areas in which unconsolidated sediments

Table 1. Ranking of coastal sensitivity index variables for Canadian coasts, adapted from the coastal risk classes of Gornitz (1990, 1991), Gornitz and Kanciruk (1989), and Gornitz et al. (1991).

	Ranking of sensitivity index				
	Very low	Low	Moderate	High	Very high
VARIABLE	1	2	3	4	5
1 Relief (m)	>30	21-30	11-20	6-10	0-5
2 Rock type	Plutonic rocks, high-grade metamorphic & volcanic rocks	Metamorphic rocks	Most sedimentary rocks	Poorly consolidated sediments	Unconsolidated sediments, ice
3 Landform	Fiord, high rock cliffs, fiard	Moderate and low rock cliffs	Beach, unconsolidated sediment over bedrock	Barrier, bluffs, salt marsh, peat, mud flat, delta, spit, tombolo	Ice-bonded sediment, ice-rich sediment, ice shelf, tidewater glacier
4 Sea-level change (cm/100 a)	>-50	- 50 to - 20	-19 to +20	21 to 40	>40
5 Shoreline displacement (m/a)	>+0.1 accreting	0 stable	-0.1 to -0.5 eroding	-0.6 to -1.0 eroding	>-1.0 eroding
6 Tidal range (m)	<0.50	0.5-1.9	2.0-4.0	4.1-6.0	>6.0
7 One year maximum wave height (m)	0-2.9	3.0-4.9	5.0-5.9	6.0-6.9	>6.9

predominate at the coast are scored 5. Glacier ice was also placed in this category. Sources of geological data are cited in the text, which described this variable for the various regions.

The sensitivity of the coast to wind, wave, and tide processes is largely governed by the type of coastal environment present. Owens (1977a) provided an overview of the types of coastal environments in Canada. An essential complement to this work is The Coastline of Canada, edited by S.B. McCann (1980), which gives detailed accounts of a range of coastal environments, and includes coastal classifications for extensive areas, such as the entire British Colombia coast (Clague and Bornhold, 1980). Other sources of data are cited in the text and include reports commissioned as a result of oil exploration and development (see, for example, Woodward-Clyde Consultants Ltd., 1980, 1981; Chevron Canada Resources Limited, 1982), atlases published by Environment Canada on the Beaufort Sea and Lancaster Sound (D.F. Dickens Associates Ltd., 1987; 1990), and Geological Survey of Canada publications such as McLaren (1980) for Labrador, and Cameron et al. (1989) for all of eastern Canada.

In a departure from Gornitz's method, coastal landform categories are organized slightly differently (Table 1). Rocky coasts fall into categories 1 and 2, and beaches and bluff coasts consisting of unconsolidated sediment overlying bedrock are in category 3. The bulk of coastal types that are deemed sensitive to rising sea level are in category 4. This group includes barriers, beach-ridge plains, salt marshes, deltas, mudflats etc. Finally, in recognition of the special sensitivity to rising sea level of landforms in Canada's northern areas, we introduce category 5. This comprises ice shelves, tidewater glaciers, and ice-bonded unconsolidated sediments occurring in bluffs.

Vertical land movement is an important indicator of risk of inundation. Rates of relative sea-level change, based on tidal data from stations on the Canadian Atlantic and Pacific coasts, are taken from Carrera et al. (1990). Where tidal data are unavailable, sea-level trends are derived by extrapolation of trends over the past two millennia on published radiocarbon curves (cited in the text). As noted earlier, these rates may differ from those determined from tide-gauge data. Carrera and Vaníček (1988) showed that for Charlottetown, Halifax, and Yarmouth, sea-level trends observed on tide gauges averaged 0.1 m/century greater than the long-term trends.

Shoreline displacement is a difficult parameter to determine, because erosion is commonly restricted to small parts of an otherwise stable coast, and so few sites have been monitored. The scoring system differs from that used by Gornitz and her co-workers because some coasts (Prince Edward Island, for example) experience extensive, persistent erosion, but at average rates less than 1 $m \cdot a^{-1}$. In the original scheme, these areas would be put in the same category as stable, bedrock-dominated coasts. Most rocky coastlines have been assigned a rate of 0 $m \cdot a^{-1}$, although very slow recession commonly occurs.

The geographic variation of Canadian coastal environments raises some problems with the methodology of assessing erosion. In the Arctic, coastal erosion occurs entirely during the open-water season of 3-4 months or less. Therefore, averaged annual rates of erosion are somewhat misleading when compared with similar rates from more temperate regions. It could be argued that the erosion rate in the Arctic should be based on a normalized year which has been corrected for the length of time open water processes are acting. In the Beaufort Sea region this would result in a tripling of the calculated cliff retreat rates based on yearly averages. This would be especially important in areas where sea-level impacts range between moderate and severe. In the interests of simplicity, we have not altered the method in this manner, but it is important to note this phenomenon when attempting to compare the results of the method in widely disparate geographic locations.

The index of tidal range used is the mean range (large tide), as published in the Canadian Tide and Current Tables (Canadian Hydrographic Service, 1992).

The value for wave height used for the Atlantic, from southwestern Nova Scotia to southern Baffin Island, is the largest annual significant wave height, and is based on 11 years of wave-chart data (Neu, 1982). These values neglect the effects of refraction and shoaling in the coastal zone, which can be important in large bays. Depending on exposure, the inner parts of such bays have been assigned wave levels that would score either 1 or 2 in Table 1. A serious difficulty has been the lack of wave data for the Pacific coast which is strictly comparable to Neu's (1982) data set for the Atlantic. Data in Brown et al. (1986) suggest that the outer coast has maximum annual significant wave heights considerably in excess of 7 m. The outer coasts of the Queen Charlotte Islands and Vancouver Island have therefore been given a high (5) ranking for wave-energy levels. It is difficult to apply the scoring system to the remainder of such an intricate coast. Most of the mainland fiord coast has been given a very low score. The coasts of Hecate Strait, Queen Charlotte Sound, Queen Charlotte Strait, Strait of Georgia, and Juan de Fuca Strait have been scored as moderate. Parts of these large regions may have lower wave-energy levels, and other parts may have higher. For example, Brown et al. (1986) showed 1% exceedence for combined wave heights (broadly equivalent to significant wave heights) greater than 6 m close to the mainland coast in Queen Charlotte Sound.

Assigning a score for wave energy in the Arctic poses problems, because of the extent of sea ice. Accordingly, the region has been allocated a score of 1 for wave energy, except for Hudson Bay and the Beaufort Sea coasts which have been scored 2. The southeast coast of Baffin Island, which is exposed to Atlantic wave processes and which has a longer period of open water than other parts of the Arctic, has been assigned scores based on Neu (1982).

COASTAL IMPACTS OF SEA-LEVEL RISE IN CANADA

A total of 2899 NTS map sheets was used to calculate coastal sensitivity to sea-level rise. In several cases, where extreme contrasts existed between two parts of a sheet in terms of coastal type, two indices were calculated for the same sheet.

The distribution of index values is shown in Figure 1b. They range from 0.8 to 57, with a strong mode in the 2 to 4 interval. The 25th, 50th, and 75th percentiles are 2.3, 3.8, and 5.9 respectively.

On the map the scores are grouped into three categories: less than 5 (low sensitivity), 5-15 (moderate sensitivity), and greater than 15 (high sensitivity). This was preferred to a percentile-derived categorization, and was based on calculations using low, moderate, and high combinations of the input parameters. On this basis, most of the coast (67% of the total NTS map sheets) falls into the low sensitivity category, 30% is moderately sensitive, and 3% is highly sensitive.

Figure 2 (in pocket) serves only to focus on the relative sensitivity of the coastline. An understanding of the nature and degree of predicted impacts requires discussion. The classification of coastal environments by Owens (1977a) provides a convenient framework for this purpose. The environments are defined on the basis of "...the physical processes that act on the shoreline, and on the geology and relief of the coastal zone" (p. 6). Owens' classification takes into account coastal landforms, and therefore delineates broad areas with similar characteristics and correspondingly similar susceptibility to impacts. Three large regions are defined: the Atlantic, Pacific, and Arctic coasts. These are subdivided into 25 subregions. These groupings are shown in graphical and tabular form in Figure 2. The distribution of sensitivity scores by regions is shown in Figure 3. The predicted impacts are discussed below.

Impact on Atlantic coastal environments

The Atlantic coast has a length of 45 369 km, which is 18.6% of the Canadian coastline. Sea-level rise could have serious ramifications for this large region for several reasons. Firstly, all of the coast of Nova Scotia and Prince Edward Island, and much of the coast of New Brunswick and Newfoundland, are submerging, largely due to continuing effects of deglaciation. Secondly, large parts of Atlantic Canada's coastline consist of environments which are sensitive to sea-level rise: salt marshes, barriers, estuaries, intertidal flats, and unconsolidated bluffs. In this region a significant proportion of the Canadian population lives close to the coast in communities ranging from small coastal settlements to cities such as Québec, Saint John, St. John's, Halifax, and Charlottetown. Rising water levels in urban areas could have an impact on a wide range of human structures and activities.

Labrador and outer Newfoundland

This region comprises the southern and eastern coasts of Newfoundland, from Cabot Strait to the Strait of Belle Isle, and the Labrador coast between the Strait of Belle Isle and Cape Chidley (Fig. 4a, b). In Newfoundland the relief is moderate to high, and resistant metamorphic and intrusive rocks predominate (Forbes, 1984; Colman-Sadd et al., 1990). Along the Labrador coast areas of high relief are common (McLaren, 1980), especially in the north, and include the Kiglapait Mountains (850 m), the Kaumajet Mountains (> 1200 m), and the Torngat Mountains (1600 m). South of Lake Melville the rocks in coastal areas are typically metasedimentary granitoid gneisses. From Lake Melville to Nachvak Fiord, granitic and granodioritic gneisses predominate, and highly metamorphosed rocks of the Churchill Province occur farther north (Greene, 1970).

The region is mesotidal, and wave-energy levels are high along the outer coast. High wave-energy levels in Labrador are inhibited by ice, and furthermore, strong wave-energy gradients from outer to inner coast occur (Rosen, 1980). Winter and Spring pack ice also occurs along the northern and eastern coasts of Newfoundland. Tide-gauge data (Carrera et al., 1990) indicate submergence on the southern and southeastern coasts of Newfoundland (+3.75 and +1.93 $mm \cdot a^{-1}$ at Port aux Basques and St. John's respectively) but sea level is probably stable on the northern coast of the island, close to the Strait of Belle Isle. Tidal data are insufficient to determine present trends of mean sea level in Labrador. Andrews (1989a) cited a 5 $m \cdot ka^{-1}$ rate of emergence for Nain, but speculated that erosion of archaeological sites on the outer coast indicated a rising sea level in that area. Sea-level curves suggest that emergence is occurring in Labrador, as a result of continuing crustal recovery. The rates of mean sea-level change (in $mm \cdot a^{-1}$) (Clark and Fitzhugh, 1987, 1990, 1991) are as follows : -1.7 at Groswater Bay, -1.6 at Okak, -2.5 at Nain, -3.6 in the Goose Bay area, and -1.3 in the Strait of Belle Isle region. Emergence rates are lower along the outer coast.

The coastlines of this region are predominantly rocky and stable, although small-scale erosion of bluffs occurs in many areas. Our assessment shows that most of this region would not be highly impacted by sea-level rise: sensitivity scores are generally low, with a few areas of moderate and high sensitivity. They range from 0.9 to 23 (n=205), with a mean of 4.3 and a strong mode in the 2-4 range.

Newfoundland: Cabot Strait to head of Fortune Bay

This fiord coast (Fig. 5) has a low sensitivity to rising sea level. Increased erosion may occur near Burgeo, where coastal dunes are eroding and a large transgressive barrier may move landward at an accelerated pace. Parts of the Hermitage region are moderately sensitive, particularly where raised marine terraces (Tucker et al., 1982) are exposed in coastal bluffs. Higher rates of bluff erosion will probably occur here, accompanied by changes to the beaches and barriers which receive sand and gravel from this source. Settlements wholly or partly located on beach deposits, at Harbour Breton and English Harbour East, will have an increased risk of inundation compared with the situation today.

Newfoundland: Burin Peninsula to Bonavista Bay

This coast has a predominantly low sensitivity to sea-level rise. Exceptions include the southwestern coast of the Burin Peninsula, where glacial materials are abundant (Tucker and McCann, 1980). Rapid retreat of bluffs near Grand Bank already threatens the coastal highway, and sea-level rise would exacerbate this condition. Farther north on this stretch of coast, reworked glacial deposits have accumulated in

Arctic Coasts

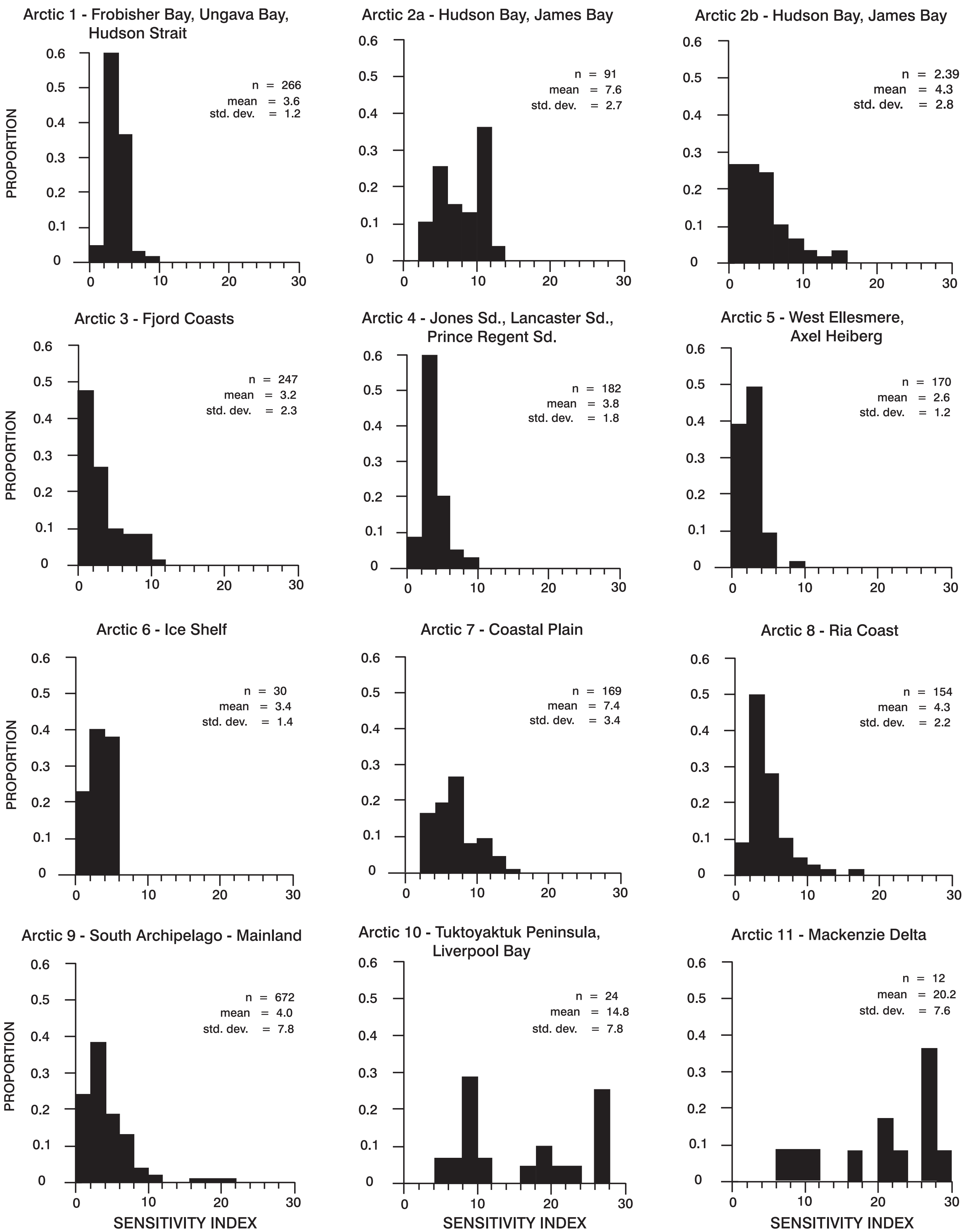

Figure 3. *Histograms showing the distribution of sensitivity scores in Atlantic, Pacific, and Arctic coastal environments. The omissions are Sable Island, covered by one NTS map sheet, and the Yukon coast, with seven map sheets all yielding the same score.*

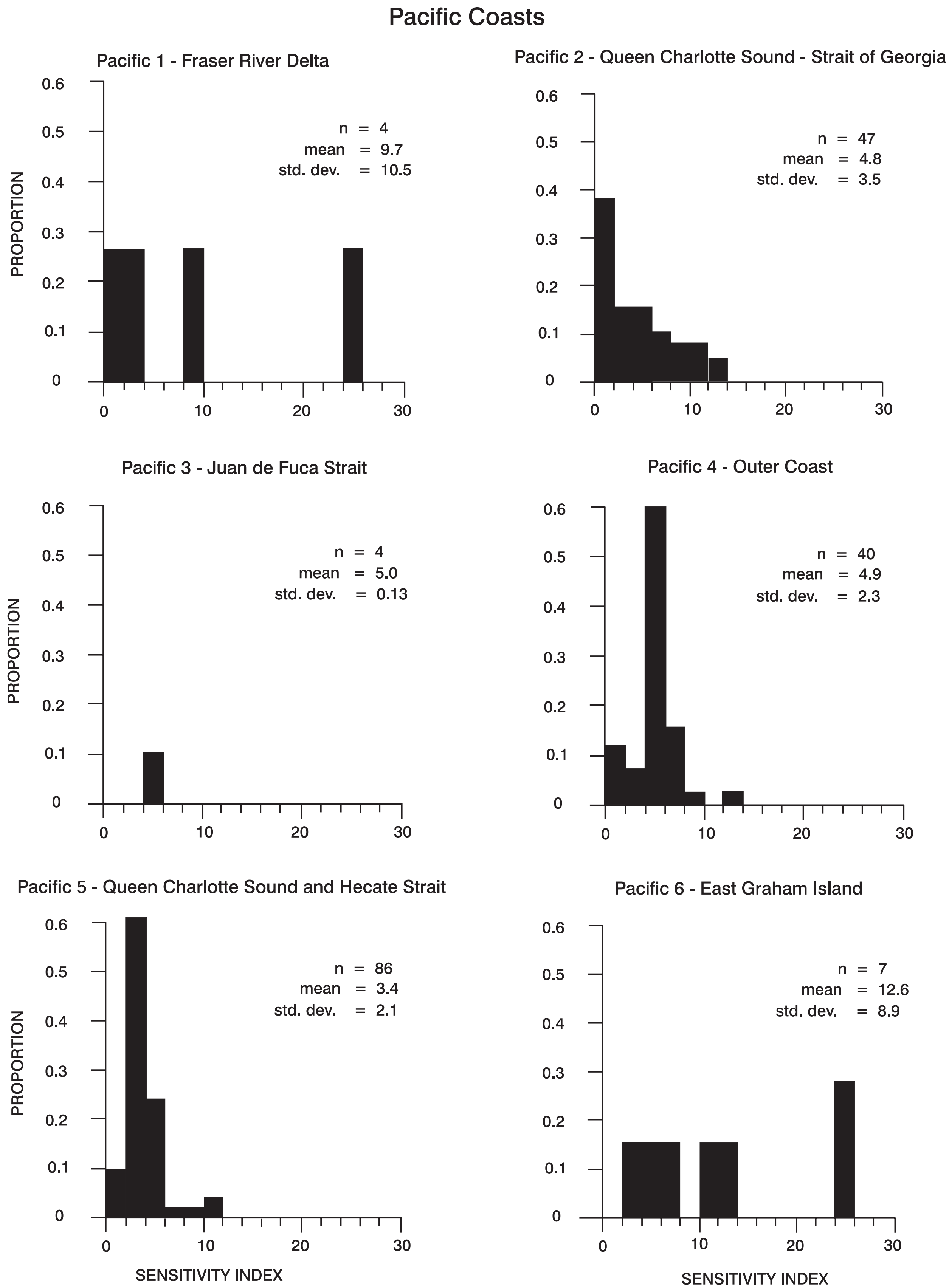

Figure 3. *(cont.)*

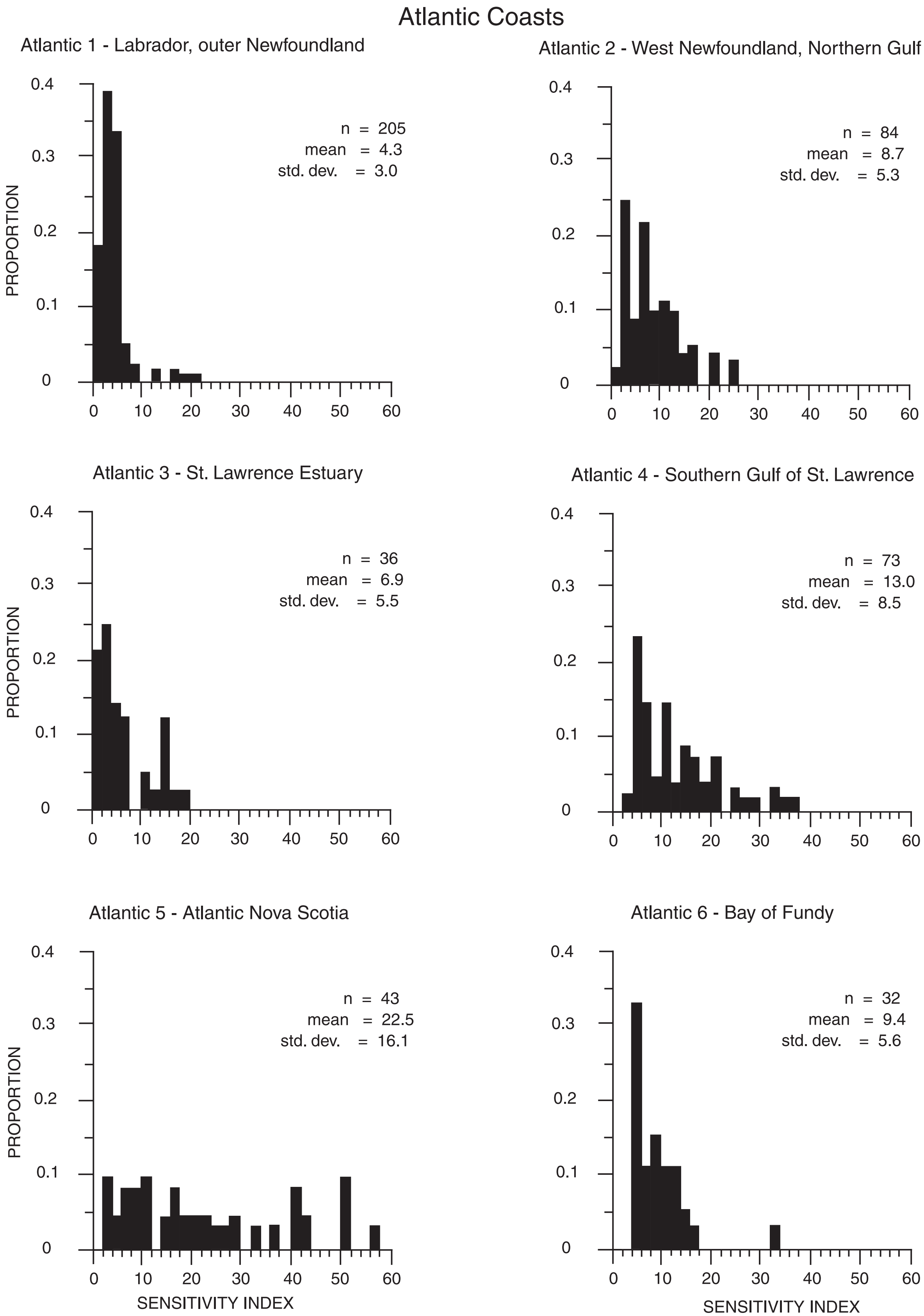

Figure 3. *(cont.)*

transgressive barriers such as that at Grand Beach (Forbes, 1984). These barriers may be subject to more frequent overwash and more rapid landward movement with higher sea levels.

The distribution of glacial sediments exerts a strong control upon the character of the coast throughout Newfoundland. Thick glacial sediments generally occur well inland, and coastal regions are usually sediment-deficient (Liverman and Taylor, 1990). Barriers and strand plains are usually located near glacial deposits (Shaw and Forbes, 1987; Shaw et al., 1990) and are at risk from sea-level rise, but are typically too small in extent to influence the scores at that scale. A typical example is the strand plain at Frenchman's Cove on the Burin Peninsula, where a settlement and a provincial park occupy much of a complex of prograded gravel beach ridges partly covered by freshwater marsh and woodland (Shaw and Forbes, 1987). Rising sea level would inundate the low-lying beach ridges which fringe the lagoon. The settlement may be cut off from the mainland by two other effects: 1) destruction of the narrow neck in the southwestern part of the barrier by runup during storms, and 2) more rapid landward migration of the narrow, north-facing transgressive sand and gravel barrier which links the beach-ridge plain to the mainland.

The Placentia strand plain (Forbes, 1985; Shaw and Forbes, 1987; Forbes et al., 1989) is a sensitive site. The earliest gravel beach ridges, at the back of the barrier, are extremely low-lying, and only remain above MHW because the tidal range behind the barrier is reduced due to constriction of tidal flow (Shawmont Martec Ltd., 1985). The site has become more urbanized in recent years and, at present, parts of the town are flooded whenever high tides and heavy rains coincide. This condition would be aggravated by sea-level rise, which may also increase rates of erosion at several nearby sites. For example, erosion of till bluffs now threatens the lighthouse at Point Verde (however, quarrying of an adjacent gravel pit also puts the lighthouse at risk!).

Another group of susceptible landforms comprises the bayhead barriers on the Avalon Peninsula (Shaw and Forbes, 1987). In an earlier phase these were prograded strand plains; subsequently, the oldest (> 1.2 ka), lowest beach ridges have been submerged in lagoons. Further sea-level rise will flood the remaining ridges, and the barriers may be transformed into high, single-ridge, gravel storm beaches which could move landward as a result of more frequent overwashing. In some situations, as at Portugal Cove South (Shaw et al., 1990), coastal highways will be threatened.

The high gravel barrier that spans Holyrood Pond is the largest in the region and is highly at risk. Holyrood Pond is a deep fiord basin, and the high sand and gravel barrier sits on a bedrock sill, fed by extensive eroding glacial bluffs (Forbes, 1984, Forbes and Taylor, 1987; Shaw et al., 1990). The barrier is occasionally overwashed when high, long-period, storm waves approach from the south-southeast (Forbes, 1985). Parts of the settlement are flooded, and traffic on the coastal highway is disrupted. Coastal protection works have been erected and further work must be done if this problem becomes exacerbated due to sea-level rise. Areas at some risk on the north side of the Avalon Peninsula include bluffs in southern Conception Bay, low-lying communities in Conception, Trinity, and Bonavista bays, and the gravel barrier complex at Bellevue Beach (Trinity Bay), which is the site of a provincial park.

Newfoundland: Cape Freels to the Strait of Belle Isle

The region between Cape Freels and Hamilton Sound ranges from highly to moderately sensitive. The coastline contains a dune-ridge foreland, overwashed sandy barriers, and coastal dunes (Shaw and Forbes, 1990a). These deposits formed in their present positions as early as 4000 BP, when relative sea level stabilized at a level just below that of today. The coastline is undergoing rapid change, possibly as a result of a recent trend of rising relative sea level; an accelerated rise of sea level would increase rates of coastal retreat and the frequency of overwashing. The most threatened part of this region is at Cape Freels, where a large double tombolo barrier is anchored to a small bedrock island. Ruffman et al. (1991) documented newspaper reports of a northeasterly storm that overwashed the tombolo in 1947, isolating the settlement. The possible disintegration of this barrier and the reorganization of the immediate coastline would result in the destruction of paleo-Indian archaeological sites described by Tucker (1984).

North of Cape Freels, close to the settlement of Musgrave Harbour, the large peat-covered beach-ridge foreland at Man Point is being eroded rapidly, exposing truncated beach ridges on the foreshore (Shaw and Forbes, 1990a). Littoral drift of the mobilized sand is towards the northwest, and prograded beach ridges have recently formed in Ragged Harbour cove. The accelerated destruction of the foreland due to rising sea level may result in further progradation at the end of the littoral drift pathway (in Ragged Harbour), showing that in some coastal settings at least, sea-level rise will stimulate the formation of new beach systems. Low-lying areas and port facilities in Bay of Exploits (Botwood and Lewisporte) are among the sites in this area that may be sensitive to sea-level rise.

Labrador: Blanc-Sablon to Groswater Bay

Despite high wave-energy levels, the coast in this region has low sensitivity to impact from sea-level change on account of residual crustal recovery, high relief, and a rugged hard rock coast.

Labrador: Groswater Bay and Lake Melville

This region shows great variation in sensitivity, reflecting inter-regional variations in wave energy levels, tides, mean sea-level trends, and coastal landforms (Reinson et al., 1979). The present trend of slow emergence would be reversed if sea-level rise were to occur. The exposed unconsolidated coasts at the mouth of Groswater Bay, at Byron Bay, and Trunmore Bay have a score of 16, in the high range. These areas contain extensive tracts of prograded beach and dune ridges, and coastal dunes fronted by broad dissipative beaches which are fully exposed to Atlantic wind and wave processes during the six month open water season. Rapid sea-level rise would probably initiate coastal retreat, despite the continued delivery of fluvial sediment, and increased instability in the coastal dune belt.

Higher sensitivity indices pertain to the embayed lowland coasts of Groswater Bay. Although wave energy is low compared with the outer coast, sea-level rise could inundate the extensive tracts of coastal marsh, salt marsh, and delta lowlands here. The sheltered rocky coasts of The Narrows, in the vicinity of Rigolet, have low sensitivity indices, but somewhat higher values are associated with the Lake Melville region, as a result of the widespread occurrence of coastal marshes, deltas, sandy beaches, spits, and bluffs of unconsolidated sediments. The sensitivity of this region is mitigated by low tidal range, low wave-energy levels, and continued crustal emergence.

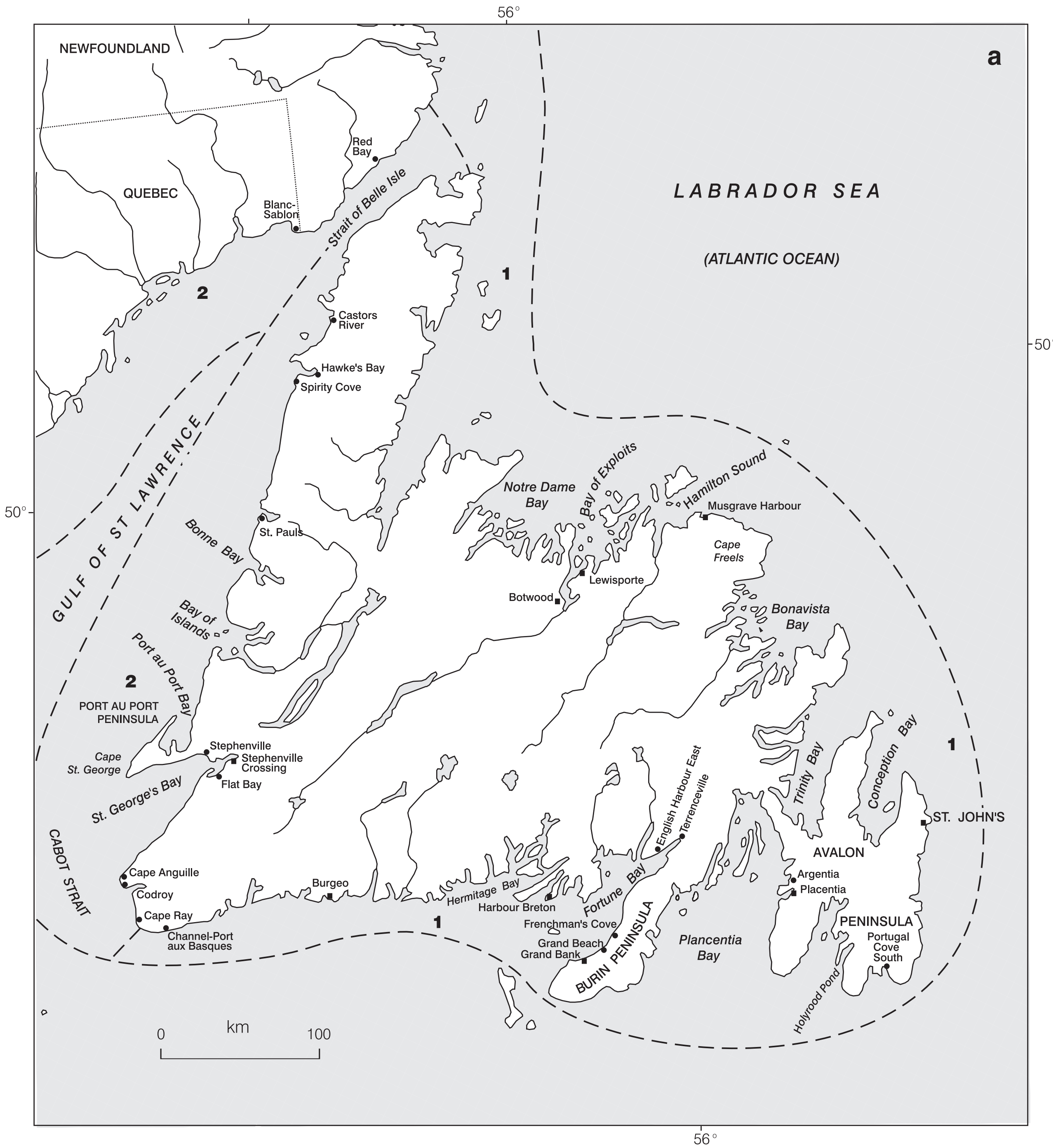

*Figure 4. Maps of the coasts of Newfoundland (**a**) and Labrador (**b**). The limits of Atlantic coastal environments 1 and 2 within the map area are indicated (dashed line).*

Labrador: Cape Harrison to Nutak

This region is relatively insensitive to the effects of sea-level rise and scores are mainly in the low range. However, some scores in the moderate range occur, largely because of the more frequent occurrences of unconsolidated shores here (McLaren, 1980) than elsewhere in Labrador. Bouldery intertidal flats and boulder barricades comprise distinctive shoreline types which occur throughout Labrador, in northern and western Newfoundland, on the Quebec shore of the Gulf of St. Lawrence, Ungava Bay, and Baffin Island, in moderate- and low-energy environments (Fig. 6). It is uncertain whether these coastal landforms generated by ice processes (Rosen, 1980) will aggrade sufficiently to keep pace with sea-level rise.

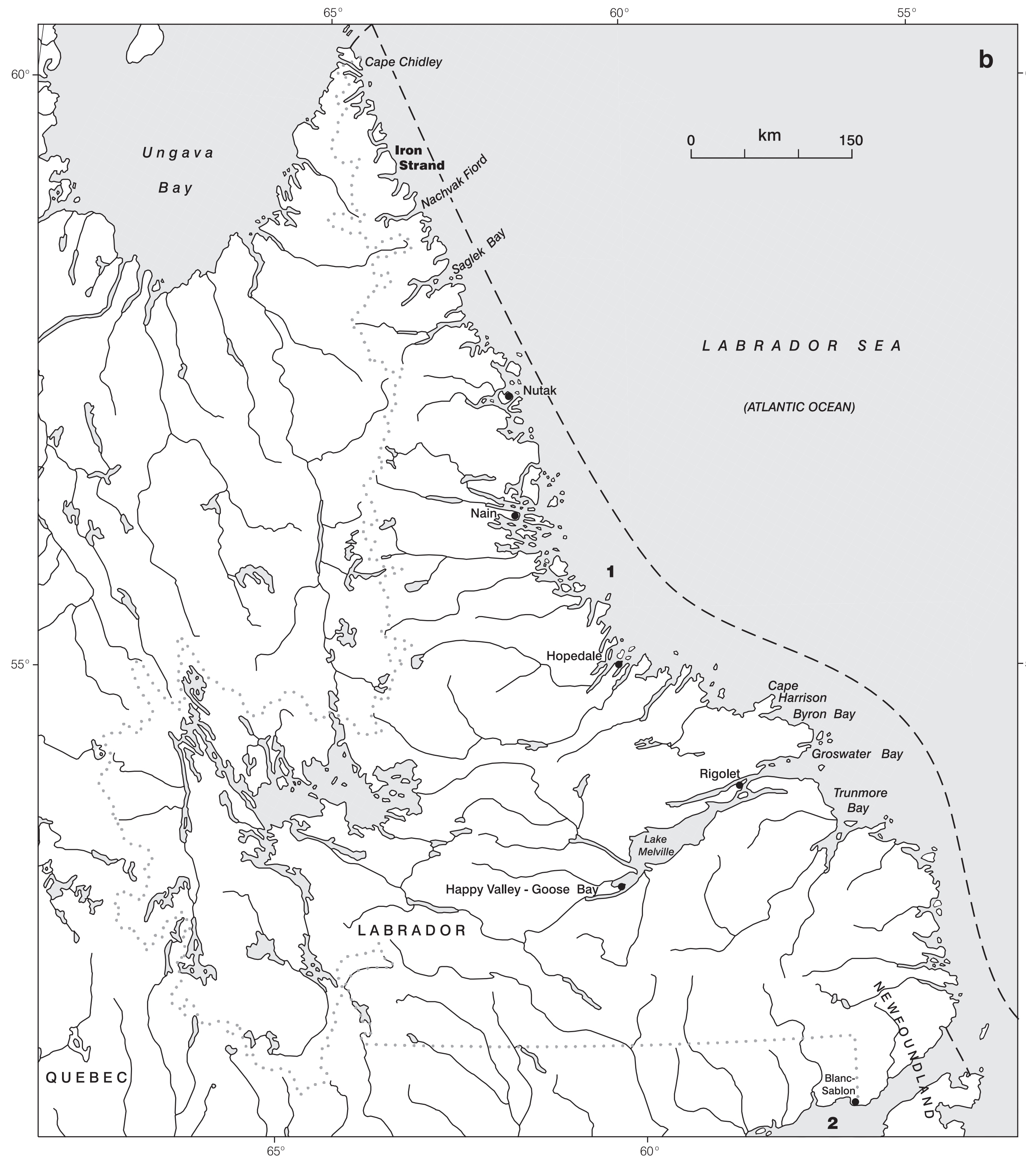

Figure 4. *(cont.)*

Figure 5.

La Hune Bay, southeast of Burgeo on the south coast of Newfoundland. The steep, bedrock fiord sidewalls of Devonian granite reach an elevation of 300 m. This is typical of the low-sensitivity fiord coasts of the island. Note the absence of beaches. Photograph by D.L. Forbes, 9 August 1981. GSC 1995-287

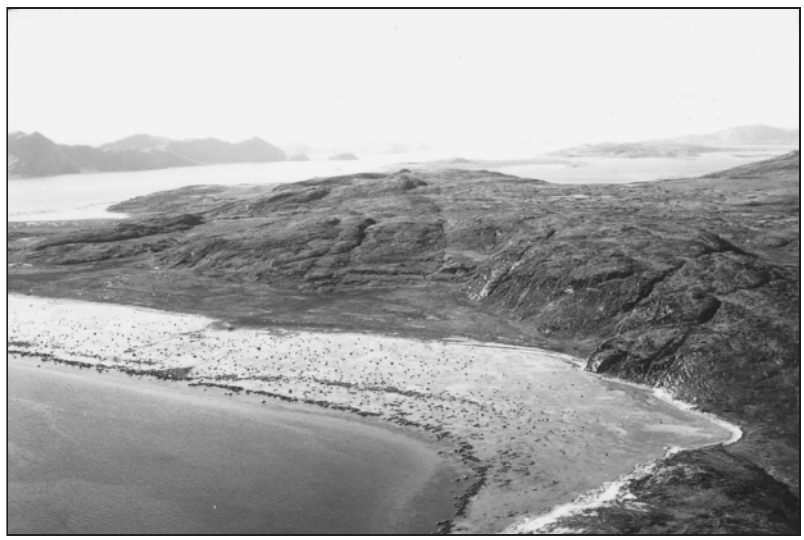

Figure 6.

Wide intertidal flats with a boulder barricade, South Aulatsivik Island, near Nain, Labrador, from McLaren (1980). The hills in this view rise to slightly over 400 m. GSC 203475-X, dated 14 September 1977. Overall this area has been assigned a low sensitivity score, but this type of environment may be somewhat sensitive.

Labrador: Nutak to Cape Chidley

The coast north of Nutak, including the fiord coast north of Saglek Bay, has low sensitivity scores because of a high-relief, hard-rock coastline (Fig. 7), and continued coastal emergence. One exception is Iron Strand (score 16.0) where unconsolidated coastal forelands, barriers, deltas, beaches, and lagoons are located on the exposed outer coast. Coastal erosion and barrier retreat would result from rising sea level, and an additional hazard would be posed by an increase in the duration of open water beyond the present six months. Numerous small deltas in the region, such as that of Nakvak Brook in Saglek Fiord, could be inundated if the rate of sea-level rise were to exceed the current rate of emergence. Extrapolation of the data taken from Clark and Fitzhugh (1987, 1990, 1992) suggests that emergence is 2.0 $mm \cdot a^{-1}$ at the head of Saglek Fiord, but almost zero on the outer coast and in the Cape Chidley area.

Western Newfoundland and northern Gulf of St. Lawrence

This region comprises the gulf coast of Newfoundland and the mainland coast of the Gulf of St. Lawrence, from Pointe-des-Monts to Blanc-Sablon. In western Newfoundland both moderate and high relief occur. Rocks comprising an overlap sequence of post-Ordovician age occur in the southwest, and weakly metamorphosed sediments of Cambrian to Middle Ordovician age outcrop in the northern part of the Great Northern Peninsula. Bedrock is largely concealed by glacial deposits in several areas, principally in St. George's Bay, and on parts of the Great Northern Peninsula. The northern gulf coast is an area of moderate to high relief, underlain by hard crystalline rocks.

The gulf coast of Newfoundland is mesotidal; on the mainland coast the range of large tides increases from 1.2 m at Red Bay, in the Strait of Belle Isle, to 2.2 m at Harrington

Figure 7.

Steep rocky coast with low sensitivity to sea-level rise: Finger Hill Island, Kaumajet Mountains, Labrador. The cliffs rise to 825 m (McLaren, 1980). GSC 203476-A, dated 14 September 1977.

Harbour, and 3.7 m at Sept-Îles. The Port-aux-Basques tide-gauge data indicate a current sea-level rise of +3.75 $mm \cdot a^{-1}$ according to Carrera et al. (1990), or +3.05 $mm \cdot a^{-1}$ according to Shaw and Forbes (1990b), and the gauge at Lark Harbour shows a sea-level trend of +2.10 $mm \cdot a^{-1}$. The rate decreases northwards, and the zero isobase is located in the Strait of Belle Isle region. On the mainland coast, sea level is increasing by 1.87 $mm \cdot a^{-1}$ at Sept-Îles but falling by 0.13 $mm \cdot a^{-1}$ at Harrington Harbour (Carrera et al., 1990) . Wave-energy levels in western Newfoundland are lower than along the Atlantic coasts of the island. Annual significant wave heights are in the 6-7 m range (Ploeg, 1971).

The coastal environments of the region are highly diverse, and include fiords, low rock coasts, deltas, coastal bluffs, coastal dunes, barriers, boulder-strewn tidal flats, boulder barricades, and very limited marsh development (Forbes and Frobel, 1986a, b). This diversity is reflected in sensitivity scores which range from 1.6 to 25 (n=84) with a mean of 8.7, and modes in the 2-4, 6-8, and 10-12 class intervals. The distribution of scores is skewed towards high values. The northern gulf coast has low to moderate sensitivity, except where deltaic and modified deltaic deposits occur. These latter areas have scores in the high range. Except for the highly sensitive St. George's Bay area, most parts of the western Newfoundland coast are moderately sensitive to impact, and two areas have low scores.

Western Newfoundland: Cape Ray to Cape Anguille

This moderately sensitive coast has coastal bluffs and dune-covered barriers that are anchored between bedrock headlands and extend across embayments such as the Codroy Valley. A coastal highway runs along the barriers in places. A sea-level rise could increase rates of bluff erosion (already significant in the Codroy area), cause more rapid barrier migration, inundate low backbarrier areas, and destabilize the coastal dunes.

Western Newfoundland: Cape Anguille to Cape St. George (St. George's Bay)

Outer St. George's Bay, bordering the Anguille Mountains and the Port au Port Peninsula, has a high bedrock coast with low sensitivity. However, the largest area of high sensitivity to sea-level rise on the island of Newfoundland lies at the head of this bay. In marked contrast to other parts of the island (Liverman and Taylor, 1990), thick glacial sediments are exposed in 30 m high bluffs (Flint, 1940; MacClintock and Twenhofel, 1940; Brookes, 1974; Grant, 1991). Accelerated sea-level rise could increase rates of coastal retreat, and this would have greatest economic impact in the urbanized area around the regional centre of Stephenville.

Erosion of bluffs by wave action in St. George's Bay (Fig. 8) has injected large amounts of sediment into the littoral system, resulting in large prograded gravel barriers at Stephenville Crossing, Stephenville (Fig. 9), and Flat Island (Shaw and Forbes, 1987, 1990c). These barriers formed over the past two millennia, when sea level was rising at about 1 $mm \cdot a^{-1}$ (Brookes at al., 1985), so that the oldest beach ridges at both sites are very low. The landward beach ridges at Stephenville are visible below the water of the lagoon (Grant, 1975). Parts of these barriers would be permanently inundated by a sea-level rise.

Other parts of the low gravel barriers in St. George's Bay would be more liable to inundation in storms. The salt marshes, which occupy swales on the island, would be especially susceptible. A storm surge in 1933 flooded the settlement of Sandy Point, on Flat Island (Ruffman et al., 1991). Large-scale overwashing of the urbanized Stephenville Crossing barrier occurred in 1951 (Ruffman et al., 1991.), and the gravel beaches which form the isthmus linking Port au Port Peninsula to the mainland were also badly overwashed at this time. Accelerated sea-level rise would increase the possibility of similar events in the future.

Figure 8.

The erosion of these 20 m high coastal bluffs at the head of highly sensitive St. George's Bay, Newfoundland, releases sediment to the littoral system. Rapid sea-level rise could cause more rapid erosion here, but the increased amount of available sediment, perhaps, would allow the large gravel strandplain nearby (at Stephenville) to keep pace with sea-level rise. Photograph by J. Shaw, 13 October 1991. GSC 1995-277A

Figure 9.

Oblique aerial photograph of a gravel strand plain at Stephenville. The ridges formed during the past several millennia and have been partly submerged due to slow sea-level rise. Clearly, future rapid sea-level rise would inundate much of the area in this photograph. Photograph by J. Shaw, 13 October 1991. GSC 1995-277B

Western Newfoundland: Cape St. George to the Strait of Belle Isle

The rocky coasts of the Port au Port Peninsula have low scores. More sensitive areas occur along the southeastern shores of Port au Port Bay, where salt marshes, barriers, *Salicornia* flats, and a freshwater bog are environments susceptible to alteration. Apart from the sheltered fiord inlets of Bonne Bay and Bay of Islands (Forbes and Frobel, 1986b), which have low sensitivity, the remaining coast is moderately sensitive. Threatened areas include the barriers, lagoons, coastal dunes, tidal flats, and marshes at St. Pauls Inlet, rapidly eroding glacial bluffs at Spirity Cove, and eroding coastal bluffs in numerous other locations. Many of these areas are close to the coastal highway. Inundation may threaten small salt marshes in the Castors River area, and intertidal flats at Hawkes Bay. The low-relief northern coast, fringing the Strait of Belle Isle, is developed in carbonate rocks, and is fringed by gravel beaches and wave-cut platforms. Few problems are anticipated in this region should sea level rise.

Northern Gulf of St. Lawrence: Baie-Comeau to Blanc-Sablon, Anticosti Island

This coast (Fig. 10) comprises alternating intervals of contrasting coastal environments (Dubois, 1980, 1984), including rocky coasts, deltas, and constructional forms such as tombolos and spits. Syvitski (1986) described this as eastern Canada's only major deltaic coast. The large delta complexes at Manicouagan River/Outardes Islands; Moisie/Sainte-Marguerite; Magpie/Saint-Jean/Mingan; and Natashquan account for 7% of the coastline. The antecedents of these modern deltas are the lobes of paraglacial deltaic sediments which developed during the retreat of Late Wisconsinan ice (Syvitski and Praeg, 1989). During the Holocene regression,

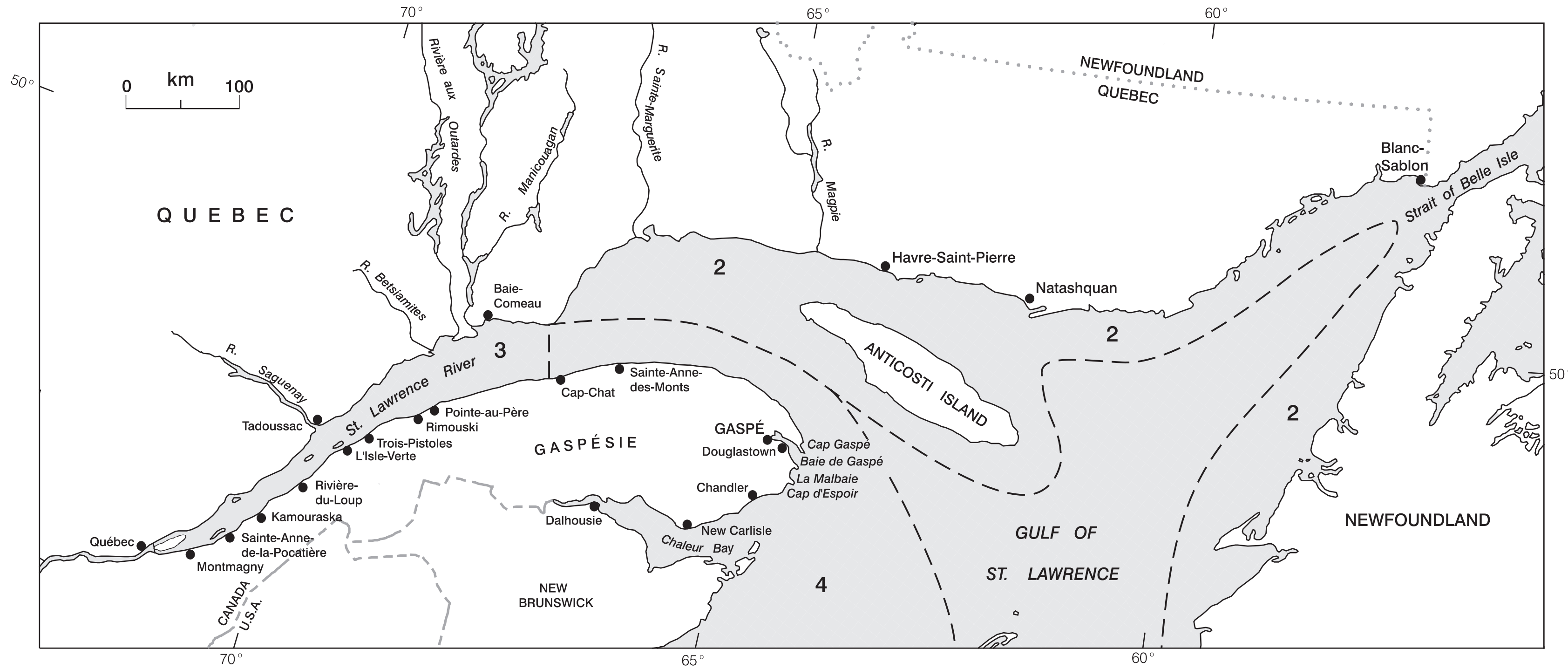

Figure 10. *Map showing the limits of Atlantic coastal environments 2, 3, and 4 (dashed line) in the Gulf of St. Lawrence and the St. Lawrence estuary.*

Figure 11.

Eroding coastal bluffs near Havre-Saint-Pierre, northern shore of the Gulf of St. Lawrence. The bluff is cut into stratified clay (rhythmites) of the Goldthwait Sea, draped by alluvial sand deposited during the Holocene by the Romaine River. Photograph by J.-C. Dionne.

rivers deeply incised the deltas (Sala and Long, 1989), thus providing sediment to the coastline to form prograded beach-ridge complexes. The most sensitive areas in this region are the delta complexes, which are susceptible to inundation and accelerated coastal erosion; coastal bluffs are also susceptible to erosion (Fig. 11). An outcome of the latter process may be an increase in the rate at which heavy mineral placer deposits, such as those described by Hein et al. (1993), are formed in this area.

Anticosti Island is surrounded by a rock platform with a mean width of 500 m. The north shore is a resistant rocky coastline with cliffs up to 120 m high. Along the southern shore, small lagoons, partially or completely enclosed by barriers, occur at the entrances of some rivers. At the entrance to Galiote River, for example, a 3 km long barrier encloses the Grand lac Salé Lagoon. Transverse spits occur on the coastal rock platform and have been studied by Lessard et al. (1989). Most of the island is moderately sensitive; however, several areas are highly sensitive, mainly to accelerated rates of barrier migration.

St. Lawrence estuary

The St. Lawrence estuary (Fig. 10) properly begins at the upper limit of salt-water intrusion, near Québec City, and extends 400 km downstream to Pointe-des-Monts. Tidal range (large tides) is 4.6 m at Pointe-au-Père and 5.8 m at Québec City, upstream of which it decreases. Submergence is occurring along the south shore, at rates of 1.70, 1.05, 0.88, and 0.10 $mm \cdot a^{-1}$ at Saint-François, Québec City, Saint-Jean-Port-Joli, and Pointe-au-Père respectively (Carrera et al., 1990). Sea level is falling along the north coast, at rates of 1.21 and 0.62 $mm \cdot a^{-1}$ at Tadoussac and Baie-Comeau respectively. Wave-energy levels are low, due to fetch restrictions. Shore ice starts to form in late November and by late January most of the estuary is frozen, and remains frozen until late March. The mobile ice is an important geomorphological agent (Dionne, 1987), and ice jams are responsible at times for severe flooding in the upper reaches. The north side of the estuary has resistant, rocky shorelines, with deltas in places east of the Saguenay River. In Charlevoix and on the south shore, wide intertidal mud flats backed by tidal marshes alternate with low rock shores.

Sensitivity index scores (n = 36) range from 1.5 to 20, with a mean of 6.9. The distribution is skewed towards high scores, with a primary mode in the 2-4 class interval, and a secondary mode at 14-16. The distribution of scores is interesting: the estuary above Québec City and the north shore downstream to beyond the mouth of the Saguenay River have low scores. The south shore has mostly moderate scores. In this subregion two areas of high sensitivity occur, one on each shore.

Trois-Rivières to Québec City

Shore platforms cut into slates and shales, 700 to 800 m wide and backed by cliffs up to 50 m high, fringe both sides of the St. Lawrence estuary upstream from Québec City (Dionne, 1987). Here, combined high discharge and high tides produce floods reaching up to 5.5 m above the mean annual water level. At Grondines, 80 km upstream from Québec City, shore erosion has occurred during extreme floods in the past 35 years. During these extreme events landward displacement of the shoreline up to 3-4 m has ensued, together with an average retreat of the forest margin of 1 $m \cdot a^{-1}$ approximately (Bégin et al., 1991). These trends would be increased by further sea-level rise. For the most part, however, sea-level rise is not a major threat here.

North shore of the St. Lawrence estuary: Québec City to Pointe-des-Monts

From Québec City to a point past the mouth of the Saguenay River, the resistant bedrock coast has low sensitivity to sea-level rise. However, coastal marshes are presently being eroded in several places. At Cap-Tourmente, 50 km downstream from Québec City, mean annual retreat rates of the upper shore range from 1.8 m to 2.5 m (Troude and Sérode, 1985), and a low terrace is now partly submerged by the highest tides (Dionne, 1986). At Saint-Joseph-de-la-Rive, 100 km downstream, the micro cliff of a tidal marsh has been eroded over a period of 25 years at a mean rate of 1.2 $m \cdot a^{-1}$ (Quilliam and Allard, 1989). Additionally, along the shores of the Saguenay River, other forms of erosion are occurring; glacial marine muds are exposed in eroding and slumping bluffs in places. A reversal of the sea-level trend would accelerate erosion at these and other sites. From a point east of the mouth of the Saguenay River to one just past Baie Comeau, the coast is moderately and highly sensitive to sea-level rise. The most sensitive areas include the deltas of the Betsiamites River and Outardes Islands/Manicouagan Rivers (Fig. 12).

Figure 12. *Landsat 5 image dated 18 May 1984 showing the St. Lawrence estuary. The most sensitive areas are deltaic complexes such as those of Rivière Portneuf (**a**), Rivière Betsiamites (**b**), Rivière aux Outardes (**c**), and Rivière Manicouagan (**d**). Also shown are the locations of Baie-Comeau (**e**) and Rimouski (**f**).*

South shore of the St. Lawrence estuary: Lévis to Cap Chat

This moderately sensitive region has alternating rock platforms in Ordovician shales, and contains embayments with wide intertidal mudflats and salt marshes. East of Rivière-du-Loup, the rock platform predominates. Intertidal flats are rarely thicker than 0.6 m and upper marshes are generally 1 to 2 m thick. The marshes are usually adjacent to either a rocky cliff (as at Cap-à-l'Original) or a Late Holocene raised marine terrace 2 to 6 m high. The latter is called the Mitis Terrace (Dionne, 1990). The impacts of sea-level rise would include increased erosion of shorelines developed in Quaternary deposits. Near Rimouski the raised marine terrace is only 1 m above highest tide levels. Cottages and a rail line located on this terrace would be threatened by increased erosion.

The most sensitive areas in this region are coastal marshes. High rates of tidal-marsh erosion have been recorded at many locations (Dionne, 1986). At Montmagny, 80 km downstream from Québec City, the mean rate is 1.02 $m \cdot a^{-1}$, while at Rivière-du-Loup, 200 km downstream, mean rates of 2.01, 3.18, and 4.06 $m \cdot a^{-1}$ are cited. Erosion has also been recorded at La Pocatière, Kamouraska, L'Isle-Verte, and Trois-Pistoles. Recent sea-level rise is thought to be a factor in the rapid erosion of tidal marshes. Even without higher erosion rates due to accelerated sea-level rise, the upper marsh in some areas could disappear within 20 to 25 years and a major highway would be threatened in places.

Southern Gulf of St. Lawrence

This region comprises: 1) the Gaspésie, Chaleur Bay, and the Îles-de-la-Madeleine; 2) the gulf coast of New Brunswick; 3) the gulf and Northumberland Strait coasts of Prince Edward Island; and 4) the gulf and Northumberland Strait coasts of Nova Scotia. Owens (1977a) typified it as a broad lowland, bordered in the east and west by the uplands of the Gaspésie and Cape Breton Island. The last two areas comprise resistant metamorphic or sedimentary rocks and igneous or volcanic rocks, respectively. The southern gulf region has a great diversity of coastal environments (Owens, 1974).

The coastal region is predominantly microtidal, with higher ranges at the head of Chaleur Bay (3.3 m, large tides) and the mouth of the St. Lawrence River (3.5 m). Rates of mean sea-level rise ($mm \cdot a^{-1}$) vary across the region as follows: +0.10 at Pointe-au-Père (Qué.), +0.55 at Sainte-Anne-des-Monts (Qué.), +4.57 at Dalhousie (N.B.), +2.12 at Lower Escuminac (N.B.), +3.55 at Charlottetown (P.E.I.), +3.28 at Rustico (P.E.I.), +3.68 at Pictou (N.S.), and +4.31 at Point Tupper (N.S.) in the Strait of Canso.

The fetch in this closed sea is generally less than 300 km, and wave activity is restricted by ice for periods up to 4 months each year. Ploeg (1971) gave wave data for 10 stations in the Gulf of St. Lawrence, using the parameter "significant wave height to be expected once a year". Values range from 4.9 m at Sept-Îles to 7.9 m off West Point (Anticosti Island) and 7.6 m off Cape North (P.E.I.). For this study reduced values of wave height have been adopted for large embayments such as the St. Lawrence Estuary, Northumberland Strait, and Kouchibouguac Bay. For the last location a score of 1 has been assigned, which is in good agreement with field evidence (Bryant, 1978). The distribution of sensitivity index scores (n=73) displays a primary mode in the 2-4 class, with secondary modes in the moderate and high domains. The mean score is 13.0.

Gaspésie: Cap-d'Espoir to Cap Gaspé

Beginning just east of Cap-d'Espoir (Fig. 10) this coast extends north, and then west to Cap Chat. Bedrock is deformed lower Paleozoic sedimentary strata. This is a mesotidal region in which sea ice restricts wave action from late December until early April. Although the coast is predominantly rocky, sensitive coastal environments occur within several large, east-facing embayments. At La Malbaie, a 7 km- long barrier which carries the rail line is threatened by overwashing and migration; also, the extensive tidal marshes behind the barrier might be inundated. Immediately to the north, parts of the Baie de Gaspé coast consist of highly sensitive environments: barriers, spits, salt marshes, intertidal flats, and delta flats. The Penouille spit (Allard and Tremblay, 1979) is a cuspate foreland in Forillon National Park, and is linked to the mainland by a narrow sandy ridge which could be breached by storm action under higher sea levels. Sandy Beach spit extends out from the south coast, protecting Gaspé Harbour, and has been overwashed in recent years (M. Allard, pers. comm., 1992). Immediately south of Sandy Beach, a bay-mouth barrier extends from Haldimand to Douglastown, and carries a railway and a road; also, it protects intertidal flats and the delta of the Saint-Jean River.

Gaspésie: Cap Gaspé to Cap Chat

The coast largely comprises resistant upland cliffs (Owens, 1977a), fronted in many places by quasi-horizontal shore platforms 60-120 m wide (Trenhaile, 1978; Trenhaile and Layzell, 1980). Average annual rates of cliff recession were estimated by Trenhaile (1978) to be 10-30 mm. Even if rates of cliff retreat and platform formation accelerate, these processes will remain sufficiently slow to have relatively little perceived impact. The rocky coastline is interrupted by small rivers with sand or gravel barriers at their mouths, protecting intertidal flats and salt marshes in the vicinity. Some of these barriers carry the regional highway, whereas others carry the highway and railway.

Chaleur Bay

The southern coast (Fig. 10, 13) of Chaleur Bay differs from the outer gulf coasts in that barrier beaches are fewer and coastal cliffs commoner, both in friable Carboniferous sandstone and in the easily erodible marine clays that are highly susceptible to slumping. Coastal areas around the bay are moderately sensitive to sea-level rise. It is anticipated that the coastal erosion problems now experienced at many locations (Airphoto Analysis Associates Consultants Limited, 1975) will be exacerbated, and will have a major impact in this region where the coastline is more highly developed (cottages and permanent homes) than elsewhere on the New Brunswick coast. Difficulties may arise at Belledune, where a heavy industrial complex is partly located on a cuspate foreland, and at Dalhousie, where a large pulp mill is located at the coast.

West of New Carlisle, the northern coast of the bay is also moderately sensitive to sea-level rise. Increased erosion of coastal bluffs, today retreating at 1.8 $m.a^{-1}$ in one area (Pelletier and Champagne, 1987), is one anticipated hazard. There may be some impact on the spit complex at Bonaventure, which is presently modified for use as a port. Much of the coast east of New Carlisle is highly sensitive, partly because it is exposed to higher wave activity than the coast of Chaleur Bay farther west. Bedrock cliffs that are fronted by rock platforms are common here, and bluffs of unconsolidated sediment occur also, together with sensitive beaches and spit barriers. Pelletier and Champagne (1987) cited erosion rates of 0.17 $m{\cdot}a^{-1}$ for rock cliffs and 0.36 $m.a^{-1}$ for bluffs in unconsolidated sediments. Higher erosion rates can be anticipated

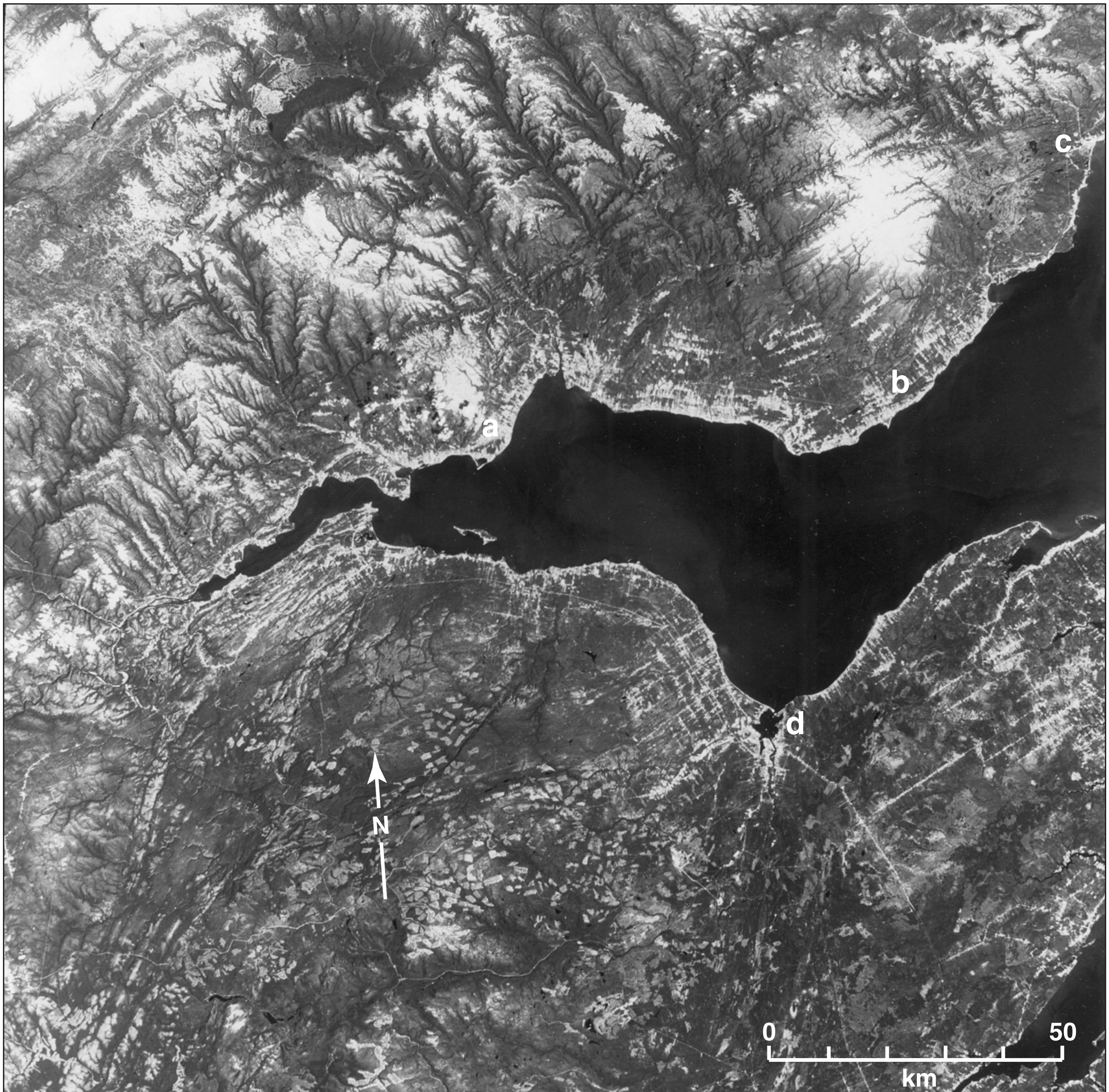

Figure 13. *Chaleur Bay, as imaged from Landsat 5, 20 May 1984. This region is moderately and highly sensitive. The most vulnerable locations include spit complexes at Pointe Tracadigache (**a**) and Paspébiac (**b**), and barriers at Chandler (**c**) and Bathurst (**d**).*

throughout the region. One location that will be affected is the foreland at New Carlisle, part of which retreated 84 m between 1963 and 1980. Emplacement of a groyne system to protect this site was already suggested by Pelletier and Champagne (1987).

The spits, barriers, and associated lagoons on this coast have been modified by dredging and jetty construction to use the area for ports (Pelletier and Champagne, 1987). Rapid sea-level rise may modify littoral drift systems, perhaps making it more difficult to maintain channels. The barrier across Baie du Grand Pabos, at Chandler, carries the Canadian National rail line, while the barrier across the mouth of Petit Pabos River, just to the north, carries both the rail line and the main regional highway. At both places these communication links are threatened by overwashing and barrier migration.

Îles-de-la-Madeleine

The Îles-de-la-Madeleine (Fig. 14) are composed of low, bedrock outcrops occurring in the central Gulf of St. Lawrence. Some of these islands are linked by sandy barrier-beach tombolos to form a 70 km long continuous island which encloses shallow lagoons (Owens and McCann, 1980; Drapeau and Mercier, 1990). Several major inlets occur on the east coast, and spit complexes are located at the northern and southern ends of the island. Wide, dissipative sandy beaches are backed in places by extensive coastal dunes; elsewhere, extensive prograded dune-ridge plains extend from the backbarrier lagoons to the present coast. Although Owens and McCann (1980) reported little gross change in the previous 200 years, parts of the system, nevertheless, are subject to progressive coastal retreat through overwashing.

The range of impacts expected on any low barrier coast could occur here. These are as follows: more frequent overwashing, inlet opening and closing, barrier migration, coastal dune erosion, and, perhaps, inundation of some low, backbarrier dune ridges. The overall result may be a reduction of the area of the central lagoons. Like Sable Island, however, the sufficient supply of sandy sediment in the area should ensure that the islands will retain their essential form.

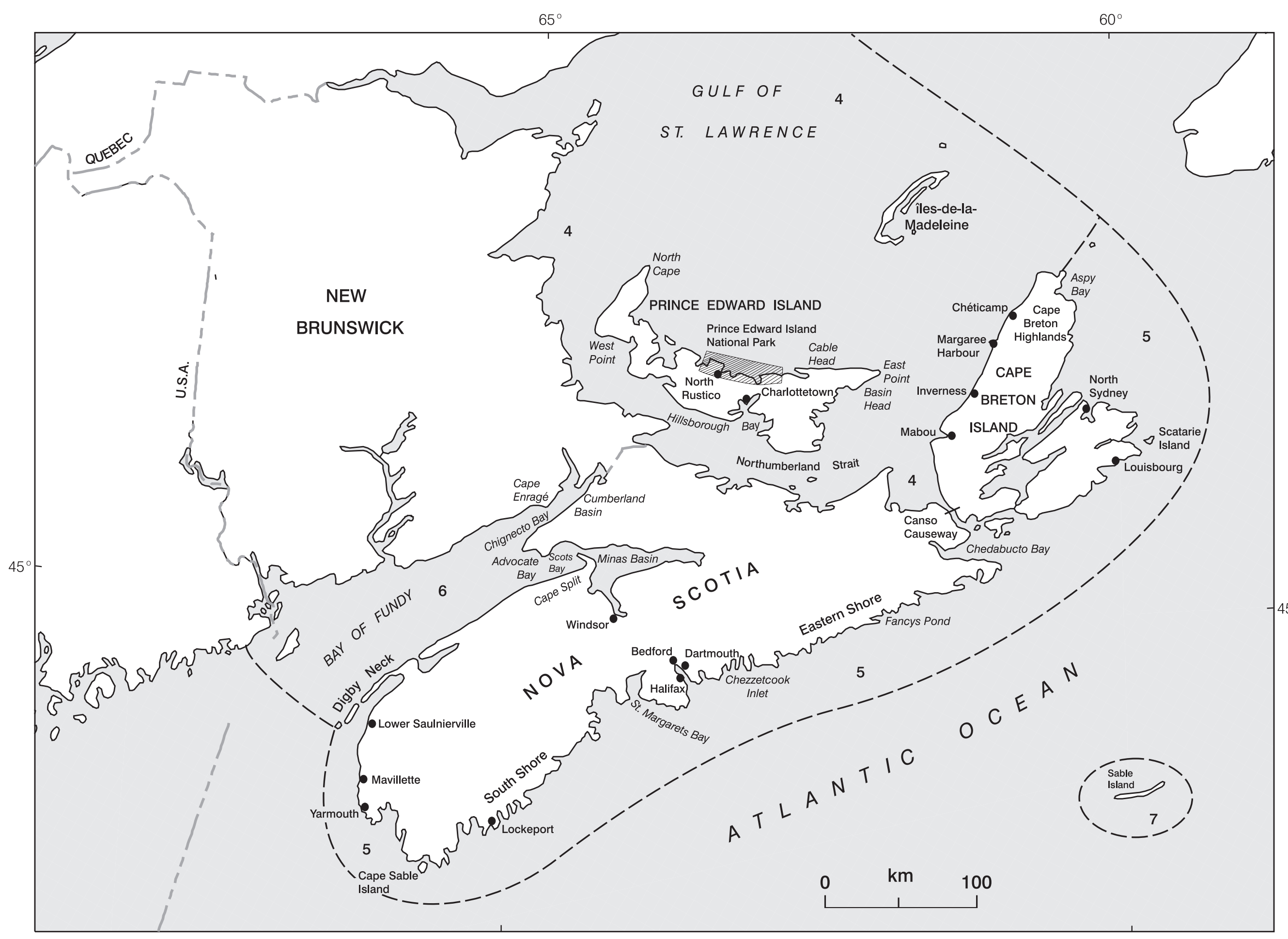

Figure 14. Coastal regions of Nova Scotia, Prince Edward Island, and Îles-de-la-Madeleine with the boundaries of the Atlantic coastal environments shown (dashed line).

The gulf coast of New Brunswick

The gulf coast of New Brunswick (Fig. 15) contains areas of moderate and high sensitivity to sea-level rise. The region has extremely low relief in that the 100 m contour is usually at least 40 km inland from the coast. The terrain consists of gently dipping Carboniferous sandstone with a veneer of glacial and marine sands and gravels, which are overlain by thick Holocene peat in some places. Barrier islands and spits extend across shallow, drowned embayments (Airphoto Analysis Associates Consultants Limited, 1975) to form the longest barrier coast in Canada (McCann, 1979; Reinson, 1980). The largest such embayment is the estuary of the Miramichi River.

Between barriers some headlands have vertical sandstone cliffs; elsewhere, cliffs of Holocene peat up to 5 m high overlie several bedrock platforms. Most of the coast is experiencing erosion. The report by Airphoto Analysis Associates Consultants Limited (1975) suggests that during the Holocene transgression the coast has retreated 14 to 19 km, which is an average rate of 3 $m \cdot a^{-1}$. More recent rates are lower: about 5% of the coast is retreating at more than 0.6 $m \cdot a^{-1}$, and about 50% at 0.3 to 0.6 $m \cdot a^{-1}$.

The gulf coast of New Brunswick: Baie Verte to Richibucto Cape

The moderately sensitive Cape Tormentine region comprises intervals of rocky coast and discontinuous barrier beaches. Both coastal types will undergo increased recession, either through accelerated erosion of cliffs, or because of increased barrier rollover rates. The coast extending to the west, towards Shediac Bay, is rated highly sensitive, but the western part of Shediac Bay and the barrier coast extending northward has only moderate scores. This anomaly results from a deficiency in the method of scoring relief, because the NTS sheets here encompass relief far inland. The coast just north of Buctouche, as far as Richibucto Bay, has a score just less than 15, the threshold of high sensitivity to sea-level rise. Buctouche Spit is a 10 km long drift-aligned barrier that is accreting at its southern end (Fig. 16).

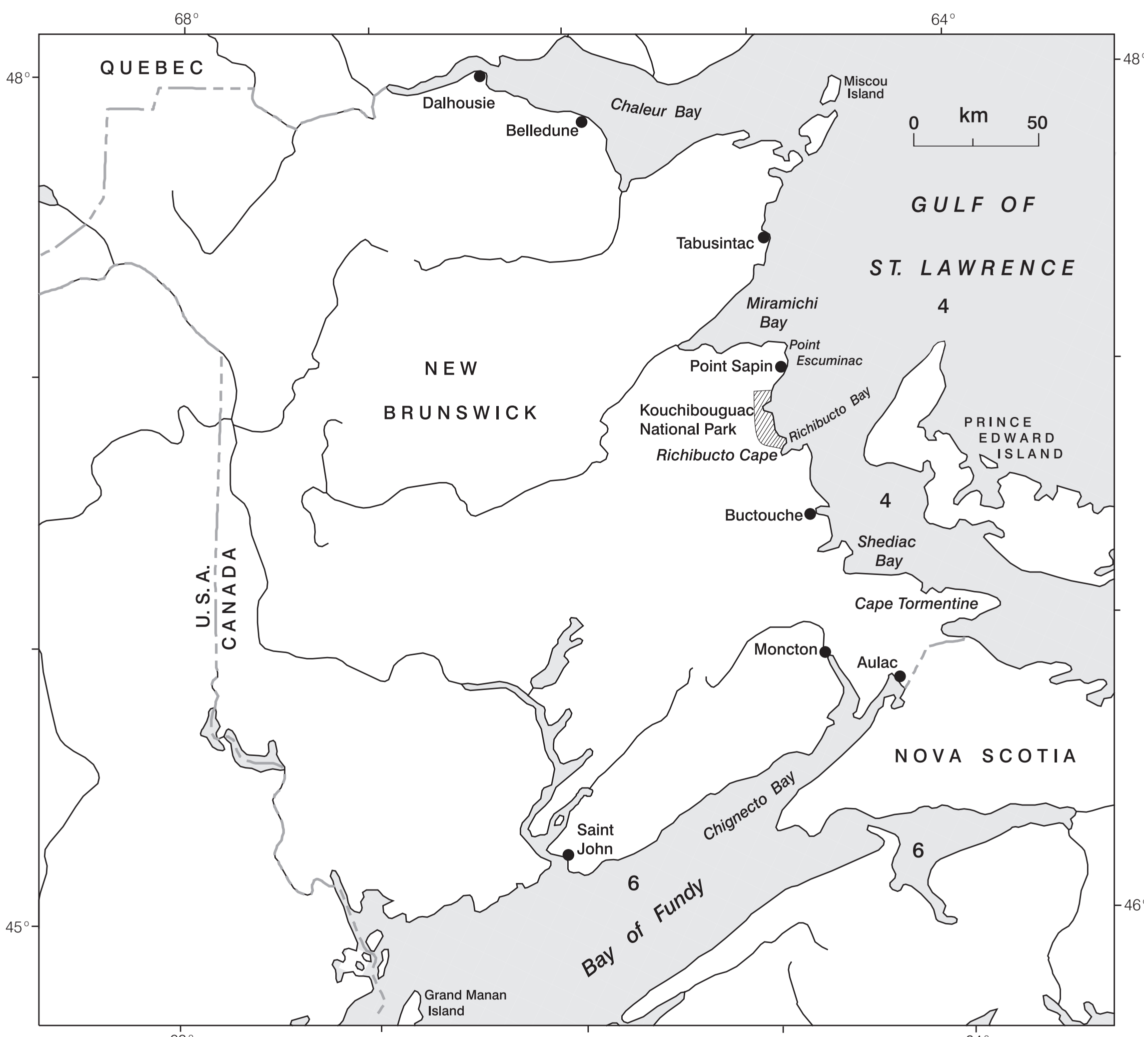

Figure 15. *Map of New Brunswick and parts of adjacent provinces showing the coastal environments discussed in the text.*

Figure 16.

Buctouche Spit, on the Northumberland Strait coast of New Brunswick. This photograph taken in November 1972 by E.A. Bryant shows the narrow, proximal part of the spit, experiencing erosion (see the truncated recurves in the foreground) and overwashing (in the distance). The low, mainland coast can be seen in the distance, behind the frozen lagoon. Overall this part of the New Brunswick coast scores as moderately sensitive to sea-level rise, but Buctouche Spit is highly sensitive. GSC 1995-279A

The northern end of the spit may undergo increased erosion, and some of the lower recurves may be inundated. Richibucto Cape consists of rapidly eroding sandstone cliffs. The old coast road here has already been abandoned (Thibault and Frobel, 1987) and permanent homes are set well back from the shore.

The gulf coast of New Brunswick: Richibucto Cape to Point Escuminac

Prominent headlands at Richibucto Cape and Point Escuminac anchor a chain of barrier islands which stretch in an arc across a wide coastal embayment containing a series of drowned river valleys (Thibault and Frobel, 1987). Kouchibouguac National Park is located here (McCann et al., 1973; Greenwood and Davidson-Arnott, 1977). This region differs from that to the south in that freshwater bogs are common in the coastal zone. Further inundation and erosion of these bogs and adjacent woodlands are to be expected. The peatlands occur along the mainland coast, backbarrier lagoons, and along the headland coast at the northern end of the embayment where they form eroding cliffs up to 6 m in height (Airphoto Analysis Associates Consultants Limited, 1975). Bégin et al. (1989) described coastal retreat processes at Point Escuminac, where sandy beaches are retreating landward across woodland underlain by peat bog at rates of 0.48 to 1.76 $m \cdot a^{-1}$. Forbes (1982) reported mean recession rates of 0.97 ± 0.4 $m \cdot a^{-1}$ over 25 years along 12 km of coast lying between Point Escuminac and Point Sapin.

The gulf coast of New Brunswick: Point Escuminac to Tabusintac (Miramichi Bay)

Exclusive of Chaleur Bay, Miramichi Bay is the largest embayment in the region. The barrier islands stretching between headlands at Escuminac and Tabusintac are about 30 km seaward of the head of the bay. The outer barrier coast is highly sensitive to destabilization. Changes in barrier morphology may influence the circulation through the various inlets to Miramichi Bay (Reinson, 1977), perhaps requiring more frequent dredging than is necessary today. The inner coast is moderately sensitive to sea-level rise. Low-lying peat bogs with eroding cliffs, the so called "blacklands", fringe the mainland behind the barriers, for example at the junction of northern Miramichi Bay and Tabusintac Bay (Reinson, 1980). These may erode faster than today, or undergo inundation.

The gulf coast of New Brunswick: Tabusintac to Miscou Point

This is the most northerly segment of the New Brunswick barrier coast, and terminates at Miscou. This segment comprises a series of barrier islands and spits, with occasional bedrock headlands (Reinson and Frobel, 1980). The coast is highly sensitive. Most of the anticipated impacts described above might be observed here. These are as follows: increased erosion of bedrock headlands (as at Miscou lighthouse), more frequent barrier overwashing and retreat, and erosion and inundation of peatlands. The last may be severe in this region, in which coastal bogs are common.

The coasts of Prince Edward Island

The coasts of Prince Edward Island (Fig. 14), except for some parts of the Northumberland Strait coast, are highly sensitive to impact from sea-level rise. The factors that cause this include low relief (the highest elevation on the island is +45 m) and friable bedrock, principally composed of gently folded Permian-Carboniferous rock. These alluvial fan 'redbeds' consist of poorly lithified conglomerates, sandstones, shales, and mudstones. The coastline is highly variable in character and includes bedrock cliffs, sandy barriers, coastal dunes, salt marshes, estuaries, and intertidal flats (Owens, 1979; Taylor and Frobel, 1992).

Sea level has been rising rapidly (+3.55 $mm \cdot a^{-1}$ at Charlottetown), and coastal erosion is pervasive on the island's coastline. The average rate of shoreline retreat at

1 km intervals along the coast is approximately 0.3 $m \cdot a^{-1}$, with a maximum of 3.5 $m \cdot a^{-1}$ (LRIS, 1988). This erosion is perceived as a problem on the island: at a workshop in 1989 a university geologist stated (tongue in cheek) that the island would disappear in 7000 years time!

The gulf coasts of Prince Edward Island. A major sandy foreland is located at West Point. From there to North Point, the coast comprises rocky cliffs, with narrow sandy beaches and scattered small barriers. This region will experience erosion rates even higher than present if sea level should rise. The coast from North Point to Cable Head has a number of wide, shallow, estuarine embayments enclosed by sandy barriers and spits, commonly with extensive coastal dunes (Fig. 17). Low cliffs of eroding sandstone are common at headlands. This coastal region, which lies at the heart of the P.E.I. tourist industry, could undergo even higher rates of coastal change than at present. These changes could include increased barrier retreat through overwashing, as well as beach and cliff retreat (Fig. 18) and submergence of backbarrier marshes and intertidal flats. Accelerated coastal retreat could increase the costs of maintaining a tourist infrastructure by increasing the frequency at which boardwalks, steps, groynes, and seawalls would have to be replaced. Some of these additional expenditures will be in the Prince Edward Island National Park, in which a coastal highway has already been severed by widening of a tidal inlet (Forbes et al., 1989). From Cable Head to East Point the coast comprises bedrock cliffs and bluffs of glacial sediment predominantly, with a few pocket beaches and small barriers. It is presently eroding at rates approaching 0.6 $m \cdot a^{-1}$ (LRIS, 1988).

The Northumberland Strait coasts of Prince Edward Island. Sand moving along the north coast accumulates in sand beaches and barriers which lie south of East Point (Owens, 1979; Frobel, 1990). Increased erosion of the north-facing

Figure 17.

The gulf coast of Prince Edward Island is highly sensitive to impact. Most of the coast consists of unconsolidated materials, such as in this view of coastal dunes on Hog Island. Photograph by E.A. Bryant in 1972. GSC 1995-279B

Figure 18.

The coastal road along the barrier near Rustico, on the gulf coast of Prince Edward Island, was severed due to rapid widening of the tidal inlet. This is the kind of dynamic coast which is highly sensitive to a rapid sea-level rise. Photograph by R.B. Taylor, 3 October 1990. GSC 1995-282 coast will maintain a supply of sediment, despite some loss to the large offshore shoals here; thus, the beaches and barriers may be maintained. One somewhat sensitive area is the beach-ridge foreland at Basin Head (Owens, 1979), which will be submerged on its landward side and trimmed at the coast. Elsewhere on this coastal section, higher rates of erosion and submergence of backbarrier wetlands could occur.

The southeastern coast contains bedrock cliffs predominantly, and intertidal platforms and flats. Increased erosion is expected. Hillsborough Bay is a large drowned embayment, with low-energy intertidal flats and marshes up to 1 km wide; therefore, inundation of low-lying areas may occur here. P. Lane and Associates Ltd. (1988) attempted to determine the impacts of a 1 m rise in sea level at Charlottetown. The report itemized impacts in detail: the sewer station would be below high tide level; problems would be expected with low-lying parts of the sewage system; and flooding of public and private buildings would occur. The report laid out the steps which must be taken to achieve a risk benefit analysis to produce guidelines for cost-effective development in Charlottetown.

The coast west of Hillsborough Bay is varied, with occurrences of estuaries, low bedrock cliffs, and intertidal flats. Egmont Bay has low barrier beaches, estuarine flats, and marshes. As elsewhere on the island, a sea-level rise due to global warming, superimposed upon already high rates of submergence, would result in inundation of numerous small low-lying areas, and higher retreat rates for erodible bedrock cliffs and barrier beaches.

The gulf and Northumberland Strait coasts of Nova Scotia

The Cape Breton coast, from Cape North to the Canso causeway (Fig. 14), is only moderately sensitive to impact. Stretches of high rocky coast alternate with sections of eroding coastal bluffs which supply sediment to gravel beaches. Small areas of higher sensitivity include the gravel barrier beach at Petit Étang, and the beaches at the entrances to Margaree Harbour, Inverness, Mabou, and Judique North. The thin neck of land that joins Chéticamp Island to the mainland and the breakwater that extends across to Port Hood Island could also be adversely affected by rising sea level or erosion of the adjacent shores.

The Canso Causeway, linking Cape Breton Island to the mainland, is a 1.5 km long structure constructed with its roadway at a height of 4 m approximately above high water level (HWL). At present spray sometimes blows across the causeway, but traffic is not interrupted. With sea level 0.65 m higher there could be a potential for damage during storms. It is possible that the causeway will be enlarged to carry 4 lanes of traffic in the near future, in which case the possible sea-level rise should be taken into account.

West of the causeway the coast is moderately sensitive to sea-level rise. A complex series of baymouth barriers forms the head of St. Georges Bay. Pomquet Beach consists of a series of prograded beach ridges, but many of the other baymouth spits which protect harbours such as Tracadie and Antigonish are much narrower and more vulnerable to change. Farther west toward the New Brunswick border the outer shoreline consists of low to moderately high rock and unconsolidated cliffs. Wide intertidal sand flats, with a ridge and runnel topography, and warmer Northumberland Strait waters help to make this coastline a very popular place for building cottages and resorts. The shoreline is underlain by easily erodible sandstone and capped by glacial deposits. Many of the cottage owners have lost property because of the combined effects of wave erosion and increased groundwater seepage associated with land clearing and cottage development. Taylor et al. (1985) cited a mean maximum recession rate along the Northumberland Strait of Nova Scotia of $0.7\ m \cdot a^{-1}$.

Several long barrier beaches join bedrock cliffs along the embayed shores between Merigomish and Caribou Island. Some of the beaches are prograding, such as the beach at Caribou Island, where sand has accumulated against a causeway built in 1922 (Taylor et al. 1985), while others such as Big Island Beach (Merigomish) are rapidly retreating. Big Island Beach joins Big Island (Merigomish) to the mainland. A road runs along the top of the beach to the island. Several attempts have been made to arrest the landward movement of the beach, including the construction of vertical walls, groynes, and boulder rip rap. In 1991 the beach was only 80 m wide at the eastern section and much wider at the western end, with a series of beach ridges and sand dunes up to 6 m elevation (Forbes and Trider, 1992). Accelerated erosion of the outer shores under a rising sea level will result in increased sedimentation within the inner bays such as Tatamagouche, Fox, and Pugwash harbours which, in turn, will affect the present extent of wetland and marsh vegetation.

Atlantic Nova Scotia

In this region of moderate to low relief, except for the Cape Breton Highlands, bedrock in coastal areas is composed of Paleozoic metasediments predominantly, with areas of granite. Less resistant Carboniferous sediments are exposed along sections of the Cape Breton coast, and west of Halifax, granites are dominant. Glacial till deposits mantle bedrock over large areas of this coastal region. Rates of sea-level rise (Carrera et al., 1990) are high (Fig. 19), amounting to 4.75, 3.56 , and 3.87 $mm \cdot a^{-1}$ at Yarmouth, Halifax, and North Sydney, respectively (roughly comparable rates were determined by Shaw and Forbes, 1990b, and Middleton and Thompson, 1986). These rates are due largely to crustal subsidence, possibly supplemented by eustatic rise (Carrera and Vaníček, 1988).

Erosion is prevalent along the Atlantic coastline of Nova Scotia (Fig. 20). Taylor et al. (1985) provided data on coastal bluffs composed of glacial till, based on measurements at eight sites. They reported mean rates of $1.1\ m \cdot a^{-1}$ along the Eastern shore and $0.4\ m \cdot a^{-1}$ along the South Shore, although recent measurements show a maximum rate of $10\ m \cdot a^{-1}$. Taylor (1988) cited mean coastal recession rates of more than $2\ m \cdot a^{-1}$ at sites on Sable Island.

The tidal range (large tides) is about 2 m, except in the southwest where it increases near the Bay of Fundy from 3 m at Cape Sable Island to 7 m in Digby Neck. Wave-energy levels on the outer coast are generally high (Taylor et al., 1991).

The intricate Atlantic coastline of Nova Scotia has numerous embayments, some of which have been overdeepened by glaciers. Such examples include Bedford Basin and St. Margarets Bay (Piper et al., 1986). Other embayments have been partly filled by sediments during the Holocene transgression, and contain a range of coastal environments such as *Zostera* flats, flood deltas, and salt marshes. These environments are generally protected from ocean waves by an outer estuary zone of gravel barriers which link eroding remnants of drumlins.

Except for bedrock-dominated stretches, the Atlantic coast of Nova Scotia is deemed to be highly sensitive to accelerated sea-level rise on account of low relief, erodible substrates, sensitive coastal environments, high rates of relative sea-level rise, moderate and high rates of shoreline displacement, high wave energy, and moderate tidal ranges. Scores range from 2.1 to 57, with a mean of 23 (n=43).

Digby Neck to Halifax Harbour

Digby Neck is a rocky promontory developed in Mesozoic basalts, jutting into the Bay of Fundy in western Nova Scotia. The coast has a moderate sensitivity score. Between Digby Neck and Halifax the coast is highly sensitive, except for intervals of granitic coast directly west of Halifax. Among the most sensitive sites is Lower Saulnierville (Taylor et al., 1985), where low, glacial till bluffs predominate at the coast. Retreat will be more prevalent here, and will result in a loss of agricultural land. Breaching of narrow sand and gravel barriers could cause inundation of the coastal lowlands. At Mavillette beach (Taylor et al., 1985), formerly dyked salt marshes are protected by a sandy barrier. Eroding till bluffs to the south supply sediment to the barrier, which could maintain itself despite sea-level rise. If the salt marshes are more frequently inundated, low-marsh ecozones may replace higher ones.

Coastal barriers that protect back-barrier lagoons and marshes are prevalent on the coast of Cape Sable Island. In this area we anticipate inundation of backbarrier lowlands and destruction of wharf facilities built on spits. The causeway to Cape Sable Island, completed in 1949, was damaged by Hurricane Edna in 1954, and by the occurrence of two storms in 1976, including the Groundhog Day Storm (R.S. Fry, pers. comm., 1991). The presence of higher water levels will almost certainly increase the likelihood that the causeway will be damaged by future storms. If it were

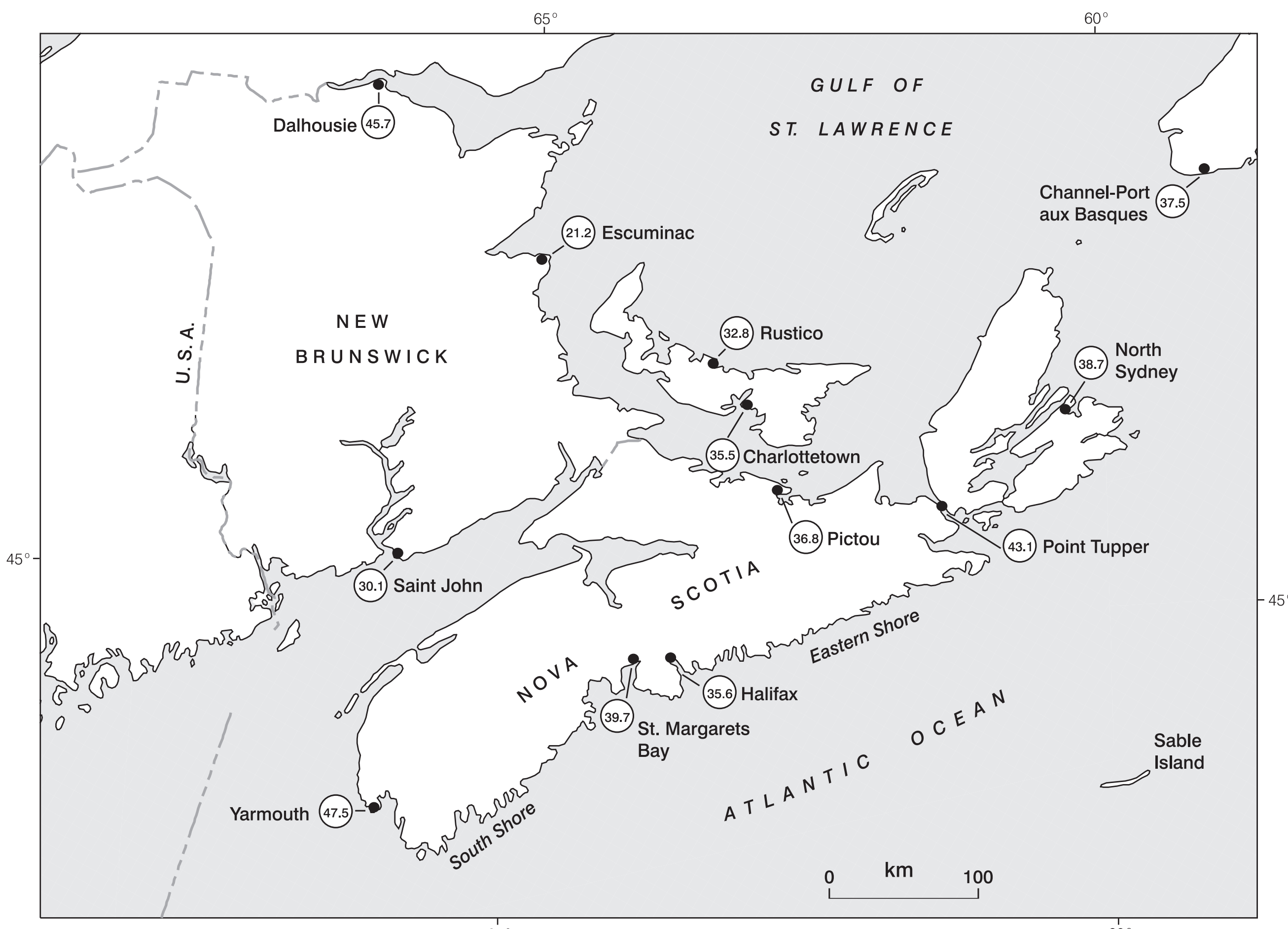

Figure 19. Rates of relative sea-level rise (cm/century) obtained from tidal records at selected locations in Atlantic Canada. This figure, based on data from Carrera et al. (1990), is taken from Shaw et al. (1993).

breached and not repaired, strong tidal currents would destabilize the beaches which have formed in the region since 1949.

Crescent Beach barrier at Lockeport carries the road connecting that town to the mainland (Taylor et al., 1985). This beach may migrate in adjusting to sea-level rise. Across from Lockeport Harbour lies the sandy, flood-dominated barrier at Ram Island (Grant, 1975). Submerged in the backbarrier lagoon are a solitary gravel storm beach and a prograded gravel beach-ridge complex. These features represent the earliest phase of barrier development, and were formed when sea level was below that of today. They are overlain by a series of later, higher recurves on the west side of the barrier. The most recent activity in the barrier system, presumably in response to rapid sea-level rise, is envelopment of old, submerged beach ridges by rapidly expanding flood-deltas. Future changes to be expected here include inundation of backbarrier lowlands, continued transfer of sediment into the flood delta complex, and the slow retreat of the sediment-starved barrier by overwashing and erosion.

The largest urban area in Nova Scotia comprises the communities of Halifax, Dartmouth, and Bedford. These centres are located around Halifax Harbour, which is a deep, sheltered, bedrock embayment. Spread around the harbour and basin are dockyards and munitioning areas, oil refineries, commercial port facilities, residential areas, parks, railways, and bridges. Accelerated sea-level rise could seriously affect these existing facilities, but will be factored into the design of a proposed sewage treatment plant (G. Fader, pers. comm., 1992). Erosion of drumlins at the mouth of the harbour has consumed one island in recent decades. Further loss of this and similar recreational areas can be anticipated in the event of accelerated sea-level rise.

The Eastern shore from Halifax Harbour to Cape Canso

The relationships between rising sea level and coastal evolution on this coast have been the subject of numerous studies (cf. Scott, 1980; Boyd et al., 1987; Carter et al., 1990a, b; Forbes et al., 1990, 1991b; Orford et al., 1991a, b, 1992; Shaw et al., 1992, 1993; and Jennings et al., 1993). We can draw some general conclusions regarding future changes by

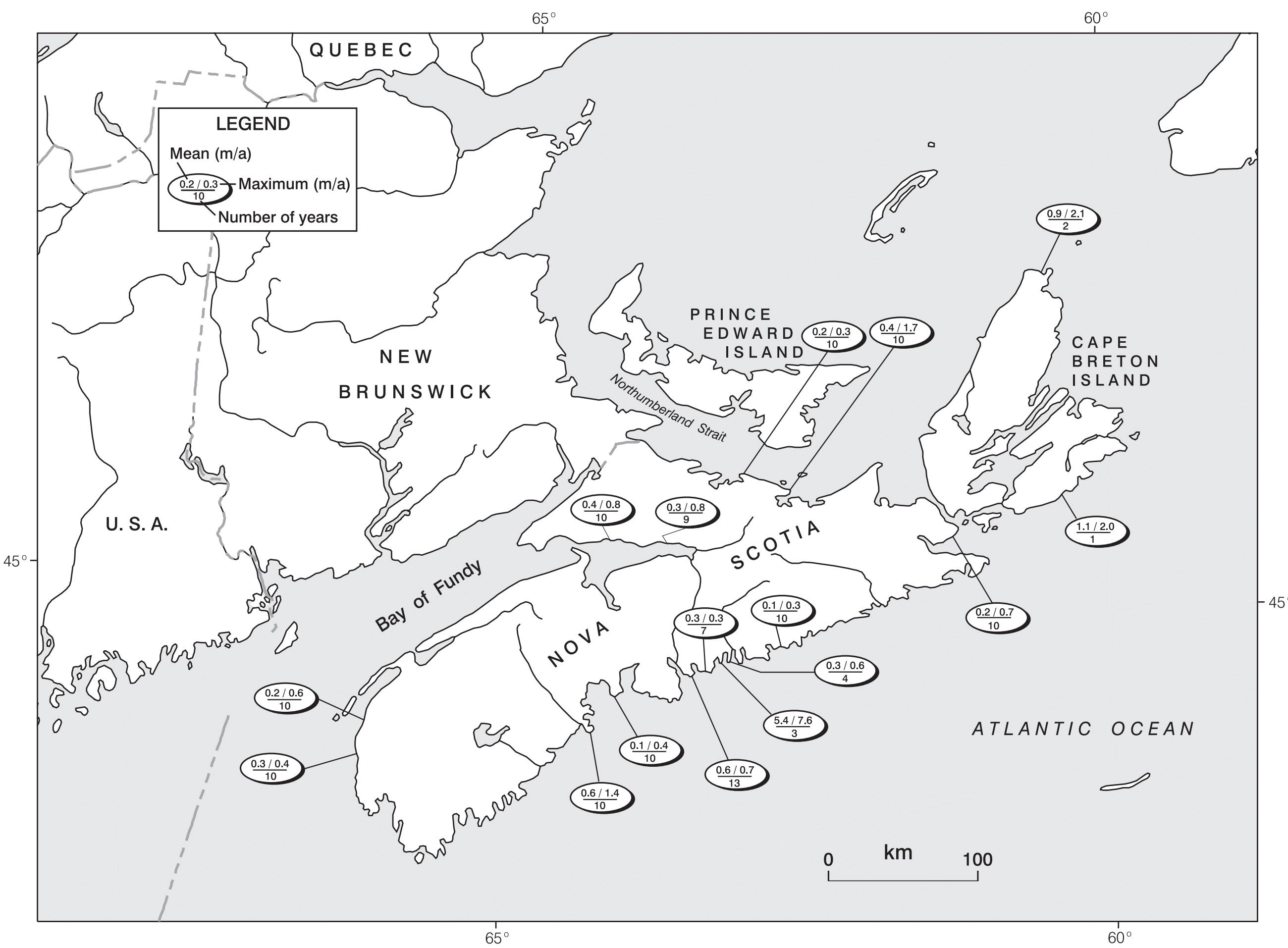

Figure 20. *Mean and maximum rates of cliff-top retreat in unconsolidated bluffs at selected sites in Nova Scotia. The compilation is based on repetitive ground surveys between 1980 and 1991. Taken from Shaw et al. (1993).*

examining one area of detailed study. This area is Chezzetcook Inlet, which is a large estuary lying 30 km east of Halifax. The estuary is surrounded by fields of drumlins which, during the Holocene transgression, provided intermittent sediment sources for beaches (Boyd et al., 1987). Carter et al. (1987, 1989, 1990a, b) and Orford et al. (1991a) described this process as the passage of an erosional front associated with the Holocene marine transgression. Recent measurements on eroding drumlins indicate recession rates of up to 7 m·a^{-1}.

In the outer estuary, drumlins act as anchor points for the system of gravel barriers which protect the estuary from Atlantic waves. Story Head barrier (Fig. 21) links an eroding drumlin to the mainland. After 1954 the mixed sand and gravel barrier began to undergo a rapid acceleration in the rate of landward migration by washover. During the next 30 years it moved an average of more than 8 m·a^{-1} (Forbes et al., 1991b); the rates varied in relation to the rate of relative sea-level change (Orford et al., 1991b). A drumlin remnant at the east end of the barrier was eroded completely, and is now a boulder shoal. At the same time, expanding flood deltas have enabled estuarine infilling to keep pace with sea-level rise, thus transforming *Zostera* mud flats into *Spartina* marshes in the middle estuary zone (Orford et al., 1991a). Today the barrier is at a critical stage of its development. Starved of sediment, it has been breached at the junction between the eastern (swash-aligned) section and the drift-aligned trailing spit attached to the drumlin. In the near future it will be separated from the drumlin, which will eventually be trimmed to a shallow, bouldery shoal. In effect, the entire outer barrier system is in the process of reorganization.

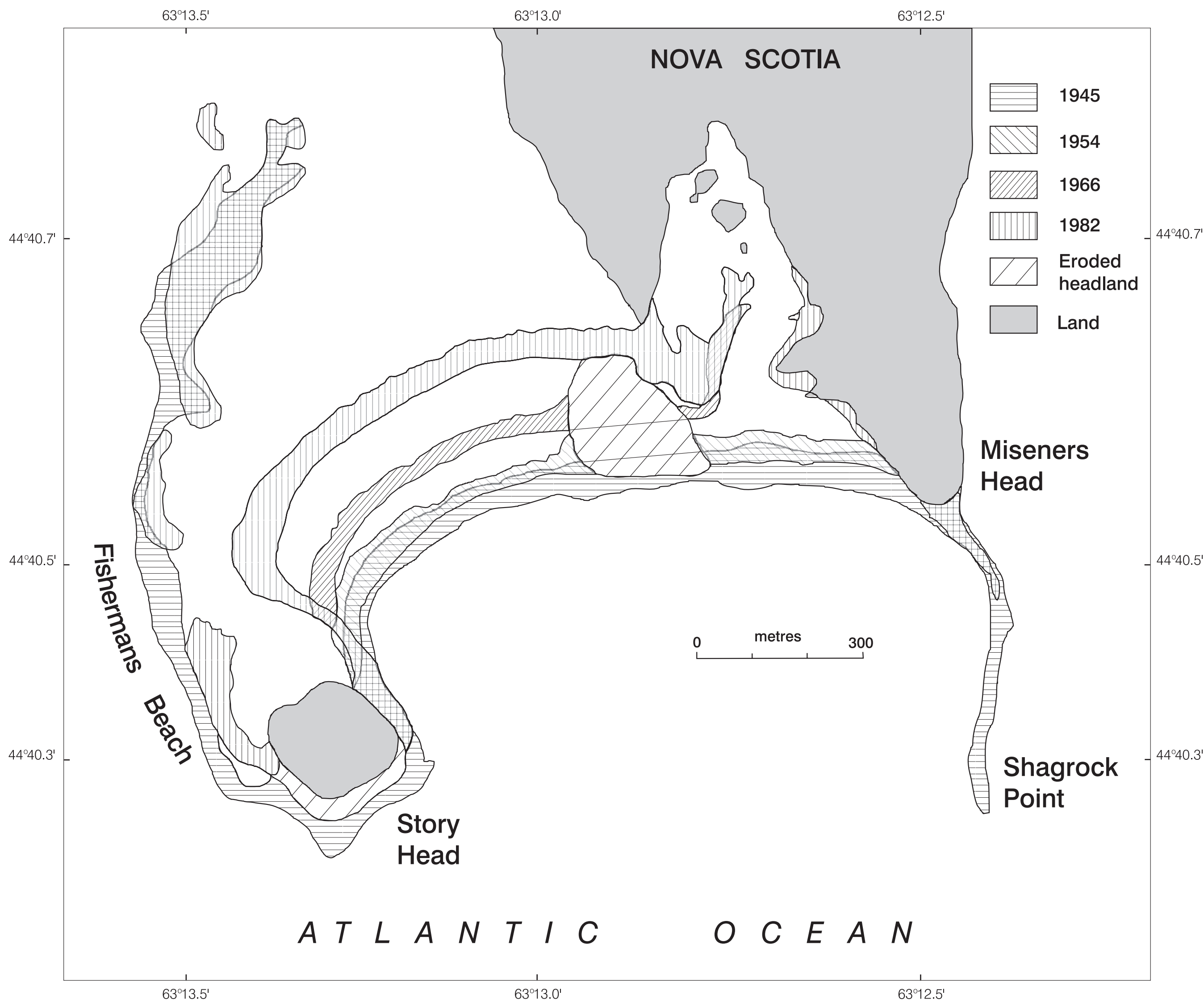

Figure 21. *Diagram showing coastal retreat at Story Head, Nova Scotia. The mixed sand and gravel barrier migrated landward across estuarine mud at 2 m·a^{-1} from 1917-1954, and more than 8 m·a^{-1} between 1954 and 1982 (Forbes et al., 1991b).*

Figure 22.

The pumping station, essential for operation of the Fortress of Louisbourg as a tourist facility, has been flooded during storm surges on the Nova Scotia coast in recent years. This is a good example of a valuable archaeological site threatened by coastal erosion, and one that is highly sensitive to further change if sea level rises more rapidly. Photograph taken in March 1992 by R.B. Taylor. GSC 1995-283

These types of processes can be expected to continue along the Eastern shore, but at rates faster than at present if sea-level rise accelerates. For example, rates of bluff and beach retreat on the outer coast will increase; salt marshes may adjust to more frequent flooding; and inundation of low, interdrumlin, coastal, freshwater marshes will result in landward expansion of salt-marsh ecozones.

Although some effects of the ongoing transgression are easy to extrapolate, it is the consequences of complete barrier breakdown that are more difficult to predict, such as that now occurring at Story Head. Some part of the sediment released by the destruction of Story Head may accumulate nearby, thus forming the nucleus of a new beach-ridge complex. There could be a different outcome at Fancy's Pond, which is located farther along the Eastern shore (Shaw et al., 1992). Behind the high active beach, prograded beach ridges decline in elevation landward, so that the oldest ridges are submerged in backbarrier lagoons. Drowning of the old strandplain is predicted, and the barrier will become a single gravel ridge which may eventually migrate landward as sediment supply diminishes and the frequency of overtopping increases.

Cape Canso to Cape North

The predominantly rocky southern shore of Chedabucto Bay lying west of Cape Canso is only moderately sensitive; in contrast, the north side of Chedabucto Bay is highly sensitive. Increased erosion of till bluffs can be anticipated, with gravel and sand being moved westward to the Ragged Head barrier complex. The high salt-marsh, which overlies partly submerged gravel beach ridges behind the present barrier, will be transformed into a low marsh environment. The Atlantic coast of Cape Breton Island lying immediately east of Chedabucto Bay comprises a series of eroding till headlands that alternate with gravel barriers enclosing brackish and freshwater lagoons (Wang and Piper, 1982). The high sensitivity of this stretch of coast is due to a potential for increased coastal retreat, barrier migration, and inundation of salt marshes and low-lying backbarrier areas.

The restored 18th century French fortress at Louisbourg (Fig. 22) is highly vulnerable to the effects of rising sea level. Grant (1975) discussed archaeological evidence for a 0.8 m sea-level rise over the previous 250 years here, which is an average rate of +3.2 mm·a^{-1}. Analyses of tidal data by Carrera et al. (1990) found rates of +3.87 and +4.21 mm·a^{-1} at nearby North Sydney and Point Tupper respectively. A gravel barrier protects part of the fortress site. Recent overwashing, assisted by gravel removal (Taylor, 1992) (which has had similar negative effects elsewhere in Nova Scotia – cf. Taylor et. al., 1985) has worsened flooding of the modern pumphouse that is vital to operation of the site as a tourist attraction. Inexorable retreat of the coast is a process that threatens destruction of the unexcavated remains of much of the fortress walls and the former settlement.

East of Scaterie Island the coastline is moderately sensitive to sea-level change, although barrier and lagoon complexes scattered across the region are susceptible to the types of change discussed above (Fig. 23). The high, rocky coast of the Cape Breton Highlands has low sensitivity, with the exception of the large barrier complex at Aspy Bay. Here a low, backbarrier prograded beach ridge complex, thinly mantled with peat in places, will probably either be permanently inundated, or become a low marsh environment.

Bay of Fundy

Coastal areas of this large bay (Fig. 14) have moderate relief. Rocks surrounding the outer bay consist of resistant volcanics (Ferguson and Fyffe, 1985), whereas those which predominate at the head of the bay are composed of less resistant Carboniferous and Triassic sediments. Tidal ranges of the Bay of Fundy are among the world's highest; the mean range of ordinary tides varies from 4.5 m at the mouth of the bay to 12 m at the head, and the mean range of large tides varies from 6 to 16 m. The bay is near resonant to tidal inputs of semidiurnal frequencies, but Godin (1992) reported a growth of the major tidal component, M2, at Saint John, at a rate of 1.0-1.5 mm·a^{-1}. This accelerating trend is driven by sea-level rise and redistribution of sediments in the Minas and Cumberland basins. Significant

Figure 23.

The Nova Scotia coast is often damaged by storms and their accompanying surges. At the settlement of Neils Harbour, buildings which had stood for more than 90 years were destroyed when the beach was pushed landward in 1983. Photograph by R.B. Taylor, 1 November 1983. GSC 1995-284

wave heights range from 7 m at the mouth of the bay, in southwestern Nova Scotia, to 3 m at the mouth of Chignecto Bay (Amos and Zaitlin, 1985), and 1.5 m in the inner part of the latter. Mean sea level is rising at a rate of 3.01 $mm \cdot a^{-1}$ at Saint John (Carrera et al., 1990).

The varied coastline (Owens, 1977b) is notable for the large areas of intertidal flats and tidal marshes at the head of the bay. These constitute a highly productive ecosystem, exploitation of which was the basis of the Acadian settlement of the 17th century. Rates of erosion in this region vary greatly. Bedrock cliffs in the Minas Basin are eroding at a mean rate of 0.55 $m \cdot a^{-1}$ (Amos and Long, 1980), although the maximum rate is 1.5 $m \cdot a^{-1}$. In bluffs of glacial material in the same region the mean rate is 1.6 $m \cdot a^{-1}$. The sensitivity of this region increases towards the head of the bay. The mean score is 9.4 (n=32), the range 4.1 to 32, and the primary mode is in the 4-6 range.

The south coast – Digby Neck to the head of the bay

The coast is low and rocky in the southwest, and is characterized by scattered occurrences of pocket beaches. Close to Cape Split, cliffs up to 30 m high are located behind a wide rock platform veneered with coarse gravel. The region has predominantly low sensitivity. At the head of the bay, resistant bedrock cliffs predominate but major embayments at Scots Bay, Advocate Bay, and Salisbury Bay contain gravel barrier beaches fronted by wide intertidal mud and sand flats. Salt marshes lie behind the barriers. This area is moderately sensitive to impact due to rising sea level. The results could include more rapid barrier migration, and more frequent flooding of back-barrier tidal marshes.

Minas Basin

This moderately sensitive coastline consists of bedrock cliffs and bluffs, salt marshes, and wide intertidal sandflats and mudflats (Amos and Long, 1980). Impacts due to sea-level rise will include increased cliff and bluff erosion, and penetration of marine influence farther inland than at present, such as along rivers. However, parts of this region have been modified by engineering structures whose impacts exceed any potential impacts due to rising sea level. In particular, the causeway built at Windsor in 1970 forced rapid accumulation of mudflats, which impaired navigation up to 20 km downstream (Thurston, 1990). Similar impacts occurred in Chignecto Bay, at Upper Dorchester and Moncton, New Brunswick.

Chignecto Bay

This region lying in the Cumberland Basin is highly sensitive on account of extensive areas of tidal marshes and mudflats. In attempting to determine the impact of rising sea level on salt marshes, both here and elsewhere in the Bay of Fundy, certain considerations must be borne in mind. First, the projected increment is small relative to the tidal range. Rising sea level in the mid-Holocene caused the tidal range to be amplified, mainly between 7000 and 4000 BP, according to Scott and Greenberg (1983). The marshes persisted during this period, despite rapid increases in MHW level.

The second consideration is that the marshes have undergone considerable human modification. About 90% of the original 357 km^2 of salt marsh in the upper Bay of Fundy were once dyked; today, only 15% of the original salt marsh remains open to the sea. Some formerly dyked areas have been converted into freshwater wetlands in which invasive cattails have been controlled by re-admitting salt water to the former marsh.

Potential impacts of sea-level rise include the expansion of both salt-marsh and freshwater marsh environments due to higher water tables. This is one area of Canada where the threat of inundation must be rated high, because of increased risk of the dykes being breached during storm surges. The dyked areas are used not only for agricultural purposes, but also for transportation links. At Aulac, New Brunswick, the railway to Nova Scotia is adjacent to a dyke, and the newly widened Trans-Canada Highway is just beyond. Inundation of this region could disrupt agriculture and communications on a large scale.

The south coast of New Brunswick: Chignecto Bay to Grand Manan

This stretch of the New Brunswick coast has moderate relief, predominantly resistant bedrock, and little sediment in the littoral zone (Owens, 1977a). Martec Ltd. (1987) assessed the impact of a 1 m sea-level rise on the city of Saint John. They identified and mapped the 1:20-year and 1:100-year storm surge and flood levels associated with higher mean sea levels, and identified the natural and human features and activities that would be at risk. The impacts include inundation of sewage and industrial waste lagoons, industrial and harbour facilities, residential areas, farmland and part of the Trans-Canada Highway along the Saint John River, and potential surge damage to a power plant.

Sable Island

Sable Island (Fig. 14) is situated 200 km offshore from Nova Scotia, on Sable Island Bank, a sandy, relatively shallow part of the Scotian Shelf. It is unsettled except for a manned weather station. The island is 40 km long, less than 1.5 km wide, and represents the subaerial portion of a thick, late Quaternary sand body (Boyd et al., 1988). It is the remnant of a much larger island that was submerged during the Holocene transgression (King, 1970). It comprises high (up to 30 m) coastal dunes, scattered shallow ponds, sandflats, and sandy beaches fronted by nearshore bars (Taylor, 1988; Taylor et al., 1991). The Canadian Coast Guard maintains two navigation lights on Sable Island.

The island has a very high sensitivity index (54). In considering what this may mean in terms of impact, it should be remembered that the coastal environments on the island and adjacent shoreface are highly dynamic today. This is a result of high exposure to Atlantic wind and wave processes. Sand is continually cycled between the shoreface, nearshore bars, beaches, and coastal dunes (Taylor, 1988). Regarding the long-term effect of these processes, Scott et al. (1984) noted that the island had coastal dunes at 11 000 BP, that it had been shrinking northward, and that organic deposits in the centre of the island have maintained their position during the past 7000 years. From these observations, the following can be inferred: 1) the energetic process regime will be maintained or increased; 2) the island may continue to shrink as it has done for thousands of years; and 3) it will maintain its elevation through concurrent dune growth.

Impact on Pacific coastal environments

The Pacific coast (Fig. 24) has a length of 25 717 km, or 10.5% of the total Canadian coastline. It is a region of high relief, with mountains rising above 2500 m inland from the mainland coast. Glacial overdeepening during the Quaternary formed an intricate network of fiords which dissects the mountains on the mainland, Queen Charlotte Islands, and Vancouver Island. The mainland coast is formed in resistant

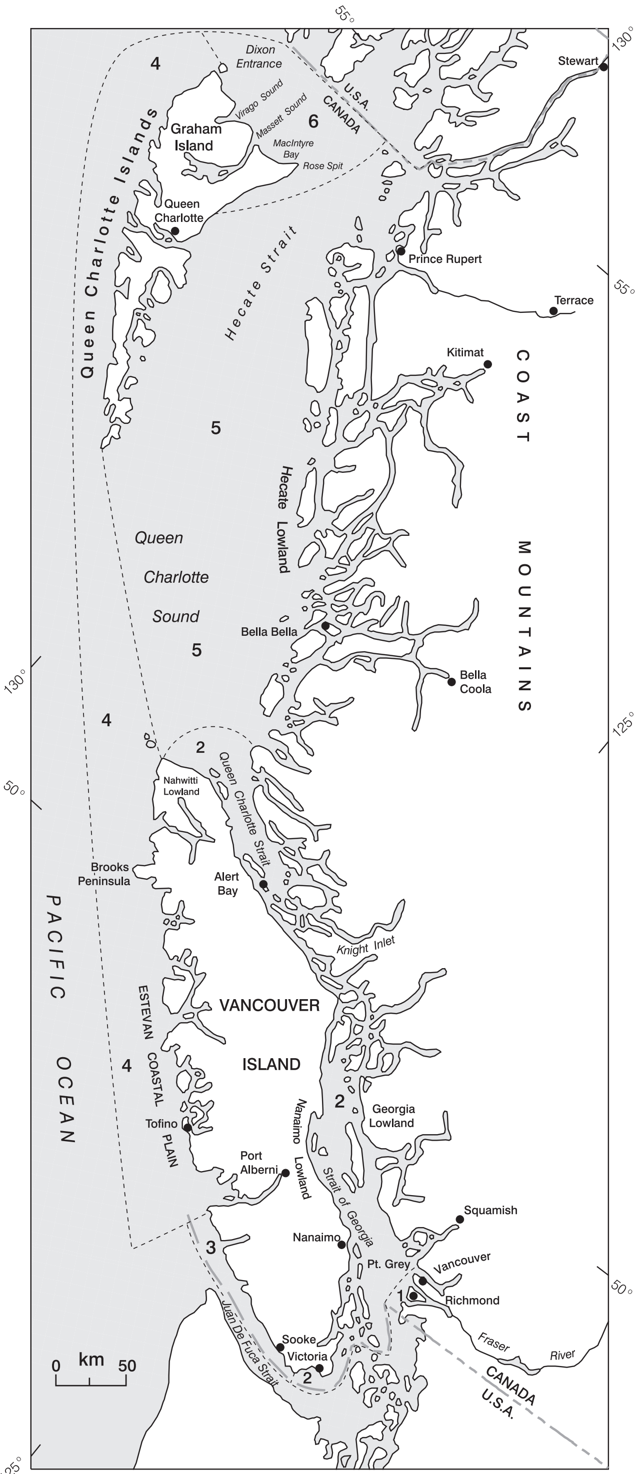

__Figure 24.__ Map of Canada's Pacific coast showing locations which are discussed in the text, together with the extent of Pacific coastal environments (dashed lines).

igneous rocks (Douglas, 1968), except for the Fraser Delta region, where Tertiary and Quaternary unconsolidated sediments occur. The Queen Charlotte Islands are underlain by volcanic rocks and granites, with a large area of unconsolidated Quaternary glacial sediments occurring in the northeast (Clague and Bornhold, 1980). On Vancouver Island, volcanic rocks, and granites predominate in the west, and Tertiary and Mesozoic sediments prevail in the east.

There is considerable variation in tidal range (Canadian Hydrographic Service, 1992), although most areas are mesotidal (mean range 2-4 m). Mean tidal ranges (large tides) at Sooke and Victoria are 3.2 m and 3.1 m respectively, but in the north of the province the range increases to 7.7 m at Prince Rupert, on the northern mainland, and 7.8 m at Queen Charlotte City, on Graham Island. Carrera et al. (1990) computed linear sea-level trends for coastal British Columbian sites and found that sea levels are falling at Tofino, Sooke, and Alert Bay, all on Vancouver Island, but are rising elsewhere. In the southern part of the province, a maximum rate of +3.07 $mm \cdot a^{-1}$ occurs at Port Alberni, and in the northern part the maximum rate is +3.32 $mm \cdot a^{-1}$ at Prince Rupert.

The northeastern Pacific Ocean is a high wave-energy environment. Brown et al. (1986) cited a report of significant wave heights greater than 20 m off the southern tip of the Queen Charlotte Islands. However, the configuration of the irregular and deeply indented coast leads to a complex distribution of wave energy because of sheltered environments in many areas. From a Petro-Canada report (1983) three coastal environments in northwestern British Columbia were delineated as follows: 1) the outer exposed coast, dominated by Pacific swell and storm waves; 2) the semi-exposed coast, with high to moderate wave energy; and 3) the mainland channel and fiord coast, with moderate to low wave energy.

Owens (1977a) described six coastal regions for this predominantly rocky coast, as follows: 1) Fraser Delta, 2) Queen Charlotte Sound–Strait of Georgia, 3) Juan de Fuca Strait, 4) Outer coast (Vancouver Island and the Queen Charlotte Islands), 5) Queen Charlotte Sound and Hecate Strait, and 6) east Graham Island. Most of the region has been assigned a score of 2 for erosion (i.e. a stable coast). One exception is the Fraser Delta, for which Clague and Bornhold (1980) cited a progradation rate of 2.3 $m \cdot a^{-1}$. At nearby Point Grey in Vancouver, average bluff recession rates of 0.3 $m \cdot a^{-1}$ occur in Quadra Sands, and threaten the Museum of Anthropology and other buildings of the University of British Columbia. In the Nanaimo Lowland, cliff retreat rates in excess of 0.3 $m \cdot a^{-1}$ are balanced by local accretion of coastal landforms, therefore scores of 2 have been applied to this region.

Clague (1989) summarized past and future trends of sea level on Canada's Pacific coast and discussed the potential impact of rising sea level. He stated that even a 2 m rise in the next century would have little effect on "the 85% of the British Columbia coastline that is rocky and relatively steep" (p. 31). He did, nevertheless, predict increased erosion of coastal bluffs (see below), and inundation of the deltas which constitute 1-2% of the coast. The results of the present study are in concurrence with those of Clague. Because of high relief, predominantly hard bedrock, an indented fiord coast, and low rates of sea-level rise, most of the region has low sensitivity, some areas are moderately sensitive, and two small areas are highly sensitive. The mean scores for the six regions range from 3.4 to 12.6. The possible effects of a future rise are discussed below with reference to the coastal units of Owens (1977a), although the nomenclature of the coastal sub-regions described by Clague and Bornhold (1980) is also used.

Fraser Delta

The Fraser Delta (Fig. 25) is an extensive feature (about 1000 km^2) that formed during, and subsequent to deglaciation by progradational infilling of the lower Fraser Valley and associated basins (Clague et al., 1983, 1991), and by continued growth into the Strait of Georgia. The subaerial delta ranges in elevation from 1-5 m above MWL, and is mantled by extensive bogs up to 4 m thick (Williams and Roberts, 1989). Extensive tidal marshes and intertidal flats form important migratory bird habitats. Submarine delta slopes are characterized by a wide variety of sedimentation rates and instability phenomena (Hart et al., 1993). Dredging of the river has reduced the amount of sediment reaching the Strait of Georgia.

The Fraser Delta supports a large and rapidly expanding human population (about 125 000 according to Clague, 1989) in the communities of Richmond and Delta. Causeways have been built across the tidal flats to the British Columbia Ferries terminal and the Roberts Bank coal-loading facility. Dykes along distributary channels and at the seaward edge of the delta plain protect urban property and farms from flooding. Many developed areas formerly occupied by marshes and swamps are 1 m or more below high tide level. Other important developments on the outer delta include Vancouver International Airport and a major sewage treatment facility.

The four NTS sheets included in this region have a mean sensitivity index score of 9.7, a minimum of 1.9, and a maximum of 24.8. The Fraser Delta is one of the two most highly sensitive areas on the Pacific coast. Sea-level rise would be added to the existing trend of +1.75 $mm \cdot a^{-1}$ at Steveston (Carrera et al., 1990). Impacts could include breaching of dykes, marsh erosion due to higher wave-energy levels on the intertidal flats, increased flooding potential in low-lying areas during periods of high discharge, coupled with high tides and wave setup. Clague (1989) suggested that groundwater levels in Richmond would reach the surface, thus requiring expenditures on pumping, and upgrading of dykes.

Queen Charlotte Strait and Strait of Georgia

This coastal region extends from the Fraser Delta northwards to Queen Charlotte Strait, and comprises a low, relatively exposed coastal plain backed by high, rugged mountains that are dissected by sheltered fiords. The Vancouver Island coasts have predominantly moderate sensitivity to sea-level rise, but those on the mainland coast are only slightly sensitive.

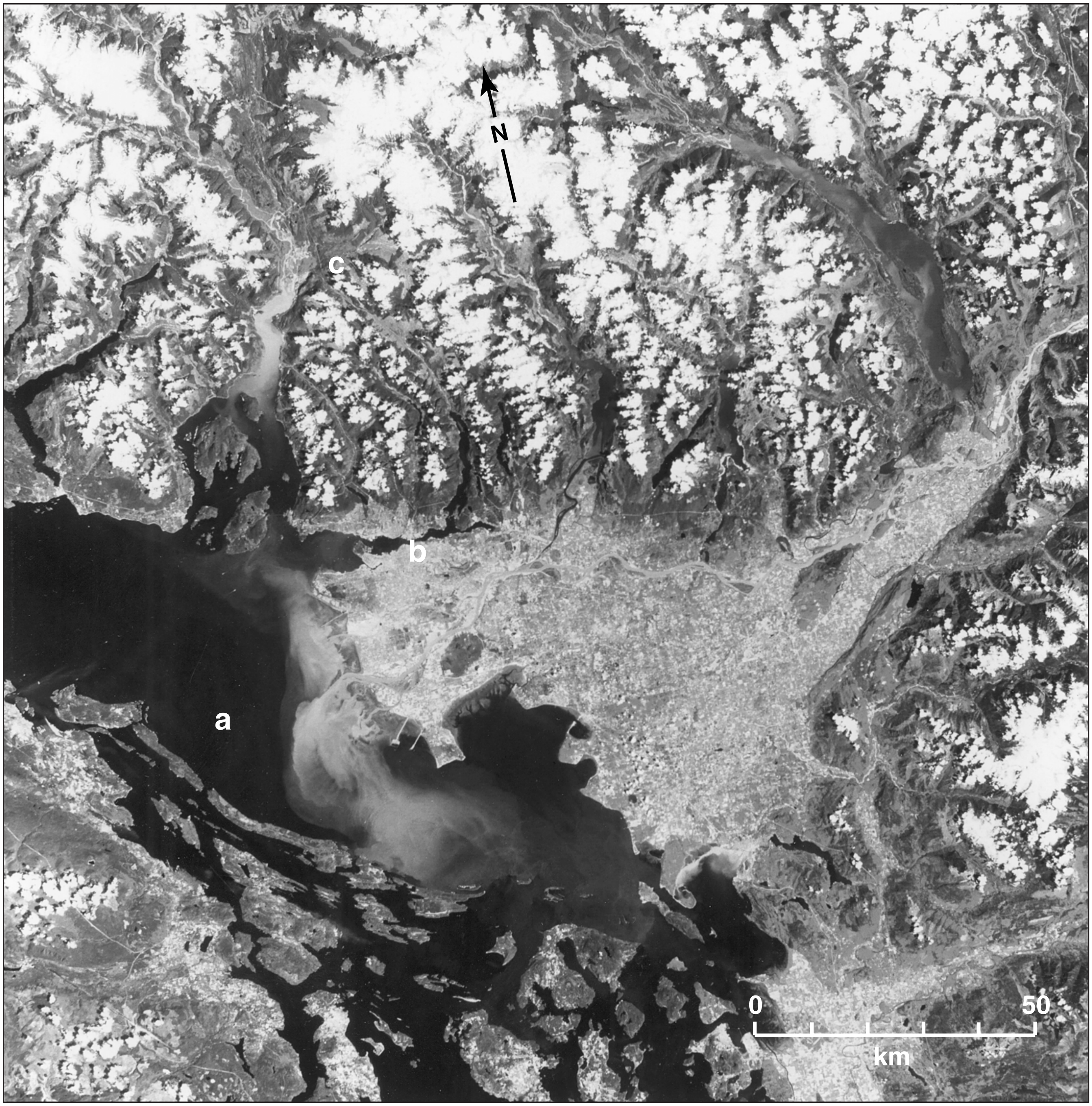

Figure 25. *Landsat 5 image of the Vancouver region, showing the highly sensitive Fraser Delta. The moderately sensitive coasts of the Nanaimo Lowland subregion (Vancouver Island and adjacent islands) lie west of the Strait of Georgia (**a**). The low-sensitivity coastline of the Coast Mountains is north of Vancouver (**b**). The delta at Squamish (**c**) is typical of fiord-head deltas on Canada's west coast. These areas of high sensitivity however, do not appear in Figure 2 due to their small size.*

Based on 47 cases, the mean sensitivity value is 4.8, the range 1.9 to 12.8. The distribution has a strong peak in the 0-2 interval.

Nahwitti Lowland

On Vancouver Island the region comprises two parts. The first is the Nahwitti Lowland, which is located at the north end of Vancouver Island and is relatively unindented compared with other parts of the island. Small deltas and gravel beaches are common in this somewhat exposed setting. Delta submergence and increased rates of beach retreat are possible hazards, although the area is not highly at risk, because it is experiencing no net submergence at present.

Nanaimo Lowland

The second subregion on Vancouver Island is the Nanaimo Lowland, which extends southwards along the east coast of Vancouver Island, to Juan de Fuca Strait. Abundant Quaternary deposits have supplied sediment to the littoral zone, thus forming numerous beaches, tombolos, and spits (see Fig. 24.28 of Clague and Bornhold, 1980). Breaching, overwashing, and migration of spits are possible consequences of sea-level rise, as exemplified at Goose Spit near Comox. A road is located on the narrow proximal section of this spit, and some development has taken place on the wider distal portion. This is a safety concern because the distal portion is susceptible to more frequent flooding or even permanent inundation. The population of the Gulf Islands, which form part of this region, is increasing rapidly. This expansion, in turn, increases the safety concerns for the area.

The extensive coastal bluffs of Pleistocene sediments in the region (Clague, 1989; McCann and Hale, 1980), like their counterparts in Atlantic Canada, are susceptible to more severe erosion in the future than at present. Rivers have formed large deltas at Comox and Nanaimo, where submergence of deltas could be a likely outcome of sea-level rise.

Georgia Lowland

The outer part of the mainland coast in this region, bordering the Strait of Georgia, was denoted the Georgia Lowland by Clague and Bornhold (1980). It is typified by a predominantly low, rocky and irregular coastline, with scattered occurrences of sand, gravel, and boulder beaches. Low rates of sea-level rise occur today, so that only small impacts may result.

Coast Mountains

The deeply dissected fiord terrain of the Coast Mountains extends north and landward of the relatively low, but more exposed, outer mainland coast. Although the fiord coasts have relatively low sensitivity, coastal deltas (Fig. 26) constitute an important class of landforms which might experience substantial impact if sea level rises (Clague, 1989). Apart from the Fraser Delta (see above), the deltas form two classes: 1) small side-entry deltas; and 2) fiord-head deltas. The first class comprises the innumerable small deltas formed where streams debouche from the mountainous hinterland into fiords. The streams, because of their small subaerial catchment, form small steep-gradient deltas, commonly with large subaqueous fans (Prior and Bornhold, 1989, 1990). These small deltas are more at risk from heavy rainfall and debris flows than from sea-level rise.

The second group, the fiord-head deltas, are large landforms developed at sites where streams draining large catchment areas meet the fiord coastline (Clague and Bornhold, 1980; Syvitski and Farrow, 1983). The subenvironments of these deltas include intertidal sand flats, low and high salt marshes, and supratidal delta plains. Rapid sea-level rise could result in inundation of some of these environments, more frequent flooding of others, and landward migration of salt-marsh zones. Industrial communities such as Squamish, at the head of Howe Sound, are located on some of these deltas.

***Figure 26.** Delta of the Klinaklini River, at Knight Inlet, British Columbia. The Coast Mountains in the background are above 1500 m in elevation. The delta is a small area of high sensitivity in a region with an overall low sensitivity to accelerated sea-level rise. Photograph by J.P.M. Syvitski, 1979. GSC 1995-278*

Juan de Fuca Strait

This region has a predominantly low, rocky coast with minor occurrences of unconsolidated bluffs and spits (Clague and Bornhold, 1980). The area is small, covered by only four NTS sheets. Sensitivity ranges from 4.8 to 5.1, on the boundary between the low and moderate domains.

The outer coast (Vancouver Island and Queen Charlotte Islands)

Although this region is exposed to extremely high wave-energy levels, nevertheless it has moderate to low sensitivity to rising sea level. This is due to the presence of hard rocky coasts, high relief, and trends of falling sea level. The distribution of the sensitivity index values shows a strong peak in the 4-6 range.

The western coast of Vancouver Island

The western coast of Vancouver Island (Chevron Canada Resources Limited, 1982) is deeply indented with fiords, many of which contain small deltas and coastal marshes (Clague and Bornhold, 1980) that are at somewhat higher risk. The Estevan coastal plain, which extends from the mouth of Juan de Fuca Strait to Brooks Peninsula, is bordered by low bedrock-dominated coasts. In places along these coasts, sandy beaches have developed from the erosion of unconsolidated Quaternary sediments. These beaches exhibit classical seasonal cycles of morphology, but may tend towards more persistent retreat if sea level rises. The seaward-facing part of the Nahwitti Lowlands lies at the extreme northern part of the region. It is an area of low relief, comprising rocky coasts with gravel beaches and small deltas. This area is moderately sensitive to rising sea levels.

The western coast of the Queen Charlotte Islands

The west-facing coasts of the Queen Charlotte Islands are developed in bedrock predominantly, and contain high cliffs and few beaches. Although this coast has low sensitivity, small deltas are common in fiords (their distribution is shown in Fig. 24.10 of Clague and Bornhold, 1980), and are slightly more sensitive to sea-level rise.

Queen Charlotte Sound and Hecate Strait

This is a large region comprising the mainland coast from a point just north of Vancouver Island to the Alaska border, and the east coast of the Queen Charlotte Islands, excluding east Graham Island (region 6). The coastline is characterized by rocky coastal lowlands backed by deeply indented fiord uplands. This coastal region has low sensitivity scores, largely due to resistant bedrock, high relief, moderate to low wave-energy levels, and moderate trends of sea level. Based on 86 cases, the mean is 3.4, the range 1.9 to 11, and the distribution has a strong mode in the 2-4 interval.

Hecate Lowland and Coast Mountains

The exposed Hecate Lowland is the northward extension of the Georgia Lowland. It is a region of low, rocky coastlines, including strandflat coasts, and scattered sand, gravel, and boulder beaches (Fig. 27). Like the Georgia Lowland it is backed by the Coast Mountains, an area of high relief dissected by fiords. Parts of the Hecate Lowland have moderate sensitivity on account of low relief, high wave energy, moderately high tidal ranges, and moderate to high rates of sea-level rise (e.g. +1.92 $mm \cdot a^{-1}$ at Bella Bella). These portions of the Hecate Lowland could be susceptible to increased rates of coastal change. Although the Coast Mountains have low sensitivity overall, deltas are numerous in this area (cf. Clague and Bornhold, 1980). Some of them are occupied by urban areas, such as those at Stewart, Kitimat, and Bella Coola. At these centres, flooding of residential and industrial areas is an additional hazard.

East Graham Island

This distinctive segment of the Pacific coast comprises two parts. One part lies west of Masset Sound, and consists of a low irregular coast that is developed in Tertiary basalts. Beaches occur on this coast along Virago Sound. The other part lies east of Masset Sound, where extensive Quaternary glacial deposits are a sediment source for wide, sand beaches backed by coastal dunes (Clague and Bornhold, 1980, p. 358; Harper, 1980). McIntyre Bay is the north-facing coast, and is backed by prograded raised beach ridges. The littoral drift system would appear to terminate in Rose Spit. South of Rose Spit the coast is eroding, and sediment is being removed from bluffs which are 60 m high in places (Fig. 28). Erosion rates up to 18 $m \cdot a^{-1}$ have been recorded recently by scientists of the Geological Survey of Canada based at Sidney on Vancouver Island.

The six NTS sheets in this grouping have a mean sensitivity value of 13, with scores ranging from 3.2 to 25. Harper (1980, p. 140) stated that shoreline progradation rates of 0.4 to 0.6 $m \cdot a^{-1}$ on the north-facing coast were "largely an effect of recent uplift on Graham Island". However, extrapolation of recent sea-level trends (Carrera et al., 1990) indicates that sea-level is rising in the area at a rate of about 15 cm/century. This contradiction is explained in a recent paper by Amos et al. (1992). These authors concluded that Rose Spit is not a spit in the true sense; it is a shelf-edge storm ridge constructed from sand moved in a northerly direction from Dogfish Banks by tides and wind currents. Progradation in McIntyre Bay is largely a result of sediment transport northward from the eroding east coast. At present the impact of a sea-level rise here is difficult to ascertain, but it may affect both onshore and offshore areas.

Impact on Arctic coastal environments

The Arctic is a remarkable region in many respects, not the least being its great length of coastline; it has a length of 172 950 km, or 70.9% of the total length of the coastline of

Canada. Furthermore the coastal areas comprise a remarkable diversity of environments that contain equivalents of all the more southern Canadian coastal types (deltas, barrier islands, spits, fringing sand beaches, and gravel beaches), as well as a suite of unique environments (e.g. ice coasts, breached thaw-lake coasts).

The geology of the Arctic shows great regional contrasts. For example, coastal regions of eastern Baffin and Ellesmere islands, and much of the mainland, are underlain by resistant Archean and Proterozoic rocks. These Precambrian rocks are overlain by Paleozoic sediments in the central Canadian Arctic Archipelago and southern Hudson Bay. Poorly consolidated

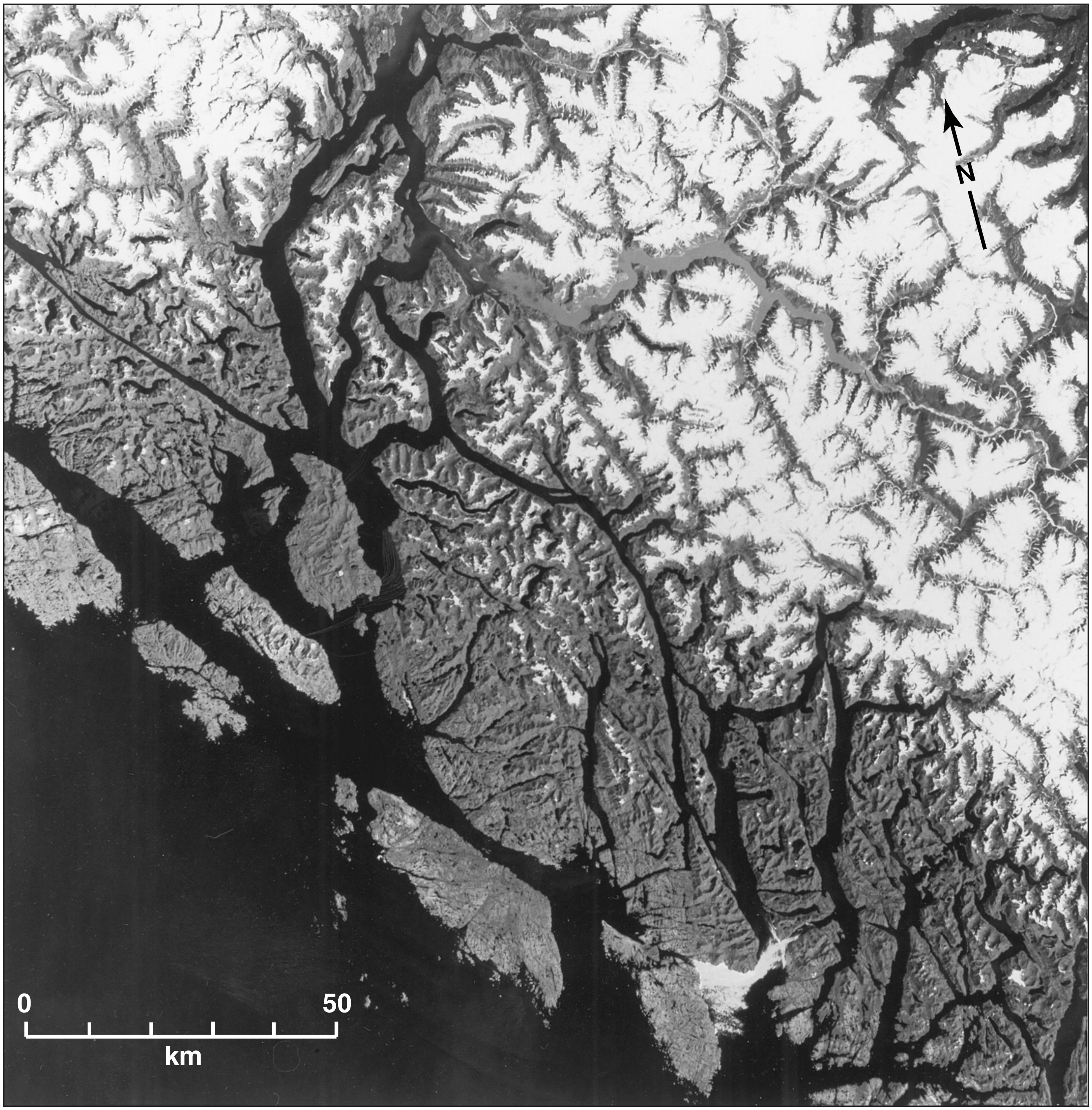

Figure 27. *Landsat 5 image, dated 16 July 1985, Hecate Lowland and Coast Mountains of British Columbia. This deeply indented, sheltered, fiord coast has mostly low sensitivity. The exceptions are parts of the low-lying outer coast, which have moderate sensitivity. Fiord-head deltas constitute areas of sensitivity which are too small to influence the overall rating.*

Mesozoic and Cenozoic sediments occur mainly on the outer fringe of Arctic islands and in areas adjacent to the southern Beaufort Sea.

Tidal range decreases northward and westward across the Arctic Archipelago. The large tidal range is highest (13.1 m) in Frobisher Bay, Baffin Island, more than 4 m along parts of Foxe Basin, 1-2 m in Barrow Strait, and typically less than 0.5 m along the western and northern fringe of the Canadian Arctic Archipelago and the Beaufort Sea. However, in the Beaufort Sea storm surges can raise tide levels by as much as 2-3 m (Harper et al. 1988). Along the eastern fringe of the Canadian Arctic Archipelago large tidal range varies from more than 4 m on southern Baffin Island, to less than 1 m on central Baffin Island, to more than 4 m in Nares Strait, and to less than 1 m on north Ellesmere Island. Tides are less than 4 m in Hudson Bay and James Bay.

Very few long-term tide-gauge records are available from the Canadian Arctic. The only records considered useful for the present study are those from Churchill (Manitoba) beginning in 1940 (Barnett, 1966, 1970), and from Tuktoyaktuk (District of Mackenzie) beginning in 1952 (Forbes, 1980). The water-level record from Tuktoyaktuk indicates rates of relative sea-level rise between 1.5 and 10 $mm \cdot a^{-1}$, depending on the method of analysis and data subset used (Forbes, 1980, 1989; Forbes and Frobel, 1985; Harper et al., 1985; Andrews, 1989a). A rate of submergence of about 4 $mm \cdot a^{-1}$, or 0.4 m per century (Andrews, 1989a), is reasonably consistent with geological evidence (Hill et al., 1985, 1993), and has been adopted here for the Beaufort Sea coast. In contrast, tide-gauge data and other lines of evidence for Churchill, on the southwestern coast of Hudson Bay, indicate continued rapid emergence at a rate of about 8-9 $mm \cdot a^{-1}$ (0.8-0.9 m per century). This location is near the centre of postglacial uplift associated with the former Laurentide Ice Sheet (Tushingham, 1992).

Elsewhere in the Arctic recent sea-level changes can only be estimated from longer-term, sea-level curves based on ^{14}C determinations (Andrews, 1989a). These curves indicate continuing emergence across much of the central Arctic, including Hudson Bay. Submergence is occurring in peripheral regions such as eastern Baffin Island, the northwestern fringe of the Arctic Archipelago, and the Beaufort Sea. Andrews (1989b) has tentatively suggested a submergence rate of about 0.5 m per century for the outermost coast of eastern Baffin Island.

Regarding wave-energy levels, the chief contrast with more temperate regions is the long duration of sea-ice cover, and the concomitant reduction in the duration of wave activity. This reduces the amount of wave erosion and sediment transport. Surprisingly, erosion rates along the Beaufort Sea coast rank with the highest recorded in Canada. This and other aspects of Arctic coastal processes are discussed below.

Information on coastal geomorphology for the Arctic was collated from many sources, including the Land Use Information Series maps (1:250 000) by Environment Canada, coastal geology maps of the north-central islands and Northwest Passage by Woodward-Clyde Consultants (1980, 1981), W.B. Barrie and Assoc. (1982), McLaren and Barrie (1985), McCann (1988), and environmental atlases for the Beaufort Sea (1987) and Lancaster Sound region (1990) by D.F. Dickins Associates Ltd. and Environmental Sciences Ltd. In addition more than 20 years of field experience by the authors of working in the Arctic was incorporated.

Systematic mapping and ranking show that the Arctic has low sensitivity to sea-level change overall, with some important exceptions; in particular, the Beaufort Sea region is highly sensitive.

Coastal processes in the Canadian Arctic

Although many of the processes operating on Arctic coasts are similar to those observed in southern Canada, others involving sea ice, permafrost, and ground ice are unique to high-latitude settings. Furthermore, the relative duration and importance of specific processes increase or decrease in relation to severity of the climate. If the regional climate warms

Figure 28.

The east coast of Graham Island is judged as one of the most sensitive areas of British Columbia coast. This photograph by C.L. Amos in 1991 shows erosion of Pleistocene fine sand in Nootka National Park. GSC 1995-280 due to global change, it follows that the relative importance of the various processes would also change. We argue that the impact of these changes on coasts may be more significant than that of sea-level changes alone, and demonstrate this view in the regional discussions later in the paper.

Wave processes

The ability of waves to modify the beach and shoreface is dependent upon the extent and duration of open water. In spring, areas of open water appear in the southern and eastern Arctic first, then progressively farther north and west as the summer advances and break-up continues. The flow of water throughout the channels is to the east and south, except for current-driven flows (and tidal flows) from the east. For example, Cape Chidley, Labrador may have 4 months of open water and be exposed to the full fetch of the Labrador Sea whereas Mackenzie King Island in the northwest experiences open water only in the form of narrow shore leads for 1-2 months.

At the local scale, the effectiveness of waves in reworking the coast is limited by the presence of shorefast ice, grounded ice, or floating sea ice offshore. During storms, higher energy waves can be generated offshore and, within hours, sea ice may be driven onshore (Fig. 29). As a result, wave energy at the shoreline is either selectively focused in non-ice covered areas, dampened in ice-covered areas, or shifted offshore to the edge of grounded ice, where ice wallowing forms depressions on the sea bed.

Wave attack on a shore is also influenced by the tidal stage at the time of the event. For instance, moderate storms that coincide with high water cause more shoreline change than storms with higher energy waves that coincide with low tide. Coastal flooding and shoreline erosion are reported to be more extensive during storm surges in the Beaufort Sea (Harper et al., 1988; Forbes, 1989) than during storms without surges. The probability of a storm occurring with maximum wind fetch, open water, and tides, is very low.

Wave energy at the coast is zero for 8 to 12 months each year, very low for most of the open water period, and high only during short, infrequent storm events. In a relative sense, wave-energy levels in much of the Arctic are several orders of magnitude lower than on parts of the Atlantic and Pacific coasts (Woodward Clyde Consultants Ltd., 1981). In compiling the wave-energy data for the Arctic, most areas have been given the lowest score for wave energy.

In calculating the sensitivity index we have not factored in the possibility of reduced sea-ice extent, although there is an emerging consensus that this will result from global warming. In a study of future sea-ice extent in the Beaufort Sea under a doubling of carbon dioxide, McGillivray et al. (1992) indicated that the duration of the open-water season would increase from 60 to 150 days at 70°N, and from 0 to 60-120 days at 80°N. The southern boundary of residual ice in late summer would migrate 570 - 860 km northward from the present position. This would increase the intensity of wave action on the mainland coast of the Beaufort Sea, as well as on Banks Island and the Queen Elizabeth Islands. For the Kopanoar wellsite, in the southern Beaufort Sea, McGillivray et al. (1992) estimated that the maximum significant wave height would increase by 39% due to fetch increase (e.g. for a 100 year return period wave height would increase from 7.3 to 10 m).

Because storm surges are also more frequent in the Beaufort Sea during years when the extent of open water is greater (e.g. the 1963 open water season had 10 surges (Henry, 1975; Milne and Herlinveau, 1977), then a greater frequency of surges is anticipated in the future. This follows from the argument that global warming will produce larger and more persistent areas of open water.

Figure 29.

Ice in the breaking-wave zone, Bylot Island, 18 August 1979. The upper beach face is protected from overwash, but the lower beach is scoured by wallowing ice. Photograph by R.B. Taylor. If the extent and duration of sea ice were to be less in the future, Arctic beaches would be more directly impacted by waves for longer periods of time. GSC 1995-281A

A reduction in sea-ice thickness and duration would, arguably, exert more influence on Arctic coasts than a sea-level rise. It is assumed in this study that shores which are very rarely worked by waves today, because of the persistence of sea-ice cover, would be more severely impacted by an increase in open water than areas that are seasonally reworked by waves at present. For example, the low, sand shores of the northwestern Queen Elizabeth Islands are characterized by poorly compacted beaches and thixotropic tidal flats which consist of larger amounts of fine sediment deposited by eolian, slope, and fluvial processes (Taylor and Forbes, 1987). An increase in wave action would result in winnowing of fines, sediment compaction, and better defined wave-built features. Ice-built features would become more ephemeral. As sea levels rise and wave energy increases it is anticipated that many of the low sand beaches and barriers will be overwashed, possibly destroyed or moved landward; ice-built shore ridges along the northwest Queen Elizabeth Islands could be destroyed or could form the core for new barrier beaches.

Within the Arctic islands the maximum potential fetch is limited by either sea ice or the presence of other islands. In areas where maximum open water occurs now, the fetch cannot increase because of topography, but, given a longer duration of open water, the frequency of large storm waves could increase. In the eastern Arctic Islands the areas where greatest changes in morphology are anticipated include the low sand barriers fronting glacial outwash plains, or coastal forelands and areas where small barrier islands and spits are built across marine rock platforms. As sea level rises and/or wave energy increases, wave propagation across the marine benches will be altered by refraction, thus causing planiform changes to the barrier beach, spit, and inlet complexes. Increased wave attack against higher parts of the present shoreline is expected to result in increased erosion but also a larger supply of new sediment for beach building. Increased sediment supply and storm frequency will result in the formation of higher beach ridges, particularly along swash-aligned beaches.

Sea ice

Although sea ice inhibits wind wave generation and propagation, ice also bulldozes, scours, mobilizes, resuspends and rafts sediment (Reimnitz et al., 1990), and is responsible for many distinctive features found along Arctic shores (Forbes and Taylor, 1994). A thinning of sea ice as a consequence of increased air temperature is expected to have a larger impact on sea-ice processes than a rise in sea level. Bilello (1961) showed that a 10°C warming would lead to a 34% reduction in winter ice thickness. It could be argued that a thinning of sea ice could result in an earlier break-up of the ice canopy and, therefore, a longer season of open water. If the sea ice becomes more mobile, a greater potential exists for ice to impact directly on the coast. Other consequences of thinner sea ice would be a slight landward shift in the zone of grounding, a higher frequency of shore ice ride-up, shallower bulldozing of shore sediment, and a decrease in the height of shore ice pile-ups.

At present in the Beaufort Sea, ice scouring is most frequent in water depths lying between 10 and 40 m. Ice is reported to be scouring the shoreface profile between depths of 12 to 15 m and depositing sediment in shallower waters by means of ice-push (Héquette and Barnes, 1990). Some workers have argued that the high rate of shoreline retreat in the Beaufort Sea is driven by ice scouring offshore as the shoreface profile adjusts to reach a state of equilibrium (Héquette and Barnes, 1990). On the other hand, Reimnitz et al. (1990) have suggested that ice can scour the shoreface and move sediment onshore to nourish beaches.

It is anticipated that the quantity of icebergs and bergy ice would increase, in some areas at least, due to increased tidewater-glacier calving. Frazil ice generation would also increase with increased wave action during freeze-up (Reimnitz et al., 1987), but little change in icefoot or shorefast ice characteristics is anticipated unless changes in tidal regimes occur.

Permafrost, ground ice, and glacial ice

All of the shores in the Arctic are underlain by discontinuous or continuous permafrost that seasonally melts at the surface. The depth of thaw varies from tens of centimetres to nearly 2 m depending on the geographic and climatic setting, position on the coast, and sediment texture. The surface of seasonally ice-bonded sediment fluctuates upward and downward within the beach in response to changes in sediment accretion or erosion (Taylor, 1980a). Hence, the combined effects of warmer temperatures and greater beach changes due to increased waves may alter beach thermal regimes.

Many sandy shores of the Arctic Coastal Plain region are fringed by a band of bottomfast ice that extends from approximately low tide level to water depths of 2-3 m (Taylor and Forbes, 1987). The origin of this ice is unknown but it is speculated that, in the central Arctic islands, it is the result of fresh groundwater draining off the land and being supercooled as it empties into the sea in the fall (Sadler and Serson, 1981). The bottomfast ice locally plays an important role in the stability of shoreface slopes. The impact of a rising sea level on these ice features is unknown.

The coasts with the highest sensitivity (Table 1) are ice-rich unconsolidated shores, and ice-shelf and tidewater-glacier shores. Tundra cliffs, particularly along the Beaufort Sea coast, consist of ice-rich unconsolidated Quaternary deposits, in which the ice content may exceed 80% by volume in places. Shoreline recession averages more than 1 $m \cdot a^{-1}$ with maximum rates exceeding 10 $m \cdot a^{-1}$ (Forbes and Frobel, 1985; Héquette and Barnes, 1990). A continued rise in sea level would adversely affect the coast by enhancing the main shoreline erosional processes, including surface wash, ground-ice slumps, debris slides, and thermo-erosional block failure (Harper, 1978; Forbes and Frobel, 1985).

Glacier mass balance is determined by the net accumulation (winter) minus the net ablation (summer). Negative balance leads to surface lowering and, with a time lag dependent on glacier size, to retreat of the terminus (Barry, 1986). Syvitski (1987) measured changes in glacier fronts in Baffin Island fiords over the period 1948 to 1985. He found typical retreat rates of 7-10 $m \cdot a^{-1}$ (up to 50 $m \cdot a^{-1}$ over shorter periods) for most glaciers and advances of 10-12 $m.a^{-1}$ at two tidewater glaciers. Retreat of glacier fronts recorded on Baffin Island in the 1980s may result from earlier climatic warming (e.g. the warming period in the 1940s – Syvitski, pers. comm., 1993).

Tidewater glaciers are common on Devon, Bylot, Baffin, and Ellesmere islands. These ice coasts have been scored as highly sensitive to sea-level change. Glacier retreat due to sea-level rise may be balanced by glacier advance caused by increased precipitation under conditions of a warmer climate (increased precipitation in both July and January was predicted by McGillivray et al., 1992). Fluctuations in ice-front position can be locally significant, and material deposited at the ice front will also vary with time and location along the terminus. In some cases there will be little or no net change recorded. However, because of the uncertainty of the response, tidewater ice shores have been assigned a high sensitivity to change. It has been estimated for the Greenland ice sheet that the rate of ice flux due to calving would increase by approximately 3.5 times for the 3°C surface warming predicted by the GISS (Goddard Institute for Space Science) scenario (Barry, 1986). Where proglacial sediment becomes exposed to waves as the ice front retreats, the texture and form of the sediment are modified by waves into new littoral features.

Fluvial processes

High volumes of discharge from Arctic rivers are confined to the short period of spring melt, or to periods of precipitation during summer. During episodes of high fluvial discharge, beach ridges in front of river mouths or deltas are breached and large pulses of sediment are deposited in the littoral zone for later reworking by waves. At present, in areas such as the Arctic coastal plain, where there is little or no wave activity to rework that sediment, deltas have prograded long distances offshore (Forbes at al., 1986; Forbes and Taylor, 1994). Increased wave action will result in greater longshore transport of fluvial deposits and faster closure of river mouths by nearshore bars during low discharge periods. Where large deltas protrude long distances offshore they will affect inshore wave patterns and may become subject to erosional trimming.

Deltas form a large percentage of the Arctic coastline particularly along the Beaufort Sea (Mackenzie Delta) and the Arctic Coastal Plain. Many of these deltas will become more susceptible to flooding as sea level rises. Increases in summer temperatures would have little effect on discharge unless both summer and winter precipitation were also to increase. Then, a more sustained runoff period would be expected as well as a more extended period of sediment deposition into the littoral zone.

Slope processes

Increased wave attack at the base of cliffs and steep shores could initiate increased instability across the upper slopes and the deposition of additional debris in the shore zone. Upper slope failure could occur along the unconsolidated shore bluffs or talus-banked cliffs of the eastern Arctic but even more so along shores composed of ice-rich, fine grained sediment, such as those found in the Beaufort Sea.

Ungava Bay, Hudson Strait, and Frobisher Bay

Except for Akpatok Island, which is composed of Ordovician sediments, this region (Fig. 30) is underlain by hard Proterozoic rocks. The coastal areas of these water bodies are characterized by moderate or high relief. Tidal ranges are high in Ungava Bay, where the range increases towards the head of the bay, from 7.3 m at Port Burwell to 13.6 m at Lac aux Feuilles. From Wakeham Bay (11.3 m), the range decreases westwards along the Ungava coast to 3.0 m at Port de Laperrière in Digges Island. Information on recent relative sea-level trends in the Ungava region must be obtained from relative sea-level curves and geomorphological data. Data published by Andrews (1989a) suggest that the outer parts of the Hall and Cumberland peninsulas on Baffin Island are submerging; elsewhere, sea level is falling. The curve given in Allard et al. (1989) for the Kangiqsualujjuaq area suggests that relative sea level has fallen there at a rate of 4.0 $mm \cdot a^{-1}$ for about 2 ka. Coastlines are predominantly rocky and this, combined with the occurrence of resistant rocks and trends of falling sea level, results in predominantly low sensitivity; however, extensive areas of moderate ranking are present. Based on a total of 264 NTS sheets, the mean sensitivity score is 3.6 with a the range 1.5 to 8. The sensitivity distribution has a strong peak in the 2-4 range.

Ungava Bay

This bay has a high tidal range (see above), and wave action is restricted to a 3-month ice-free period. The coastlines of Ungava have several aspects as follows: the eastern coast is predominantly low and rocky; the southern coast is low with wide intertidal mudflats, and includes the estuaries of the Koksoak and George rivers; and the western coast is low and rocky, with inlets containing wide intertidal mudflats. The region has predominantly low sensitivity, with some areas of moderate score (just above 5). The most sensitive environments are the wide, boulder-strewn intertidal flats described by Lauriol and Gray (1980). However, a future sea-level rise would be counteracted by continuing land emergence at rates of more than 3.0 $mm \cdot a^{-1}$, resulting in an approximately stable sea level for the next half century at least. Lauriol and Gray (1980) described elevated boulder barricades in the Leaf Basin which, they asserted, formed during pauses in land emergence. From this it could be concluded that future sea-level rise might result in the organization of boulder fields into boulder barricades.

Hudson Strait

The mainland coast of Hudson Strait is a cliff coast (Owens, 1977a) with relief up to 600 m and with numerous fiords in some sections. Sensitivity is low because of resistant Proterozoic outcrops, high relief, continued land emergence, and predominantly low wave energy restricted to a three-month period of open water. On the northern side of Hudson Strait, the coasts of Baffin Island exhibit more variability. Although one area has a score barely within the moderate domain, the coast is mostly rugged and rocky, with low sensitivity to sea-level rise.

Southeastern Baffin Island

The coast in this region is underlain by resistant Proterozoic rocks, and is predominantly steep and rocky. However, coastal variability is greater than in Hudson Strait, largely as a result of the presence of unconsolidated Quaternary sediments in some coastal areas. This has led to the formation of beaches and barriers (Miller et al., 1980); elsewhere, deltas and fluvial distributary plains occur at the heads of fiords.

This region has low sensitivity but significant areas of moderate sensitivity occur also, partly because eastern areas are submerging and can experience high wave-energy levels when exposed to storm waves generated in the Labrador Sea. The illustration on page 259 of Miller et al. (1980) shows York Sound, which is a typical susceptible environment in this region. Here, a low barrier extends across the bay. Extensive delta flats are present, and eroding, raised unconsolidated

Figure 30. *Map of the coastline of Hudson Bay and adjacent regions, with coastal environments defined by Owens (1977a) indicated. The dashed line, which crosses Hudson Bay, separates sub-environments 2a and 2b.*

deposits can be seen in the background. Barrier migration and inundation of low-lying delta flats are likely results, especially because the site is located close to the zero isobase of vertical movement.

Hudson Bay and James Bay

Tides in this inland sea (Fig. 30) range from microtidal, in the vicinity of Inukjuak, to mesotidal in northwestern Ungava and along the south and west coasts of Hudson Bay. Tidal data from Churchill indicate that mean sea level has been falling at a rate of 0.8 to 0.9 m/century (Carrera et al., 1990; Tushingham, 1992). This is somewhat greater than the rate of 6 $m \cdot ka^{-1}$ shown in Figure 8.11 in Andrews (1989a). Nevertheless, because of the lack of suitable tidal data elsewhere in the region, Andrews' compilation, based on sea-level curves, is used in calculating sensitivity indices. The data indicate that most of the region is emergent, with an uplift centre in James Bay where the rate is in excess of 12 $m \cdot ka^{-1}$. Emergence rates decline to less than 4 $m \cdot ka^{-1}$ along the north coast of Ungava.

Hudson Bay and James Bay are ice-covered for much of the year. In James Bay, ice forms in November and breakup commences in late May. Published wave data are sparse, and there is no information comparable to that given by Neu (1982) for the Atlantic seaboard. Limited summer observations in Hudson Bay show median wave heights ranging from 0.9-1.5 m. Greater wave activity would be expected to occur in the fall, just prior to freeze up; on the other hand, large areas in James Bay are relatively protected. The report by Environmental Applications Group (1983) gives predicted values of significant wave height for the 10 year storm at various locations in Hudson Bay, and these values range from 10.7-14.0 m. The same report cites Environment Canada marine observational data showing monthly wave maxima ranging from 1.5-8.2 m. Although the fetch is very large in many regions, the ice-free season is a mere 2-4 months. For the purposes of this paper, all of Hudson Bay has been given a score of 3 for wave height; however, James Bay and deep inlets are given a score of 1.

Owens' (1977a) classification divides Hudson Bay into two parts as follows (Fig. 30): 1) subregion 2a, which comprises the southwestern coasts of Hudson Bay and James Bay; and 2) subregion 2b, which consists of the eastern coasts of Hudson Bay and James Bay, the northwestern coast of Hudson Bay, Coats and Mansel islands, and part of Southampton Island. The distribution of coastal sensitivity in these two subregions differs greatly. In subregion 2a, the distribution is strongly bimodal, with a primary mode in the 8-10 interval, a secondary mode in the 4-6 interval, a range of 2.6 to 13, and a mean value of 7.6 (n=91). In subregion 2b however, the distribution has a mean of 4.4 (n=216), a range of 0.8 to 14, and a modal peak spread across the 0-6 range. To a large extent, these differences reflect the differences in relief and coastal geomorphology; for example, subregion 2a consists of sensitive beach-ridge and marsh coastlines, but coasts in subregion 2b comprise bedrock predominantly.

The eastern coast of Hudson Bay

The region from Pointe Louis-XIV (Cape Jones) to Guillaume-Delisle Lake (Richmond Gulf) is dominated by shore-parallel seaward-dipping cuestas developed in Proterozoic sedimentary rocks (Dionne, 1976b; Guimont and Laverdière, 1980), with Archean rocks at the coastline in some places. The west-facing coasts of the outer island chain are generally low and rocky, but the east-facing coasts are higher, with talus-fronted cliffs several hundred metres high in many places. Landward of the islands, the coast is variable, and commonly fringed by beaches and narrow tidal flats. Data contained in assessment reports of oil-spill sensitivity (Environmental Applications Group, 1985) show that similar coastal morphology extends along the remainder of this arcuate coastline as far as Inukjuak. The Belcher Islands comprise a series of arcuate ridges formed by gently plunging synclines and anticlines developed in Proterozoic rocks. The coastline around these islands is low and rocky.

This coastal region is one of low sensitivity for almost all criteria, and particular emphasis must be placed on the offsetting effect that continuing isostatic rebound will have on a global sea-level rise. However, there is a possibility that global change might be accompanied by changes in the discharge of rivers into the bay, and by the extension of the open-water period.

The eastern coast of James Bay

Descriptions of this region by Dionne (1976a, 1978, 1980) show that south of Pointe Louis-XIV, low-relief, Archean crystalline bedrock is mantled by Quaternary deposits which thicken southward. North of Eastmain River these deposits comprise till, glaciofluvial, and marine deposits; the thicker deposits to the south include lacustrine sediments of Lake Ojibway and marine deposits of the Tyrrell Sea. The irregular coastline along the northeastern part of the bay consists of numerous low, rocky and drumlin islands, sand and gravel beaches, tidal flats, and small salt marshes. The middle section has more extensive tidal flats, salt marshes, and deltas. At the head of the bay is a low coastal plain that is crossed by the Harricana, Nottaway, Broadback, Rupert, and Pontax rivers. The coastal region consists of extensive muddy tidal flats, salt marshes, and coastal marshes.

The eastern James Bay coast has moderate sensitivity scores, largely as a result of the relatively low wave energy and continuing isostatic rebound. If these low shores occurred on the subsiding Atlantic coast they would be highly sensitive to sea-level rise. As it is, a reduction in the rate of sea-level fall would result in accelerated vertical accretion of salt marshes in some areas, and erosion of both salt and freshwater marshes elsewhere. Another effect might be the construction of spits and barriers along the more exposed northern extremity. Extension of the open-water period, which is not factored into the sensitivity calculation, would make the region more sensitive to coastal erosion during periods of storm surges; however, other effects might include accelerated salt-marsh growth due to longer periods of storm-induced sediment suspension.

Southwestern James Bay

Coastlines extending from the head of James Bay westward to Churchill (Fig. 31) are part of the Hudson Bay Lowland (Martini, 1981, 1982, 1989), a 325 000 km^2 region in which Paleozoic and Mesozoic rocks are mantled by Quaternary deposits and thick, extensive freshwater peats. Martini et al. (1980) showed that the southwestern coast of James Bay consisted of three types: 1) estuarine coasts, in the vicinity of the Moose, Albany, and Attawapiskat rivers, with wide salt and brackish marshes that extend landward of gently sloping tidal flats; 2) gravel and sand ridges that extend seaward across the tidal flats in some interfluvial areas, and lie transverse to the

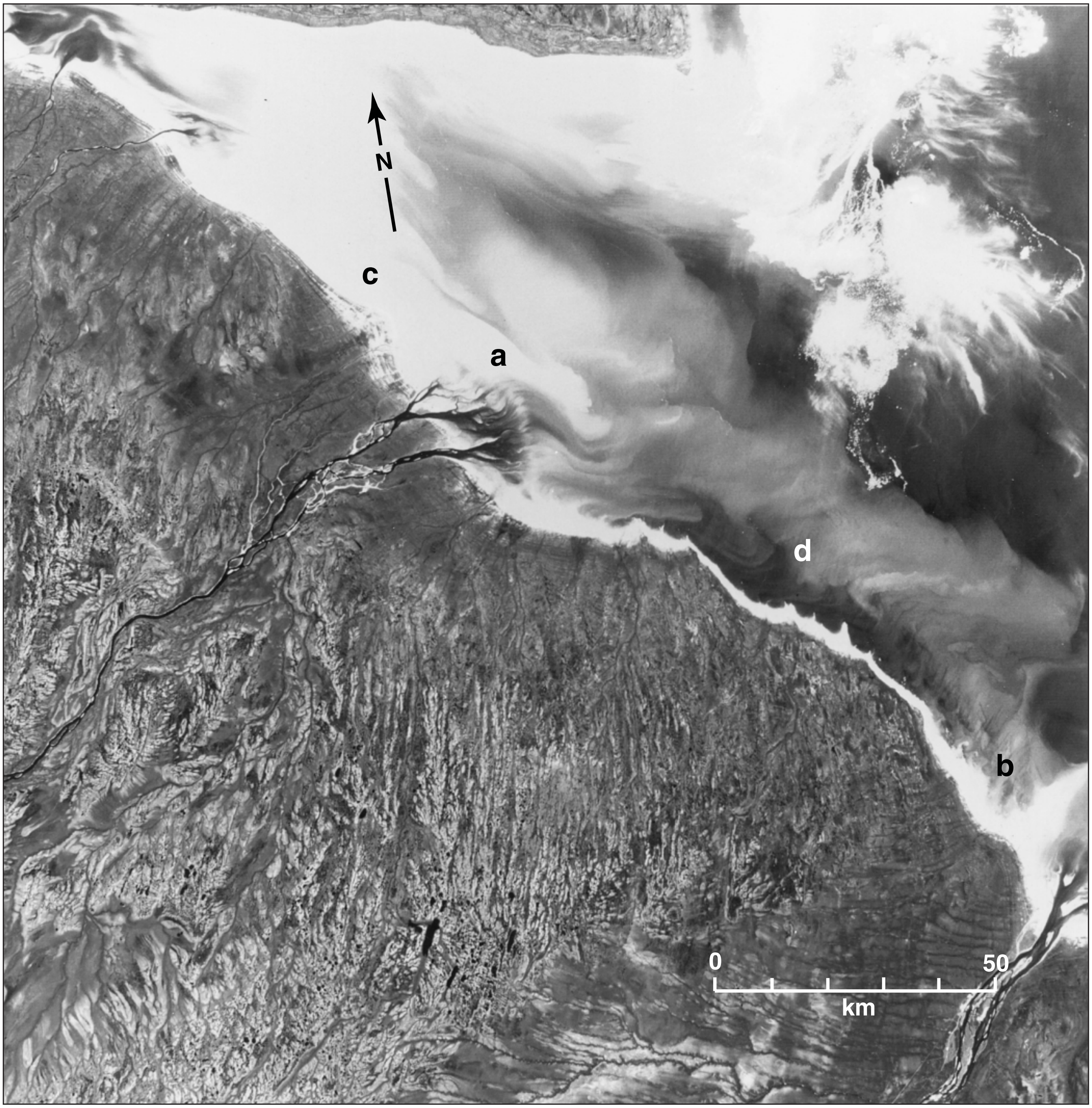

Figure 31. *This image depicts the moderately sensitive, low-lying coast of southwestern James Bay. If not for the rapid rates of relative sea-level fall occurring here, this coast would be highly vulnerable. This Landsat 5 image, dated 21 June 1985, shows the estuaries of the Albany River (**a**), Moose River (**b**), the beach-ridge coast northwest of Albany River (**c**), and a stretch of coast with the shore-normal promontories discussed by Martini et al. (1980) (**d**).*

coast; and 3) pebble and sand beach ridges that are oriented parallel to the coast in some interfluvial areas, and which are fronted by tidal flats and tracts of salt marsh. A beach-ridge coastline with limited marsh is predominant north of Akimiski Island (Taylor et al., 1989). At Cape Henrietta Maria, a large cuspate headland is formed by shingle beach ridges that are overlain by coastal dunes (Martini et al., 1980, p. 294).

As with the eastern coast of James Bay, the southern and western coasts consist of sensitive landforms largely. However, the effects of rising sea level are mitigated by low wave energies, moderate tidal levels and, most importantly, by continuing rapid, isostatic rebound. The result is that sensitivity indices occur in the low to moderate range, and the predicted effects are similar to those noted for the eastern James Bay coast (above). These effects might include the formation of higher storm beaches in some areas. Elsewhere, the result could be the vertical growth of barriers due to the combined effects of wave action and eolian activity, such as at Cape Henrietta Maria.

The southwestern and western coasts of Hudson Bay

Martini et al. (1980) and Martini (1981,1982) wrote that this coast includes the three components discussed above (estuarine coasts; parallel beach ridges and spits; and coasts with promontories and transverse ridges). The Winisk River estuary is one estuarine coast that they describe. Other major rivers discharging into the bay are the Severn, Nelson, and Churchill. The region has moderate sensitivity, largely due to continuing emergence.

In the area between Churchill River and Chesterfield Inlet, the low rocky coast contains extensive, wide tidal flats and has moderate sensitivity. North of Chesterfield Inlet (region 2b of Owens, 1977a) the indented, resistant rocky coast has greater relief than elsewhere in this region, and has low sensitivity. On both these parts of the west coast, continuing emergence is partly responsible for lowering the sensitivity to rising sea level.

Southern Southampton Island, Coats Island, and Mansel Island

In marked contrast to the northeastern coast, the western and southern coasts of Southampton Island are developed in Paleozoic rocks, and are low, with continuous beaches and wide tidal flats. On the western coast the intertidal zone is about 6 km wide (Dunbar and Greenaway, 1956). Most of this region is moderately sensitive, and the likeliest effect of sea-level rise would be a landward migration of the coast. Coats and Mansel islands belong to the Paleozoic lowlands, and have low relief, with continuous beaches backed by flights of raised beaches. They have moderate sensitivity, except for the northeastern coast of Coats Island, where Precambrian bedrock cliffs are about 200 m high.

Fiord coasts (Baffin, Bylot, Devon, and Ellesmere islands)

Syvitski et al. (1987) noted that 50% of Canada's fiords occur in the Arctic islands. Most are located within this region, which comprises Bylot, Devon, Coburg, and Ellesmere islands, and most of the eastern coast of Baffin Island (Fig. 32). Relief is generally high along the coast, and ranges to a maximum of 2133 m on Baffin Island. Typically, bedrock consists of resistant Archean and Proterozoic rocks. Exceptions include: Cretaceous and Tertiary sandstones and shales exposed along southwestern Bylot Island and small parts of northeastern Baffin Island (Jackson et al., 1975); pockets of Cambrian and Ordovician sedimentary rocks occurring along parts of eastern and northeastern Devon and northern Ellesmere islands; and Paleozoic and younger sedimentary rocks lying at the head of some fiords that extend into the central part of Ellesmere Island, such as at Makinson Inlet.

The range of large tides decreases northward from 2.8 m at Cape Dyer to 0.6 m at Cape Christian, and then increases northward. Large tidal ranges are 2 and 2.7 m on the southern and northern shores of eastern Lancaster Sound, 3.5 m at the eastern end of Jones Sound, and 4.5-4.9 m in Smith Sound. Farther northward, the tidal range decreases to 0.9 m at Alert, on the northeastern corner of Ellesmere Island (Greisman et al., 1986). No long-term tidal records are available from the region to document the submergence of 50 cm/century indicated for the past 1 ka by Andrews (1989a). Submergence occurred on Cumberland Peninsula and the northern part of Baffin Island, but the intervening stretch of coast emerged up to 2 m. The Ellesmere Island coast emerged at rates of 1- 4 m over the same period (Andrews, 1989a). Baffin Bay has the longest potential wind fetches in the eastern Arctic. However, the ever-present sea ice (Fig. 33) and the short ice-free season (<130 days) along the coastline restricts the magnitude of waves generated in the bay. In Davis Strait waves 6 m in height are common (Nordco Ltd., 1978) but in northeastern Baffin Bay the maximum recorded wave height is 6 m (Maxwell, 1982).

Few erosion rates are available. They are low for the resistant bedrock shores but are thought to be high along the unconsolidated shore bluffs of the coastal forelands of eastern Baffin Island and Eclipse Sound. During a high-energy wave event on Bylot Island, ice-bonded beach sediment was eroded at rates of 0.3-0.5 m/day (Taylor, 1980a). The coastline, described in more detail by Sempels (1982), McLaren and Barrie (1985), and Taylor et al. (1987), is dominated by numerous long, narrow fiords with high steep rock or talus-banked rocky shores. Coasts consisting of ice comprise only a small percentage of the total eastern Arctic coastline, yet tidewater glaciers are nearly continuous along eastern Devon Island and southeastern Ellesmere Island. Unconsolidated shores are restricted to the low coastal forelands, broad deltaic areas at the head of fiords, smaller fan deltas at the sides of fiords, and in areas where glaciogenic or raised marine deposits are found. They take the form of sandur plains, shore bluffs, fringing and barrier beaches, and tidal flats with boulder barricades (Krawetz and McCann, 1986). The fiord coast region is covered by 247 NTS sheets, and has a mean sensitivity of 3.2, and a range of 1.1-10. However, a strong mode in the 0-2 interval is present.

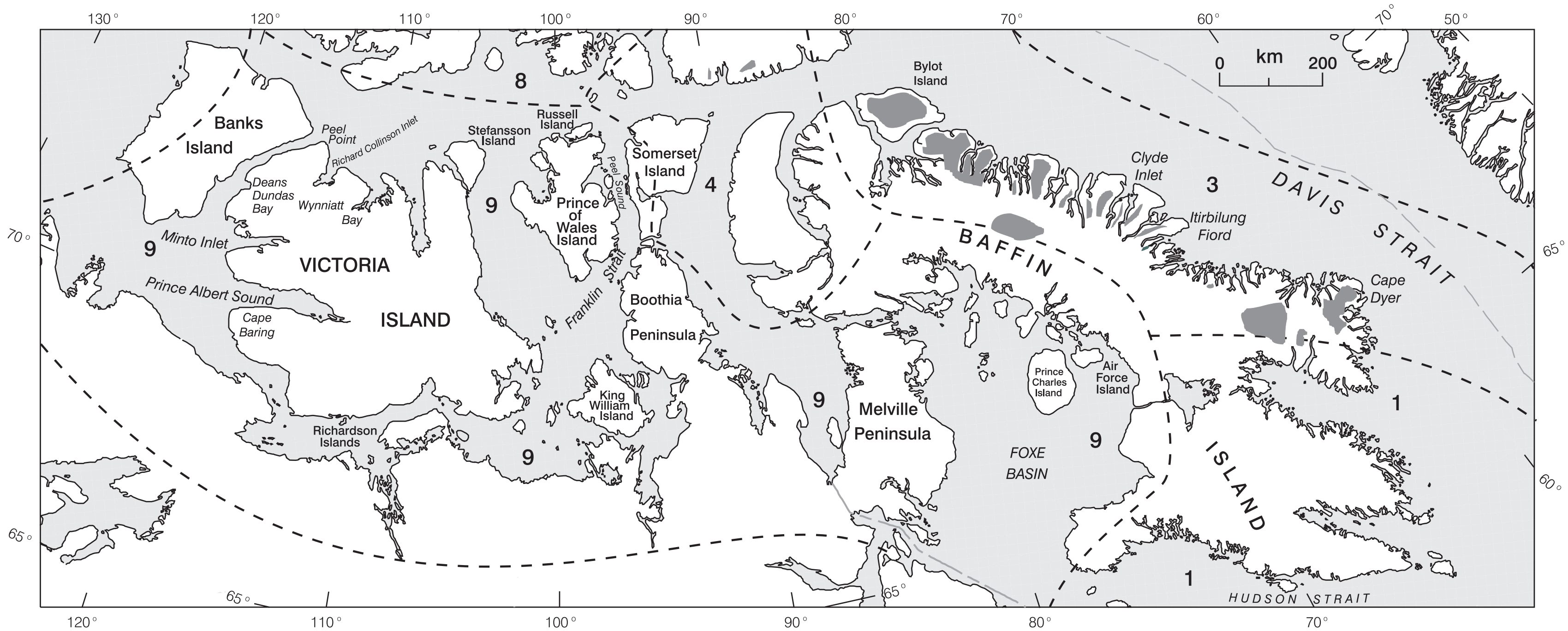

Figure 32. *Map of the southern portion of the Arctic Archipelago showing the coastal environments (which are numbered). Darker shaded areas indicate glaciers.*

The eastern coast of Baffin Island

This is a rugged, indented coast (Fig. 32) comprising long (up to 98 km), narrow (mean width <4 km) fiords. Mostly, sensitivity to sea-level rise is low, although the scoring does not indicate the numerous small areas of higher sensitivity. These areas include the following: fiord-head deltas, tidewater glaciers such as Coronation Glacier (Syvitski, 1989), ice-rich and/or fine grained coastal bluffs composed of glacial moraine and raised marine deposits, and shores lined by permanent or semi-permanent snow patches and icefoot (Taylor et al., 1987).

Nevertheless, several areas of higher susceptibility to sea-level change are mapped. These include the Clyde and Henry Kater forelands (Fig. 34), which consist of unconsolidated

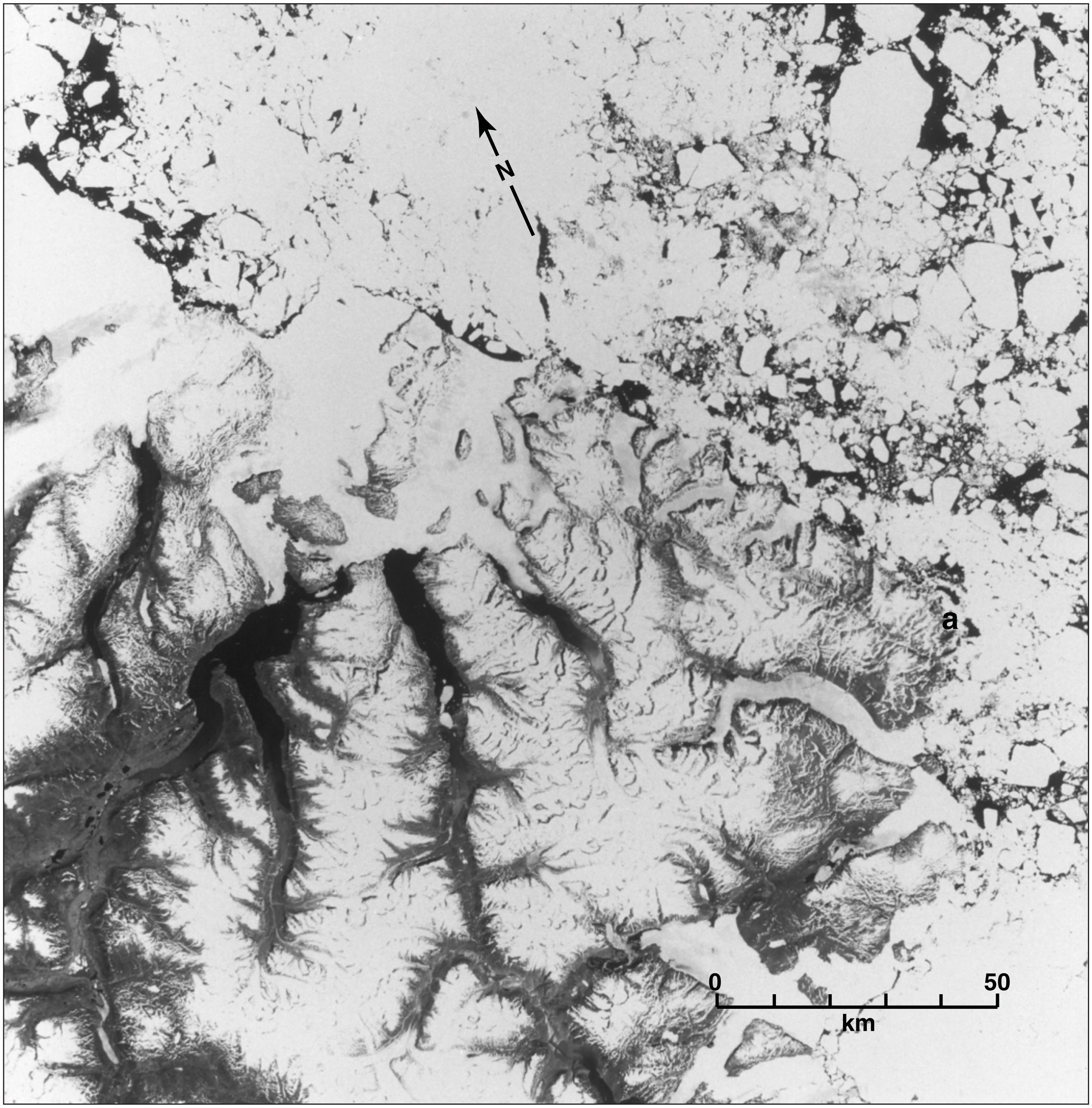

Figure 33. *Landsat 5 image of the east coast of the Cumberland Peninsula, Baffin Island, dated 16 July 1983. Cape Dyer is marked (**a**). Part of this coast has been mapped as moderately sensitive, although the scores are just above 5. The remainder of the coastline comprises a fiord coast, with low sensitivity. The protection of sheltered fiords from ocean waves by extensive sea ice is well illustrated.*

shore cliffs 5-40 m high. Erosion of these cliffs provides sediment for the adjacent long stretches of continuous beaches and barriers. Increased erosion of the shore bluffs, and sediment input to the beaches, is anticipated during an episode of rising sea level. One of the largest barrier beach/ lagoon complexes is at Cape Aston (Fig. 35), where Taylor et al. (1987) identified a seasonal flood zone 30 km long and 2 km wide landward of the present low, active barrier. This zone presently dries in late summer and is reworked by eolian processes and, presumably, would become submerged if sea levels were to rise. The stability and position of tidal inlets through the barriers would also be affected by higher sea levels because of changes in the tidal prisms, the melting of anchor ice which lines the channels, and the input of larger volumes of sediment from adjacent shore bluffs.

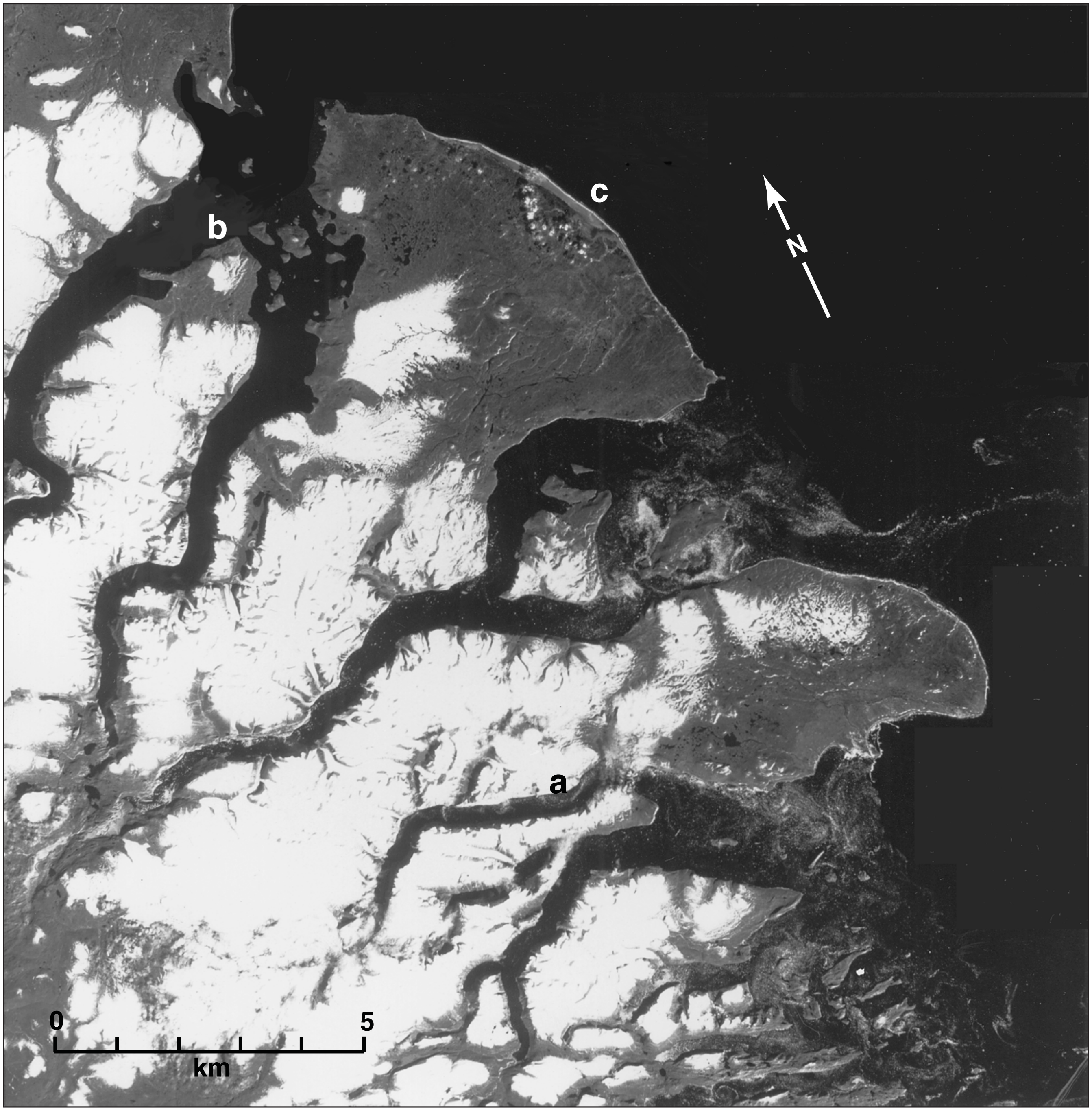

Figure 34. *Landsat 5 image of eastern Baffin Island, dated 29 August 1984, showing low-sensitivity fiords such as Itirbilung Fiord (**a**) and Clyde Inlet (**b**), and the more sensitive Cape Aston Foreland (**c**) which consists of unconsolidated sediments. Part of the foreland is shown in more detail in Figure 35.*

Other moderately sensitive coastal segments include: 1) the coast between Guys Bight and Erik Harbour, where a large bayhead barrier and several tidewater glaciers occur, to south of Cape Macculloch, where narrow beaches front easily erodible shore bluffs of muddy boulder till and raised marine deposits; 2) the low coastal plain with continuous beaches which extends along the southern section of Navy Board Inlet, including the Mala River delta; and 3) the coast at the extreme southeastern point of the Cumberland Peninsula, which is scored at the low end of the moderate category mainly because of increased submergence rates, and higher wave-energy levels. The glaciers in Erik Harbour have receded 10-50 $m \cdot a^{-1}$ since 1948 (Syvitski, 1987).

Bylot Island

Fiords are absent on Bylot Island (Fig. 32) and numerous glaciers radiate outwards from the ice-capped Byam Martin Mountains (Fig. 36), but only those on the northwestern coast, e.g. Maud Bight, extend to tidewater. The remainder have receded landward, leaving moraines and valleys infilled with outwash deposits. Moraines with relict ice from older glacial advances fringe parts of the northeastern coast (Klassen, 1985). These shore bluffs are extremely susceptible to erosion by slope and wave processes, as are the unconsolidated shore cliffs along northern Bylot Island. Barrier beaches and spits with one or more tidal passes front the larger sandur plains (Fig. 36, 37). The barrier beaches range from high gravel ridges towards the extremity of each bay, to low overwashed sand barriers towards the middle (Taylor et al., 1987; Shaw et al., 1990). The longest continuous beaches occur along the low coastal forelands at the northeastern and southwestern corners of the island. The latter area consists of an extensive low, sand beach, barrier, and nearshore bar complex, whereas the northeast coast consists of gravel barriers and beaches that fringe thin glaciomarine deposits. Between the lowlands the coast consists of high, steep rocky headlands, sea stacks, and bedrock platforms.

The unconsolidated coast of shore bluffs, deltas, barrier spits, and beaches has sensitivity scores at the low end of the moderate domain. Increased flooding behind barriers and retreat of the shore bluffs would be expected should sea level rise. However, the landward migration of barriers may be slow, because of their position in front of sandur plains. These plains are an abundant source of sand that would play a role in maintaining the positions of the barriers. The higher rocky coasts score in the low sensitivity range and, relatively, would be unaffected by changes in sea level; however, instability of upper slopes induced by the process of undercutting by waves could occur. In several cases on Bylot Island, the sensitivity scores depicted on the map inaccurately reflect the variation in coastal topography; many of the more sensitive areas are too small to influence the score at the scale of the NTS sheets (cf. Fig. 36, 37).

The east coast of Devon Island

The eastern coast of Devon Island (Fig. 38), extending from Philpots Island to Belcher Point in the north, is 60% covered by tidewater glacial ice (Fig. 39). The low rocky and bouldery shores of Philpots Island are the exception to an otherwise high and rugged coastline. Despite the high relief of much of the coast, it scores as moderately sensitive to sea-level change (scores of 8.0 are typical) because of the presence of tidewater glaciers. In the northeastern part of the island most of the tidewater glaciers are grounded, have ice-front thicknesses of 55-76 m, and appear to be receding.

Coburg Island

This island is located at the eastern end of Jones Sound (Fig. 38) and has a maximum elevation of 825 m. It is marked by high, vertical rock or ice cliffs, which represent 68% and 20% of the coast respectively. Only at the southeastern end is there a substantial area of low coast. Glacial deposits, less than 3.5 m thick, overlie a rock platform. The deposits have been reworked by waves into a series of gravel beach ridges

Figure 35.

Low-level oblique aerial photograph of the sensitive Cape Aston Foreland, showing eolian dunes on the narrow fringing barrier, and the occurrence of a wide, seasonally inundated lowland (left). Photo by R.B. Taylor. GSC 1995-281B which extend to elevations of +16 m. The present beach underwent severe erosion during storms in the mid-1970s, and still exhibited a wave-cut scarp along most of its length in the early 1980s. Coburg Island is exposed to some of the longest potential wave fetches in the eastern Arctic. It also lies adjacent to the North Water Polynya, an area of northern Baffin Bay that fails to freeze completely in winter. Coburg Island is fringed by fast ice each year but open water can develop along its south coast as early as June because of its proximity to the North Water Polynya. The low south coast and the ice coast are ranked as moderately sensitive to a positive change in sea level.

Figure 36. *Air photograph of the southeastern coast of Bylot Island, taken on 28 July 1948, showing a glacier in the distance (**a**), a low fluvial plain (**b**), a brackish lagoon (**c**), and a barrier (**d**). This coastal area, apart from the rocky headlands, is susceptible to more frequent barrier overwashing, barrier retreat, and inundation of the fluvial plain. The location of Figure 37 is shown (**e**). Department of Natural Resources, National Air Photo Library photograph T235L-100.*

Figure 37.

This photograph shows the low sandy barrier on eastern Bylot Island, with rocky headlands visible in the distance. The barrier is frequently overwashed today. The location of this photograph, taken by R.B. Taylor on 14 August 1981, is shown in Figure 36. GSC 1995-281C

Figure 38. *Map of the Queen Elizabeth Islands, showing coastal environments (numbered).*

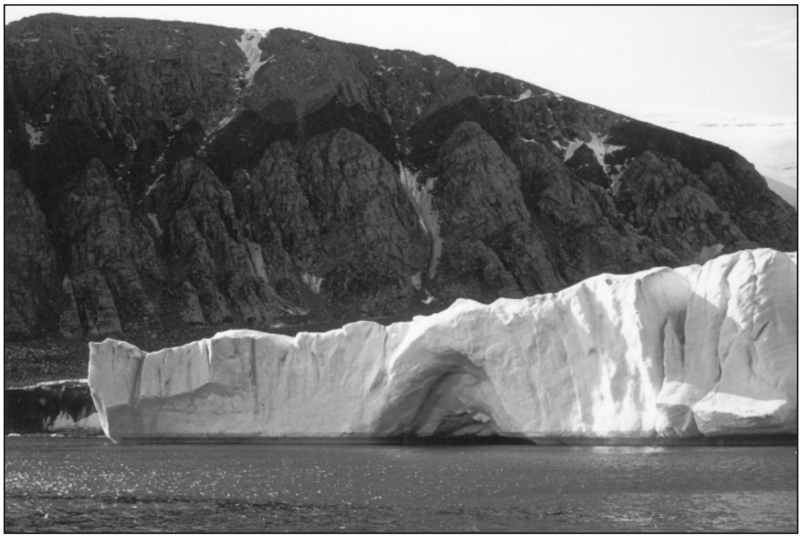

Figure 39.

Tidewater glacier in northern Devon Island, photographed in 1986 by R.B. Taylor. The potential impact of sea-level rise on calving rates is uncertain. An increase in the extent and duration of open water, which might accompany climate warming, would have an impact here. GSC 1995-285A

Eastern Ellesmere Island

A nearly continuous ice coast exists along southeastern Ellesmere Island (Fig. 38), extending from Cape Norton Shaw to Cape Rutherford on Buchanan Bay. Only small areas of precipitous, rocky shores are exposed between the glaciers that flow to the sea from the Inglefield and Prince of Wales mountains. Fiords in the south, such as Baird, Cadogan, and Talbot inlets, are ice-filled whereas farther north, long narrow fiords with steep rocky shores are freer of ice. Low unconsolidated shores are few, and are found either where sediment was deposited by retreating glaciers, or as fiord-head deltas. Tidal flats, some with boulder barricades, are associated with the mesotidal fiord shores adjacent to Smith Sound and Kane Basin (Krawetz and McCann, 1986). Sea-ice conditions are severe; some outer shores are fringed by a permanent icefoot rising 4-10 m above water level. Open-water season in the fiords is only 10-49 days (Taylor, 1973), but can be longer in areas adjacent to large river deltas and where strong tidal currents disrupt the ice canopy, such as at Flagler Bay. Wave action is considered negligible because of limited fetch and the duration of sea-ice cover, although very choppy seas can be generated during intervals when strong winds blow off the ice caps. Tidal and sea-ice processes are considered the principal dynamic factors in the shore zone (Krawetz and McCann, 1986).

The high relief, low wave activity, and falling relative sea level characterize this area as one of low sensitivity to sea-level rise. As previously discussed, small areas of higher sensitivity are too small to appear at this map scale, particularly in those regions containing deltas with intertidal flats at the heads of fiords. Tidewater glaciers account for areas of moderate sensitivity depicted on the map.

Jones Sound, Lancaster Sound, and Prince Regent Inlet

This region includes the coasts of northwestern Baffin Island, most of Devon Island, southern Ellesmere Island, southeastern Cornwallis Island, and eastern Somerset Island (Fig. 32, 38). It is a plateau region, deeply dissected by fiords. Scree-banked coastal cliffs 100 to 600 m high dominate the coastline, except where the coastal plain is sufficiently wide to allow the formation of depositional beach features. Bedrock consists of Paleozoic sediments that are unresistant and relatively flat-lying. The dominant lithology is limestone and dolomite. Glacial deposits are only abundant adjacent to present glaciers, and coastal sediment is mostly derived from local bedrock. The coasts in this region have very limited fetches. The mixed semi-diurnal large-tidal range is 2.1 m in Barrow Strait and increases to 3.6 m in eastern Jones Sound. Tidal range in Prince Regent Inlet varies from 2.7 to 2.9 m southward along the western coast and 1.6 to 2.2 m along the eastern coast (Sandilands et al., 1985). A short, open-water season has a duration of 44-67 days; however, the duration is longer than this toward the eastern parts of the region.

Shorelines in this region are reworked only during short and infrequent periods of intense wave action such as that which occurred in 1969 and 1974 (Taylor and McCann, 1983). Shoreline erosion can be significant during storm events but the beaches are commonly rebuilt following a storm, so that the net long-term change is generally less than the short-term fluctuations. The greatest shoreline changes have been recorded at coastal forelands. For example, Cape Ricketts in southwestern Devon Island was cut back 40 m and then partially rebuilt between 1968 and 1990 (Taylor and Hodgson, 1991). Large shoreline changes have also occurred where complex depositional features such as spits and barriers located on shallow rock platforms have been repositioned or re-aligned. Shores that extend farther seaward as prolongations are subject to intense sea-ice pressures, and the reworking of surficial sediment by ice-thrusting or ice-scouring during the spring and summer. The zero isobase, which represents the transition between submerging and emerging areas (Andrews, 1989a), is located at the eastern boundary of this region, on Baffin and Devon islands. All of this region has been emerging at rates varying from 20-50 cm /century since 2.4 ka BP (Taylor and McCann, 1983; Dyke et al., 1991). A total of 180 NTS sheets was used for calculating coastal sensitivity of this region; it has a mean of 3.8, a range of 1.3-9.6, and a strongly peaked distribution with the mode in the 2-4 interval.

Devon Island

The south coast is dominated by high, scree-banked plateau slopes, and contains only small areas of coastal lowland, mainly side-valley and fiord-head delta plains. Flights of gravel beach ridges occur in places. The beaches may experience increased wave reworking with a rise in sea level but the coastal slope is steep enough in most areas to prevent significant changes to the coastal planform. Therefore, sensitivity to sea-level change of most of the coastline has been ranked as low. Exceptions include the large tidewater glacier at the head of Croker Bay, and the coastal lowland that extends between Radstock Bay and Erebus Bay. These areas are mapped as moderately sensitive. The Erebus Bay site consists of a complex series of beaches, barriers, and spits which have been built across a very shallow, low gradient marine bench. A similar coastal topography with protruding deltas is identified along the western coast of Devon Island and near Cape Sparbo on the northern coast. However, the area on the northern coast is mapped as low sensitivity because of the greater abundance of rocky shoreline and the presence of resistant Precambrian bedrock.

The remainder of the northern coast of Devon Island can be divided into two main categories on the basis of differences in bedrock. Toward the west, in areas of Paleozoic and younger rocks, the shores consist of beach ridges composed of sand and gravel. Also, these shores may contain high, talus-banked plateau slopes. To the east, where Precambrian rock occurs, low rocky shores with pocket beaches are more common. The coastline of Brae Bay is mapped as moderately sensitive because of the presence of the Sverdrup tidewater glacier. The ice front varies from a few metres to an estimated 20 m above sea level, and it lies in water depths of 35-68 m (Taylor and Frobel, 1984).

Baffin Island

Northwestern Baffin Island forms the southern coast of Lancaster Sound, and the eastern coast of Prince Regent Inlet. High (up to 500 m), nearly continuous rock cliffs mark the edges of this plateau coast. The cliffs are most spectacular along both the west- and east-facing shores of Brodeur Peninsula. The northeastern part of Admiralty Inlet is a deeply indented fiord coast with few coastal lowlands present. Southward, toward the head of Admiralty Inlet, coastal relief decreases, but generally the shores are rocky because of the presence of Precambrian outcrop. A few river deltas and short sections of emerged beach ridges occur; however, most of this area has a low sensitivity index. Two significant lowland areas mapped as moderate sensitivity occur along the eastern side of Prince Regent Inlet. The coastline between McBean and Fitzgerald bays is a low beach-ridge complex dominated by the Brodeur River delta. The low limestone coast between Bernier and Agu bays consists of continuous sand and gravel beaches with a low to moderately sloping backshore that contains raised beach ridges and tundra ponds.

Somerset Island

The straight, high fault-bounded eastern coast, which extends from Port Leopold southward, represents a typical coast of low sensitivity, despite the presence of a few bay-head deltas, such as those occurring at Elwin Bay. Much of southeastern Somerset Island consists of sloping flights of beach ridges ranked as low sensitivity but two areas are ranked as moderately sensitive. The first area is the northern coast of Creswell Bay, which encompasses the Creswell River delta and an extensive tundra-pond/beach-ridge complex consisting of emerged nearshore and deltaic sediments. The second consists of the low-lying barrier, beach-ridge, and delta complex south of Cape Garry. The northern coast of Somerset Island consists of flights of well defined gravel beach ridges alternating with short sections of high, steep plateau slopes (Fig. 40). Some of the latter have narrow fringing beaches and others have semi-permanent snow patches.

Two areas that are more sensitive to change occur on the northern coast. The first area consists of a low coastal plain with barrier beaches, lagoons, and spits, and lies between Irvine and Garnier bays. The second includes two smaller coastal lowlands which have a similar complex barrier and lagoon morphology, and are adjacent to large delta complexes lying west of Cunningham Inlet (Taylor, 1980c). All of the gravel barrier and beach complexes have developed across low gradient, marine rock benches. Also included in the second area of moderate sensitivity is a wide, sandy coastal plain upon which low sand barriers would develop in the event of marine inundation.

Cornwallis Island and adjacent islands

The coastlines of these islands (Fig. 38) are underlain by Paleozoic rock and consist of high, talus-banked plateau slopes, primarily, or flights of gravel beach ridges with intermittent exposures of rock. Coastal forelands, such as Cape Dungeness on the southern coast, have formed where sediment supply is abundant. Where sediment is scarce, the beach ridges are small and less well developed, such as along the southwestern and northwestern coasts of Cornwallis Island; these coasts are given a moderate sensitivity ranking. Assistance Bay on the southern coast has a similar coastal topography but the smaller scale of the depositional features does not offset the low sensitivity of the steeper, nearby shoreline.

Ellesmere Island

The outer coast of southern Ellesmere Island (Fig. 38) consists of emerged rock cliffs and pockets of lowland, with either well defined flights of gravel beach ridges or deltaic forelands. The outer coast is cut by several long, narrow, sinuous fiords. River deltas are common within the fiords, particularly at their heads, and depositional beach features occur where the coastal plain is sufficiently wide along their shores.

The best documented beach-ridge complex is at Cape Storm, for which Blake (1975) produced a well constrained sea-level curve for the area. Although small sections of coastline are sensitive to sea-level change, most of this coast is not. The tidewater glacier at the head of South Cape Fiord, and the Jakeman Glacier at the southeastern end of the coast, are mapped as moderately susceptible to change. Part of the Jakeman Glacier is not tidewater but the recent ice-front deposits are now being reworked and modified by waves.

Western Ellesmere Island and Axel Heiberg Island

Bedrock toward the northern and eastern extremes of this region (Fig. 38) is of Paleozoic age with some pockets of Proterozoic sediment. However, most of the region is composed of less resistant Mesozoic and Cenozoic rocks. It has lower relief, less resistant rock, and a lower wave energy than the fiord coasts of eastern Ellesmere Island (Owens, 1977a), and forms the higher eastern portion of the Innuitian fold belt. Coastal elevations on Graham Island, the Bjorne Peninsula, the Fosheim Peninsula, Ellesmere Island, as well as those on eastern Axel Heiberg Island are generally less than 150 m. However, along some of the more northern fiords and central Axel Heiberg Island, elevations exceed 1000 m. Large-tide range decreases northward from 1.6 m at the southwestern corner of Ellesmere Island to 1.3 m at the southern end of Axel Heiberg and 0.6 m at the entrance to Greely Fiord. The northern parts of the region have very low wave-energy levels due to the sea-ice cover and short fetches; in more southern areas, the duration of the open-water period can be up to 40 days. Relative sea level during the past 1 ka has been falling (Andrews, 1989a) in this region, and erosion rates are unknown for the coastal sections.

This fiord coast is predominantly one of high relief, and would not be highly impacted by a future sea-level rise. The mean sensitivity score is only 2.6 (n=170), the range is 1.3-8.6, and the sensitivity distribution has a mode in the 2-4 range. The two areas of moderate sensitivity are northern Meighen Island, which is actually part of the Arctic Coastal Plain, and Phillips Bay on northern Ellesmere Island, which is discussed as part of the Arctic Ice Shelf. Tidewater glaciers occur at the head of Cañon Fiord and along several of the other more northern fiords; other glaciers terminate a short distance inland from the coast and are fronted by narrow outwash plains and deltas. The tidewater glaciers and deltas constitute small areas which, with the advent of higher sea levels, could be impacted. Sandy plains, beach ridges, deltas, steeply sloping and cliffed shores constitute most of the coastline along southwestern Ellesmere Island. Graham Island is fringed by a low coastal plain that is crossed by a radial pattern of closely spaced streams. The coasts of Axel Heiberg Island vary in nature from low beaches to high cliffs, and all are mapped as low sensitivity.

Arctic ice shelf

The northern portion of Ellesmere Island (Fig. 38) is underlain by Paleozoic and Proterozoic rocks, and is dominated by the high, ice-capped Grant Land Mountains which reach elevations of 2500 m inland and 900-1200 m along the coast. The rugged northern coast is dissected by several long 'frigid' fiords (Syvitski at al., 1987) that are rimmed by glaciers and ice-capped mountains, and covered by thick multi-year sea ice or shelf ice. The shores are lower toward the eastern and western parts of the region, and in a few places along the fiords where flights of raised marine deposits and glaciofluvial deposits are found. Most of the coast is mapped as having low sensitivity to sea-level change, primarily because of its high, rugged topography, the absence of open water, and the small tidal range of less than 0.6 m. It is also an area of falling relative sea level, which is a result of isostatic adjustments to ice loading. For example, in Clements Markham Fiord, relative sea level fell rapidly after 8 ka BP and then continued to fall at 30 cm/century (Bednarski, 1986;

Figure 40. *View of Pressure Point, Somerset Island, with Limestone Island in the distance. Beach development is restricted along this 150-300 m high, talus-fringed plateau, typical of coastal environment 4. Photograph taken by R.B. Taylor, 31 August 1976. GSC 1995-286*

Andrews, 1989a). The mean shore sensitivity of this region (n=30) is 3.4 with a range in scores of 1.1 - 5.3. The shores that are ranked with a moderate sensitivity are those with tidewater glaciers, where changes at the ice front could be expected.

The northern coast of Ellesmere Island is unique because of the presence of the only remaining ice shelves in the Northern Hemisphere. Although the ice shelves were not considered as part of the actual coastline, changes in the thickness or spatial distribution of the ice shelves may have considerable impacts on the oceanographic circulation and wave regime, and, consequently on the shores of the inner fiords. The ice shelves are floating masses of ice varying from 25-100 m thickness. They grow from sea ice, and thicken as a result of surface accumulation of snow and ice, bottom freezing, and, in places, the incorporation of glacier tongues (Jeffries, 1987). The ice surface has a distinctive "rolled" topography of parallel ridges and troughs. The ice shelves essentially form a very thick freshwater cover that influences the oceanographic circulation within the fiords and between the fiords and the Arctic Ocean.

The ice shelf off northern Ellesmere Island began forming about 4 ka BP (Lyons and Mielke, 1973), a determination which corresponds with a period of climate deterioration and the readvance of local glaciers (Stewart and England, 1983). The age of driftwood found along the inner fiords indicates that not all fiords (e.g. Disraeli Fiord) were completely sealed off by the ice until 3 ka BP. Accounts by explorers suggest that the Ellesmere Ice Shelf extended along the northern coast from Point Moss to Nansen Sound during the period 1876 to 1906 (Jeffries, 1987). Since then it has disintegrated into a series of small isolated ice shelves which comprise only about 20% of its former extent of 7500 km^2 (Spedding, 1977).

Large scale disintegration of the ice shelves during the 1960s and 1980s led to the calving of many massive ice islands. The causes and mechanisms of ice-island calving are poorly understood, but if calving is the result of a combination of climatic and oceanographic factors (perhaps tidal), then the predicted changes in global climate and sea-ice regime will have an effect on the existence of the ice shelf. In areas where calving from the ice shelf occurs at present, the ice islands are replaced by sea ice which can attain a thickness of 18 m in 50 years (Jeffries, 1987). The new ice thereby seals off the fiords and inhibits wave generation. With a warmer climate and more mobile sea ice in the future, the maintenance of ice cover may be threatened; this would result in waves reworking the shores of the inner fiords once more.

Arctic Coastal Plain

The shores of the Arctic Coastal Plain (Fig. 38) consist of lowland terrain generally below 60 m elevation, and developed in poorly lithified Mesozoic and Cenozoic sedimentary rocks. Higher coastal elevations (greater than 200 m) exist at a few locations, including southeastern Prince Patrick Island, and north-central Ellef Ringnes and Amund Ringnes islands. These micro-tidal (less than 1 m spring range) shores are ice-locked for at least 11 months each year. Very large leads, about 1000 km long, are formed in the ice canopy along the Arctic Ocean coast during spring in response to the alternate passing of cyclones and anticyclonic storms. Tidal jacking associated with the cyclones occurs as oceanic waters are forced onto the shelf beneath the sea ice (Kozo and Eppler, 1992). Yet, with the exception of the shore leads and the shallow bays and inlets, few clearly defined areas of open water exist. As a result, the generation of waves is minimal, and sea-ice action and terrestrial (fluvial and periglacial) processes dominate the present coastal morphology (Taylor, 1980b; Taylor and McCann, 1983).

Along the westernmost islands, little emergence and perhaps some submergence has occurred. The few raised beaches and terraces observed along Brock Island and northern Prince Patrick Island suggest that only 12-17 m of emergence took place, and that at some time in the last 1-2 ka BP sea level fell slightly below the present level and then rose again. This is illustrated by the occurrence of drowned river mouths (Forbes at al., 1986; Hodgson et al., 1994). Evidence for submergence, such as drowned tundra ponds, barriers, beaches, and delta fronts, is even stronger farther south, toward Banks Island (Manning, 1956).

Farther from the Arctic Ocean within the inner islands, emergence curves take a form that more closely approaches the exponential curves observed elsewhere in the Queen Elizabeth Islands (Hodgson, 1989). On King Christian, Lougheed, and Ellef Ringnes islands some 80-100 m of emergence has occurred since 10 ka BP; however, the highest well defined strandlines, at 20-30 m a.s.l., only date from about 6 ka BP (Hodgson, 1981, 1982). Relative sea level continues to fall along most of the inner islands, and some of the western ones as well. Along southeastern Prince Patrick Island and parts of Mackenzie King Island, evidence exists that sea level fell below the present elevation after 3 ka BP (Hodgson et al., 1994).

This region, with the exception of the Beaufort Sea coast, has the widest range of sensitivity scores in the Arctic. The index values range from 2.1 - 16, with modal values between 6 and 8. The mean score for the region is 7.4 (n=170), which places it at the lower end of the moderate sensitivity category. It is subdivided on the basis of physiography, sea-level history and sea-ice dynamics into two zones: 1) the Arctic Ocean coast, and 2) the inner Queen Elizabeth Island coasts.

Arctic Ocean coasts   western Banks Island

The southwestern corner of Banks Island with its low relief, well defined spits, barrier islands, and lagoons has been given a high sensitivity rating because of its potential exposure to higher wave-energy levels and the low, intricate nature of its shorelines. Shores at many of the large river mouths (such as those of Big and Bernard rivers) along western Banks Island are also extremely low in elevation, with drowned lakes, small barriers, and spits in abundance. These river-mouth shores are rated less sensitive because of the increase in sea ice cover and consequent decrease in potential wave energy. Farther north along Banks Island continuous, well defined beaches fringe moderately high unconsolidated bluffs and hills. Coastal relief increases to 60 m at Cape Prince Alfred on the northwestern corner of the island and, as a result, sensitivity to sea-level change decreases.

Arctic Ocean coasts – Prince Patrick Island to Ellef Ringnes Island

The geomorphology of these coasts is dominated by fluvial and sea-ice processes such as the formation of deltas and ice-built shore ridges. Surficial sediment is derived mainly from reworked Tertiary (Beaufort Formation) fluvial deposits (Fyles, 1990). Much of the present shoreline consists of closely spaced, or coalescing river deltas of varying magnitude. Higher shores with a moderate slope exist only along the inner parts of Satellite Bay, the floor of which transects the Queen Elizabeth Shelf from the western shore of Prince Patrick Island to the upper part of the continental slope. The remainder of the coast consists of continuous, low, fringing sandy shores, or small barrier islands, spits, and drowned tundra ponds. These extremely low, sandy shores are all ranked as moderately susceptible to change as a result of sea-level rise.

Small areas of northern Prince Patrick Island and the adjacent islands are composed of clays derived from marine shales (e.g. the Kanguk Formation). These clays are extremely sensitive to slope failure when saturated with water, and when undergoing remolding by sea ice during ice ride-up events. The intertidal flats are also very thixotropic and easily disturbed by sea ice. Ice-built barrier islands, shoals, and shore ridges, which are 8-10 times the magnitude of any wave-built features, are observed along most coasts (Taylor and Hodgson, 1991). For example, in Ballantyne Strait one or two ice-built shore ridges fringe this coast, forming the backbone of several small islands as well as a barrier around the larger Polynya Islands. The shore ridge extends to elevations varying from 3-13 m a.s.l.

It is anticipated that a rise in sea level and an increase in wave action would truncate the small barrier islands and spits, force them to migrate farther landward (by overwashing), or even destroy them (although in this case they could reform farther landward). At the numerous river mouths, delta-front flooding and increased wave erosion along the delta flanks is anticipated, particularly on deltas which extend long distances seaward of the main shoreline (Taylor and Forbes, 1987). Shoals formed along the shear zone between the landfast ice and the mobile pack ice would be drowned, eroded, or moved landward by sea-ice pressures. The ice-built shore ridge, because of its poor consolidation, would undergo increased basal erosion and slumping on its seaward side. An increased mobility of sea ice could result in increased sea-ice pressure from offshore, and the net transfer of the shore ridges farther landward. Where they are backed by lower terrain, the shore ridges could form the core of a new series of barrier islands as sea level rose.

Inner coasts of Queen Elizabeth Islands

In comparison with the Arctic Ocean coast, the shores of the inner Queen Elizabeth Islands exhibit a greater variety of geology, topography, sediment characteristics, and processes. The islands consist of a thick succession of deposits ranging from Carboniferous to early Tertiary in age. Coastal topography is controlled by geological structure and, because of the absence of wave reworking, coastal sediments closely correspond to the weathered products of the underlying bedrock (Taylor, 1980a). Hence, the main coastal types defined in the area correspond closely to the boundaries of specific geological units. Moderate- to high-relief shores (30-100 m) comprise only a small percentage of the coastline (Taylor, 1980b; Taylor and Forbes, 1987), and most coastal areas have very low relief and gentle slopes.

Four coastal types (sandflat, mudflat, scarred, and deltaic) were described from the Findlay Islands by Taylor and Forbes (1987), as type examples for this region. The sandflat coast is the most common coastal type (Woodward Clyde Consultants Ltd., 1980; Owens et al., 1981; Taylor, 1980b), and is characterized by a 1-2 km wide flat expanse of sand that is crossed and dominated by closely spaced, subparallel streams. Eolian processes are locally important. Both moderate and low gradient shores are composed of silt and clay derived from marine shales. These shores are extremely sensitive to change because of their inherent instability (due to their fine texture and high ice content) and, in the case of the mudflat shores, their low relief (Taylor, 1980b; Taylor and Forbes, 1987).

Eastern part of Prince Patrick Island and adjacent islands

Moderately sensitive shores include the low-lying barrier-beach, lagoonal shores and wide deltaic plains of southeastern Intrepid Inlet, as well as the small low sandflat shores of Crozier Channel and Fitzwilliam Strait. Mudflat shores are found along parts of Eglinton Island. Shores rated as having low sensitivity are associated with higher relief or more resistant bedrock, e.g. southeastern Prince Patrick Island. Nevertheless, these shores may undergo increased slope instability because of undercutting by waves, and the reduction or complete melting of the fringing semi-permanent snow patches and icefoots.

Mackenzie King Island

All of the coastline was mapped as moderately sensitive to change. The most sensitive areas are the mudflat and deltaic shores near Cape Beuchat and southeastern Mackenzie King Island. Several of the river mouths along the northern coast appear to be partially drowned, and a barrier beach-like feature is observed along northeastern Mackenzie King Island (Forbes et al., 1986). A further rise in sea level could cause additional drowning of these features.

Findlay Islands

These low sand and silt-clay shores are ranked as moderately sensitive to change. The shores expected to undergo the greatest change are the mudflats of southwestern and northern Lougheed Island (Fig. 41), where little or no wave action occurs. The southern shore of the smaller Findlay Islands is also considered more sensitive to change, because of its fine sediment texture and exposure to greater potential wave energy.

Cornwall Island

All of the island was ranked as having low sensitivity. The shores least likely to change are those with rock cliffs and gravel beaches on north-central Cornwall Island. The east and south-central coasts exhibit the same low, sandy and muddy shores that are ranked as moderately sensitive on other islands. Part of the problem is the relief factor provided by ETOPO-5: the low relief scores outweigh other factors used to calculate the sensitivity index. The east coast and south-central coast beaches of Cornwall Island are already reworked by waves during most years, whereas beaches on the other islands in this region are not; therefore, changes in shoreline character due to an increase in the duration of open water might be less on Cornwall Island than other parts of the Arctic Coastal Plain region.

King Christian Island

The low, vegetated, fine grained shores of northeastern and southern King Christian Island are expected to show the largest changes, because the river mouths with their steep banks are expected to be inundated when tide waters extend farther upstream. Yet the island coast here has been mapped as having a low sensitivity to sea-level change. These shores show little difference from many of the moderately sensitive shores occurring elsewhere. However, because of their slightly steeper gradient and relief they received a lower rating.

Ellef Ringnes Island and Amund Ringnes Island

Amund Ringnes Island and northeastern and southwestern Ellef Ringnes islands were mapped as having a low sensitivity because of their relatively high relief, steep backshores, and well defined beach crests. Small areas are present that have a higher sensitivity to sea-level rise, because the sandy shores are flat, muddy shores exist, or river mouths will flood. These more sensitive shores are not shown in Figure 2, because of their small extent. Only the fine grained shores of southeastern Ellef Ringnes Island and the low sandflats of its northwestern portion are mapped as moderately sensitive.

Ria coast

Most of Melville Island, Bathurst and Byam Martin islands, northwestern Cornwallis and Devon islands, and various smaller islands (Fig. 38) lie within the Innuitian geological foldbelt. Relief is more subdued and lower in the southern part of the foldbelt than in the northern part (Ellesmere and Axel Heiberg islands). Much of the area is less than 150 m in elevation, but heights of greater than 300 m are found on northwestern Devon and western Melville islands. Bedrock is composed of Late Paleozoic- to Mesozoic-age sediments predominantly. Sandstones, siltstones, and shales are the most common lithologies. Tidal range (large tides) varies from 1-2 m in the southern parts of the region, to less than 0.5 m along the northern and western coasts. The amount of coastal emergence for the past 1 ka varies. It is more than 4 m on the Grinnell Peninsula and northeastern Bathurst Island, but less elsewhere; submergence may have been occurring along the western coast of Melville Island (Andrews, 1989a).

Open-water season within the Arctic channels can be extremely variable from year to year, but it generally decreases from 1-2 months in the eastern and southern areas, to days or weeks in the northern and western parts of the region (Taylor, 1973; Markham, 1981). However, locally generated waves will rework the sand and gravel shores during infrequent storms. McLaren (1982) attributed shoreline development along eastern Melville Island more to ice scour and ice push associated with grounding sea ice, than to wave action.

Exclusive of the bedrock geology, the coastal geology of much of the region has been mapped and described in detail elsewhere (Woodward-Clyde Consultants Ltd., 1980; Taylor, 1980b; McLaren, 1982; W.B. Barrie and Assoc., 1982; McCann, 1988). East-west trending folds impart a structural

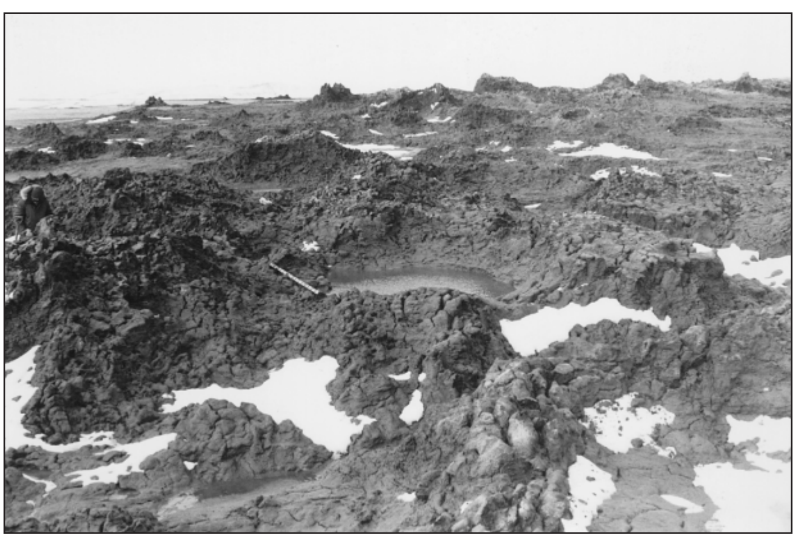

Figure 41.

The muddy shore of southern Lougheed Island was mapped by Taylor and Forbes (1987) as an "ice-scarred coast". This area is ice-congested in summer, and it is arguable that an increase in the extent and duration of open water would have as large an impact on the coast as sea-level rise would. Photograph by R.B. Taylor, August 1986. GSC 1995-285B and morphological grain to a large part of the coastline. The resistant strata comprising these folds form peninsulas, headlands, and islands and the less resistant strata form the intervening bays and inlets. This type of coast is best developed along western Bathurst and eastern Melville islands (Taylor, 1973, 1980b; McLaren, 1982). Gravel beaches form in areas underlain by shale, limestone, and dolomite, whereas sand shores are similarly associated with sandstone and siltstone. The western coast of Melville Island closely resembles a fiord coast, and the low sandflat shores of Melville, Bathurst, and adjacent islands resemble shores of the Arctic Coastal Plain. Along these shores fluvial and slope processes are locally important, but much of the coastline is dominated by large deltas that extend as far as 1-2 km offshore. Sequential surveys of selected beaches in the region show that change is greatest at, and near deltas or shores where sea-ice pressures are greater than elsewhere. The mean sensitivity for the region is 4.3 (n=154), with a strong mode in the 2-4 range, and scores that vary from 1.9-16. Thus, sensitivity in the Ria coasts is somewhat higher than in other Arctic regions, particularly those with higher relief, more resistant rocks, and less surficial sediment. For example, the sensitivity distributions for regions 4, 5, and 6 do not have a tail towards the high end of the range (Fig. 2). Several sites are present that are ranked spuriously high, because of the presence of small low islands which cause errors in ETOPO-5 and the resultant relief factor, for example the north shore of Graham Moore Bay. These sites are noted in the text.

Melville Island

The coasts lying in the southern and western parts of the island are backed by uplands and plateaus, and commonly consist of bedrock sea cliffs higher than 50 m (Hodgson et al., 1984). Coastal lowlands with deltas and beaches are sites of higher sensitivity. In eastern Melville Island, McLaren (1982) identified three main coastal types: deltas, sandflats, and raised beaches. Beach-ridge complexes with spits and barriers have developed in areas of coarser sediment (e.g. south of Robertson Point). Tundra ponds and lagoons separate the beach ridges which are modified during infrequent storm events. The other sensitive coastal areas are the large river deltas at King and Nelson Griffiths points. Sandflat shores are fringed by continuous sand beaches and are backed by low-gradient, wind-swept, raised alluvial plains. The rate of isostatic recovery along this coast is 35 cm/century (McLaren, 1982).

Sabine Peninsula and the northwestern part of Melville Island, bordering Fitzwilliam Strait, together form the Northern Lowland physiographic region (Dunbar and Greenaway, 1956, p. 239). This feature constitutes the largest area of moderate sensitivity on the island, mainly because of the high percentage of deltas and the large proportion of fine grained shores present. Forbes et al. (1986) described the highly unusual deltas that occur here and in other parts of the Sverdrup Basin (Fig. 42). They " project seaward as long, narrow, finger-like deposits with the modern braided channel confined between terraced banks." (p. 11). These deltas extend seaward in this fashion because of the absence of wave attack, increased sea-ice pressure and subsequent thrusting in these ice-congested waters, and due to other factors such as relief, bedrock lithology, and sea-level trend. With a rise in sea level, the river mouths would become intertidal farther upstream. If longer seasons of open water prevailed, the deltas would become wave-convergent points and zones of increased erosion, and would supply larger amounts of sediment to beaches alongshore.

Many of the shores in the northern part of Melville Island are underlain by marine shales (Woodward-Clyde Consultants Ltd., 1980). The surficial material derived from these rocks is fine grained, commonly ice-rich, and extremely sensitive to disturbance by natural and artificial factors. Earth flows, thermokarst, and ice-built ridges are commonly present. These shores are mapped as ridged or scarred coastal types. Intertidal flats appear to be wider along the western rather than the eastern side of Sabine Peninsula. Sediment across the intertidal flats is thixotropic and easily disturbed by sea-ice pressure. Sabine Peninsula is mapped as moderately sensitive to change, yet several small areas of banked and cliffed coast are present. Examples of these areas are the salt domes at Cape Colquhoun, which are of low sensitivity.

Byam Martin Island

Byam Martin Island is mapped as an area of low sensitivity, but this is mostly due to the high elevation component given by ETOPO-5. The coastline is low with sandflat and deltaic shores, and coarser sediment occurs where the more resistant fold strata are exposed. The shoreline is backed by raised, generally poorly preserved beach ridges (McLaren, 1982). Deltas, coastal promontories, and the northern part of the island are subject to greater sea-ice pressure which results in shore ice pile-ups in the nearshore zones, and ice-push ridges onshore.

Bathurst Island and adjacent islands

As recently as 1947, aviators of the Royal Canadian Air Force and the United States Air Force discovered that this was a group of islands and not a single one (Dunbar and Greenaway, 1956). The physiography of the islands divides into three regions, as follows: a southern plateau, a central uplands, and the lowlands of Cameron Island.

Southward from Cape Lady Franklin along the eastern coast of Bathurst Island, the shoreline consists of fringing gravel beach, rock outcrops, unconsolidated shore bluffs, semi-permanent icefoot/snowpatch, and a moderate to steep sloping backshore covered by either colluvial or raised marine deposits. The effect of sea-ice pressures onshore is evident in the form of ice-push ridges and grounded ice piles lying on many of the more exposed shores. With respect to geomorphology, the most sensitive shores are those associated with the larger river deltas (e.g. Cheyne River), where low beach ridges with tundra ponds and lagoons occur on delta plains. Other sensitive shores include the low flats at the head of Goodsir Inlet, which marks the eastern end of Polar Bear Pass (an international biological preserve), and the low beach-ridge and tundra-pond complex at Cape Evans. The sensitivity scores of these areas fall just below the moderate sensitivity category.

Most of the south coast of Bathurst Island consists of fringing sand and gravel beaches, rock outcrop backed by low bluffs, or a moderate sloping backshore with raised marine features and a discontinuous upland surface. West of Alison Inlet to Cape Cockburn, and north along the west coast to Graham Moore Bay, an extremely low sand plain is capped by an intricate pattern of low, narrow, sand and gravel beach ridges and tundra ponds. It is the largest area of moderately sensitive coast mapped on Bathurst Island. From Graham Moore Bay northward the shores consist of fringing beach, low bluff or rock outcrop backed by higher shores covered by

Figure 42. This aerial photograph shows protruding deltas at Invincible Point, on the Sabine Peninsula, Melville Island. Large fractures can be seen in the sea ice, and a zone of open water (a shore lead) fringes the coast. An increase in the duration of open water would cause these landforms to be eroded by waves. National Air Photo Library photograph A16764-3.

colluvial and raised marine deposits. Several small areas of shoreline are present, particularly at deltas, that would be sensitive to change but are not of sufficient size to raise the ranking above the low sensitivity category. Other areas such as those along northern Graham Moore Bay and Helena Island (cliffed shore) have been mapped as moderately sensitive, but their character is like other areas mapped as low sensitivity. The problem is related to the relief value assigned to the area from ETOPO-5, which is too low.

The shores of northwestern Bathurst Island are higher and steeper, and consist of coarser sediment in most areas. Small coastal lowlands and alluvial plains within May and Erskine inlets are too small to offset the other less sensitive shores.

Cameron, Vanier, Massey, and Alexander islands

All of the islands except the northern two thirds of Cameron Island have an east-west alignment of bedrock structure, with a higher central region fringed by a low to moderately sloping coastal plain. The latter is crossed by closely spaced streams. The northern two-thirds of Cameron Island more closely resembles the Arctic Coastal Plain. It has very low sandflat and deltaic shores which are severely affected by sea-ice pressures. The southern coast of Cameron Island rises to an escarpment of 30-120 m elevation. On this coast, coarse clastic beaches are commoner. They are reworked extensively by waves because of the longer duration of open water in central Arnott Strait. In lower areas the backshore consists of tundra ponds and poorly drained low-lying meadows. Beneath the plant cover, lenses of massive ice are present and, when exposed, the ice melts to form a thermokarst topography.

Short sections that may be more sensitive to change occur on each of the other islands. These include the sandflat shores of Vanier Island and the wide intertidal flats of Massey Island (W.B. Barrie and Assoc., 1982); however, most of the shores are ranked as low sensitivity. The areas mapped as moderate sensitivity are not significantly different from the remainder of the shoreline, but rank higher because of less-resistant bedrock, wave exposure, or some attribute other than geomorphology.

Southern portion of the Arctic Archipelago and the mainland coast

This is the largest, single coastal environment in the present study. A total of 672 NTS sheets were used to assess sensitivity to sea-level change. This coastal environment encompasses the eastern half of Banks Island, Victoria Island, Prince of Wales Island, western Somerset Island, northern Southampton Island, and southwestern Baffin Island, together with many smaller islands and the mainland coast extending from the Beaufort Sea to Hudson Bay (Fig. 32).

Bedrock in this region is composed of both resistant Canadian Shield rocks, as in west-central Victoria Island, Boothia Peninsula, and Melville Peninsula, and less resistant sedimentary rocks elsewhere. The relief in this coastal region is generally low. Tidal range is less than 1 m except in Foxe Basin, which has a range (large tides) of 5 m in the southeast. Most areas are ice-free by August, with freeze-up commencing in October. Relative sea level has been falling throughout the region for the past several thousand years (cf. Andrews, 1989a; Dyke et al., 1991; 1992).

The bulk of the information on the coastal geomorphology of this region was taken the report by Woodward-Clyde Consultants Ltd. (1981). Information on areas not covered by this report was extracted from maps in the Land Use Information Series of the Department of Indian and Northern Affairs. Photographs and descriptions in Dunbar and Greenaway (1956) augmented the data from other sources.

The coastlines show great variability, with almost every coastal type represented. The most prevalent ones are as follows: bedrock coasts, commonly fronted by screes; gravel and sand beaches, typically backed by raised beaches; forelands, spits and barriers, more particularly on the islands; and deltas, typically projecting out into the sea. These coasts would not be seriously impacted by an accelerated rise in relative sea level. Nevertheless, there are numerous areas at moderate risk, the most extensive of which are Prince Charles Island and eastern Banks Island. The sensitivity scores have a mean of 4.1 (n=672), and a range 1.1-20. There is a strong mode in the 2-4 range and a secondary mode in the 14-20 interval. These higher values apply to the extreme west of the region at its boundary with region 10 (see below).

Eastern Banks Island

Banks Island is underlain by Mesozoic and Cenozoic bedrock, and comprises a southern and northern plateau, and a large intervening lowland. The eastern part of the island has extensive areas which are moderately sensitive to impact as a result of sea-level rise. These sensitive coasts consist of continuous beaches in front of bluffs of unconsolidated sediment, deltas, and estuaries. Particularly sensitive environments include De Salis Bay, which has barriers and spits, and the large Parker River delta, which projects out into the ocean on the northeastern coast. Areas of low sensitivity include Durham Heights, where bedrock cliffs are up to 650 m high, and the vertical bedrock cliffs between Parker River and Cape Vesey Hamilton.

Victoria Island and King William Island

Victoria Island is the second largest island in the Arctic Archipelago, with an area of 218 000 km^2, just less than that of England and Scotland combined. It is underlain by flat-bedded Paleozoic rocks generally, with an upland strip of more resistant Canadian Shield rocks extending across the island from Hadley Bay to the northern coast of Prince Albert Sound. Northwest of the uplands is a plateau, and to the southeast a lowland that occupies about two thirds of the island (Dunbar and Greenaway, 1956). Surficial deposits include variable thicknesses of till, that may be organized into drumlin fields and raised beach deposits. Most of the southeastern part of the island, and the coastal fringe elsewhere, experienced Late Wisconsinan-Holocene marine overlap. In Figure 2, the coastline is portrayed as one having alternating sections of moderate and low sensitivity coast; however, this is deceptive, because many parts of the coast have scores straddling the boundary between the low and moderate domains. This is so, particularly in the southeastern part of the region, and is reflected in a statistical breakdown of the scores for 145 NTS sheets: the mean is 4.5, the primary mode is 3.9, and the range varies from 1.3-11.

Northeastern Victoria Island and Stefansson Island constitute a region of low relief with gravel beaches, so that much of this area is within the lower part of the moderate sensitivity domain. The coast to the south is generally low, with sensitivity scores ranging from 3-7. Parts of the coast, such as those at Cape Admiral Collinson and Albert Edward Bay, are extremely intricate, and contain drumlins. Particularly low sensitivity (<3) applies to the Richardson Islands region, where the high bedrock coast is developed in Precambrian rocks. The low, boggy coastal plain west of the Richardson Islands has moderate sensitivity. Beyond Cape Baring the coast is higher, and has low sensitivity overall, and one area of higher sensitivity, the low, deltaic area at the head of Prince Albert Sound.

Minto Inlet has continuous beaches with low sensitivity. A large, low, prograding sandy spit is located at Berkeley Point, in a region of moderate sensitivity. Extending toward the north along Prince of Wales Strait is an area of continuous, sandy beaches interrupted by deltas, the largest of which are in Deans Dundas Bay. Except for the latter, this coast has low sensitivity. The Peel Point area, located in the northwestern extremity of Victoria Island, is moderately sensitive. It is an exposed, low-relief area with barriers, spits, and lagoons present. Most of the irregular coast which extends to the southeast has low sensitivity. This coast has barrier beaches and lagoons, wide sandy beaches, and a braided stream complex at the head of Richard Collinson Bay.

The high bedrock coast in Wynniatt Bay, described by Dunbar and Greenaway (1956) as having "the highest and boldest scenery on the island", has the lowest sensitivity score (<2). More barriers and lagoons occur to the east, beyond which lies the relatively high rocky coast on the western side of Storkerson Peninsula. Most of this region has low sensitivity.

King William Island is underlain by Paleozoic bedrock, and has a low coast comprising continuous beaches backed by raised beaches. The sensitivity scores lie mostly between 4 and 6, thus giving the impression of a patchwork of moderate and low sensitivity areas on the map. Sensitive coastal types include coastal drumlin fields and a large sandy foreland at Matheson Point, in the southeast.

Prince of Wales Island and western coast of Somerset Island

Prince of Wales Island, except for a narrow coastal strip on the eastern side, is underlain by Paleozoic bedrock mantled by till and raised-beach deposits (Dyke et al., 1992). The southwestern, western, and northwestern coasts, which extend to the northeast extremity of Russell Island, are extremely low, with continuous beaches and scattered, small, braided deltas. Part of the southwestern coast is moderately sensitive, but the remainder is at low risk. Continuous beaches are located at the base of talus slopes on the northeastern coast of Russell Island. This area has a large fetch to the northeast, making it more susceptible than other parts of the island to an increase in the duration of open water.

To the south, along Peel Sound and Franklin Strait, relief is high in coastal regions with summits over 400 m in elevation (Dyke et al., 1992). Resistant gneissic shield rocks are exposed at the coast, including those occurrences at Prescott and Pandora islands. This is a region of low sensitivity overall, but present are relatively small areas of lower terrain that could be more sensitive to sea-level change. These areas lie between Browne and Young bays, and comprise valleys, coastal plains, and coastal forelands (Dyke et al., 1992). The western coast of Somerset Island, except for the coast north of Aston Bay, is an upland area consisting of Precambrian granite and gneiss. The coast has scattered small beaches, but continuous ones are present in Aston Bay. Overall sensitivity of this region is low.

Southwestern Baffin Island, islands in Foxe Basin, and Southampton Island

Much of the southwestern coast of Baffin Island is rocky and has low sensitivity (see the photograph of Fury and Hecla Strait in Dunbar and Greenaway, 1956). The largest area of moderately sensitive coast is in the southwestern portion of the island, and is called the Great Plain of the Koukdjuak. This feature comprises a relatively high inland section separated from the low coastal plain by a zone of raised beaches. The coastal plain is a strip of flat, marshy grassland 15 to 50 km wide, and is fringed by bouldery mudflats occurring in a macrotidal setting. Sea-level rise could cause the coast to migrate a substantial distance inland.

Another large region of moderate sensitivity is the Baird Peninsula on Baffin Island, together with the islands in Foxe Basin as follows: the Spicer Islands and Prince Charles, Foley, Air Force, Bray, Rowley, and Koch islands. These areas have extremely low and subdued relief, continuous beaches backed by raised beaches, and wide intertidal flats. The northern coast of Southampton Island fringes a plateau of Canadian Shield rocks. The coast from White Island to Seahorse Point has cliffs up to 400 m high in places and low sensitivity to sea-level rise, in contrast to the southwestern coasts, which are developed in Paleozoic rocks.

The mainland coast

The mainland coast of the Northwest Territories (excluding the Beaufort Sea coast) has low sensitivity to impact from sea-level rise, due mainly to falling relative sea level, low wave energy, bedrock coasts (commonly of resistant rock), and low rates of coastal change. However, there are several small regions with moderate sensitivity, and one with high sensitivity. The latter region extends from a point just northwest of the Horton River delta to Cape Bathurst. It consists of ice-rich tundra cliffs fronted by sandy beaches and, like the Beaufort Sea coasts (see below), is subject to increased rates of retreat.

The coast to the east, as far as the head of Franklin Bay, has continuous beaches backed by high cliffs, and is moderately sensitive. Parry Peninsula has a complex coastline, which consists of islands, spits, continuous beach, areas of bedrock cliff, and eroding ice-rich tundra cliffs. All of this coast is moderately sensitive, except the outermost part of the peninsula which is highly sensitive. In Darnley Bay the coast has extensive barriers, spits, and lagoons, and contains the large deltas of the Hornaday and Brock rivers; this coast has a moderate ranking.

The coastal geomorphology of the area extending from Darnley Bay to Dolphin and Union Strait is incompletely documented in the Woodward-Clyde Consultants report (1981); it is described as probably having continuous beaches on a low coastal plain. This coast has low sensitivity overall. The delta of the Croker River (Fig. 25 of Dunbar and Greenaway, 1956) is a small area of higher sensitivity. Drumlins occur in the low coastal area on the western side of Coronation Gulf, just north of Cape Hearne (Potschin, 1989). This is an area of higher sensitivity.

Bird (1967) mapped "cuesta" coasts in Coronation Gulf and Bathurst Inlet. These coasts, developed in Precambrian rocks, have high cliffs with narrow beaches at their bases; they have low sensitivity to impact from sea-level rise. The low, outer coast of Kent Peninsula is a small area of moderate sensitivity. The southern side of Queen Maud Gulf comprises a low, intricate coastline which consists of bedrock. This coast has a low sensitivity to sea-level rise. To the east, parts of the Adelaide Peninsula have low relief, fields of drumlins, and sensitivity appears to be moderate. Rugged bedrock coasts with variable relief and low sensitivity occur from Chantrey Inlet eastwards.

The western and northern coasts of Melville Peninsula comprise rugged uplands that developed in rocks of the Canadian Shield. Relief is particularly high towards the eastern end of Fury and Hecla Strait, where elevations exceed 350 m in coastal areas. The northeastern coast is underlain by Paleozoic rocks, and is lower in elevation; however, bold upland coasts continue to the southern limit of region 9, at Repulse Bay. All of Melville Peninsula, except for the slightly lower coasts lying just south of Cape Wilson, has low sensitivity.

Beaufort Sea coast

Coastal regions 10, 11, and 12 (Fig. 43), the Canadian shorelines of the Beaufort Sea, are broadly similar in geological, oceanographic, and climatic conditions that affect littoral processes (Pelletier, 1984, 1987). Engineering and regulatory

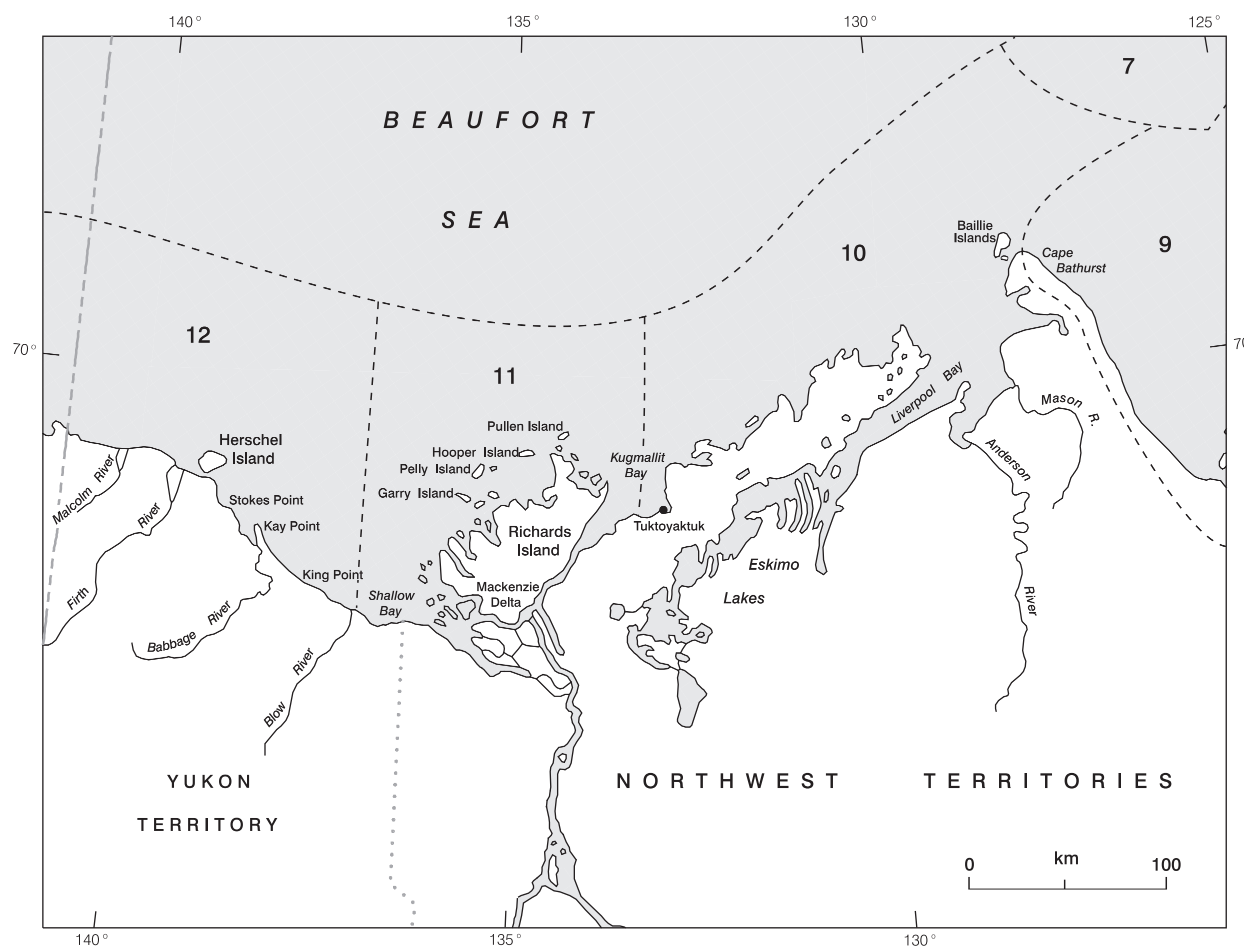

Figure 43. Map of the Beaufort Sea region showing the distribution of coastal environments 10, 11, and 12.

requirements associated with offshore oil and gas exploration in the southern Beaufort Sea have resulted in numerous detailed studies over the past 20 years or so. Planning for shore-base harbour facilities, exploratory well structures (including artificial islands), and other developments such as pipelines, has had to take account of a range of coastal hazards. These include storm effects (waves and surges), sea-ice interaction with the coast and sea bed (including ride-up, pile-up, sediment entrainment by frazil, slush, and anchor ice), frozen ground (including massive ground ice), and associated thaw instability and consolidation effects. The interaction of these phenomena with an unconsolidated and erodible shoreline in the context of slowly rising relative sea levels produces rapid coastal retreat (Mackay, 1963a, 1986; Forbes and Frobel, 1985; Harper, 1990; Héquette and Barnes, 1990; Héquette and Ruz, 1991; Ruz et al., 1992). This occurs despite fetch limitation because of pack ice, and a limited open-water season not exceeding 4 months of the year.

Coastal recession rates average more than 1 $m \cdot a^{-1}$, with maximum rates well in excess of 10 $m \cdot a^{-1}$ (Harper et al., 1985). Coastal erosion and flooding hazards in the Beaufort Sea are of concern to the oil and gas industry, for parks development, land resource management, conservation of waterfowl habitat, protection of coastal infrastructure (particularly in the context of the Inuvialuit land claim settlement), preservation of archaeological sites, and because of problems of coastal property loss at Tuktoyaktuk.

Climatic warming in the Beaufort Sea region can be expected to cause accelerated coastal erosion. More rapid sea-level rise, decreased extent and duration of sea ice (enabling generation of more energetic storm waves), and warmer ground temperatures (leading to accelerated thaw of ice-bonded sediments and massive ice in coastal exposures) will interact to increase erosion rates (Hill, 1988; Harry and Dallimore, 1989; Solomon and Forbes, 1993a).

The Canadian Beaufort Sea coast can be divided into three distinct environments (Owens, 1977a), represented here by regions 10, 11, and 12. The first environment (region 10) comprises the Liverpool Bay and Tuktoyaktuk Peninsula region, the second environment (region 11) is the Mackenzie Delta, and the third environment is the Yukon coastal plain (region 12).

The Liverpool Bay and Tuktoyaktuk Peninsula region of the Arctic Coastal Plain is covered by unconsolidated Quaternary sediments overlying older Cenozoic and Mesozoic rocks (Rampton, 1988). The Tuktoyaktuk Peninsula (Fig. 44) is characterized by large numbers of thermokarst lake basins that form a distinctive landscape and a complex embayed coast where the lakes are breached by marine transgression (Forbes and Lewis, 1984; Ruz et al., 1992). Large supplies of sand on the Tuktoyaktuk Peninsula have resulted in the formation of extensive sandy spits and barrier islands.

The Mackenzie River is one of the largest rivers discharging into the Arctic Ocean. Its delta, the largest in Canada and second largest in the Arctic Ocean, is the dominant feature of the Canadian Beaufort Sea coast. The river exerts a profound influence on coastal oceanography. Its sediment load is more than 95% of all sediment supplied to the Canadian Beaufort Sea. The Holocene delta plain (Fig. 44), a low-relief maze of channels and lakes, is rapidly eroding along parts of its seaward margin (Harper et al., 1985; Hill et al., 1991). Pleistocene deposits form a higher rolling terrain of islands in front of the delta and along its eastern margin, where the northeastern coast of Richards Island and the coast of Kugmallit Bay occur as areas of breached-lake topography (Ruz et al., 1992; Solomon and Forbes, 1993b).

The Yukon Coastal Plain forms a narrow lowland, 10-30 km wide, between the mountains and the coast (McDonald and Lewis, 1973; Lewis and Forbes, 1975). It is underlain by Mesozoic rocks, covered by a complex variety of Quaternary deposits along the coast, and is partially unglaciated (Rampton, 1982). The eastern part of the Yukon coast has a much steeper inner-shelf profile than other parts of the Beaufort Sea because of the proximity of the Mackenzie Trough offshore (Hill et al., 1986). The central part of the coast is dominated by a 70 m deep coastal basin (Herschel Basin), and lies in the lee of the dominant westerly winds, but the area west of Herschel Island is more directly affected by the polar pack and resembles the Alaskan Beaufort coast.

Although the range of astronomically forced tides in the Beaufort Sea is 0.7 m and the area is classed therefore as microtidal, storm surges as high as 2.4 m or more develop under westerly or northwesterly wind stress (Henry, 1975; Forbes, 1981; Harper et al., 1988). The open-water season typically lasts from 3 to 4 months. The extent of open water varies both temporally (through the season and between seasons) and along the coast. The median distance offshore to the edge of the pack increases eastward, from 40 km at the Alaska-Yukon boundary to approximately 120 km off the Baillie Islands. Except for the western Yukon coast (west of Herschel Island), the greater extent of open water in summer and of landfast ice in winter distinguish the Canadian Beaufort Sea coast from the Alaskan coast to the west; in the latter area, limited open water in summer and proximity of the shear zone (between landfast ice and the polar pack) in winter produce a somewhat different mix of processes over the shoreface (cf. Reimnitz and Barnes, 1987). In "bad ice years" such as 1964, 1974, or 1991, ice may remain in concentrations greater than two tenths ice cover within 40 km of the Canadian Beaufort coast through much of the summer (Markham, 1975; Henry, 1975; Solomon and Forbes, 1993a, b).

Nevertheless, wave activity can be significant under favourable conditions, when open-water fetches in excess of 400 km may develop between the coast and the polar pack. Although no long-term wave measurements are available for the Canadian Beaufort Sea, hindcast estimates (e.g. Eid and Cardone, 1992) indicate that characteristic wave heights and periods rarely exceed 5 m and 8 s, respectively. The 1% and 10% exceedence characteristic wave heights in deep water at North Head (region 11) are approximately 4.5 and 3.6 m respectively (Eid and Cardone, 1992).

Relative sea level is thought to be rising slowly along the Canadian Beaufort Sea coast (Forbes, 1980). However, the limited tide-gauge record from Tuktoyaktuk (the only permanent gauge in the area) and the high variance of these records (due to storm surge and other effects), have led to statistically

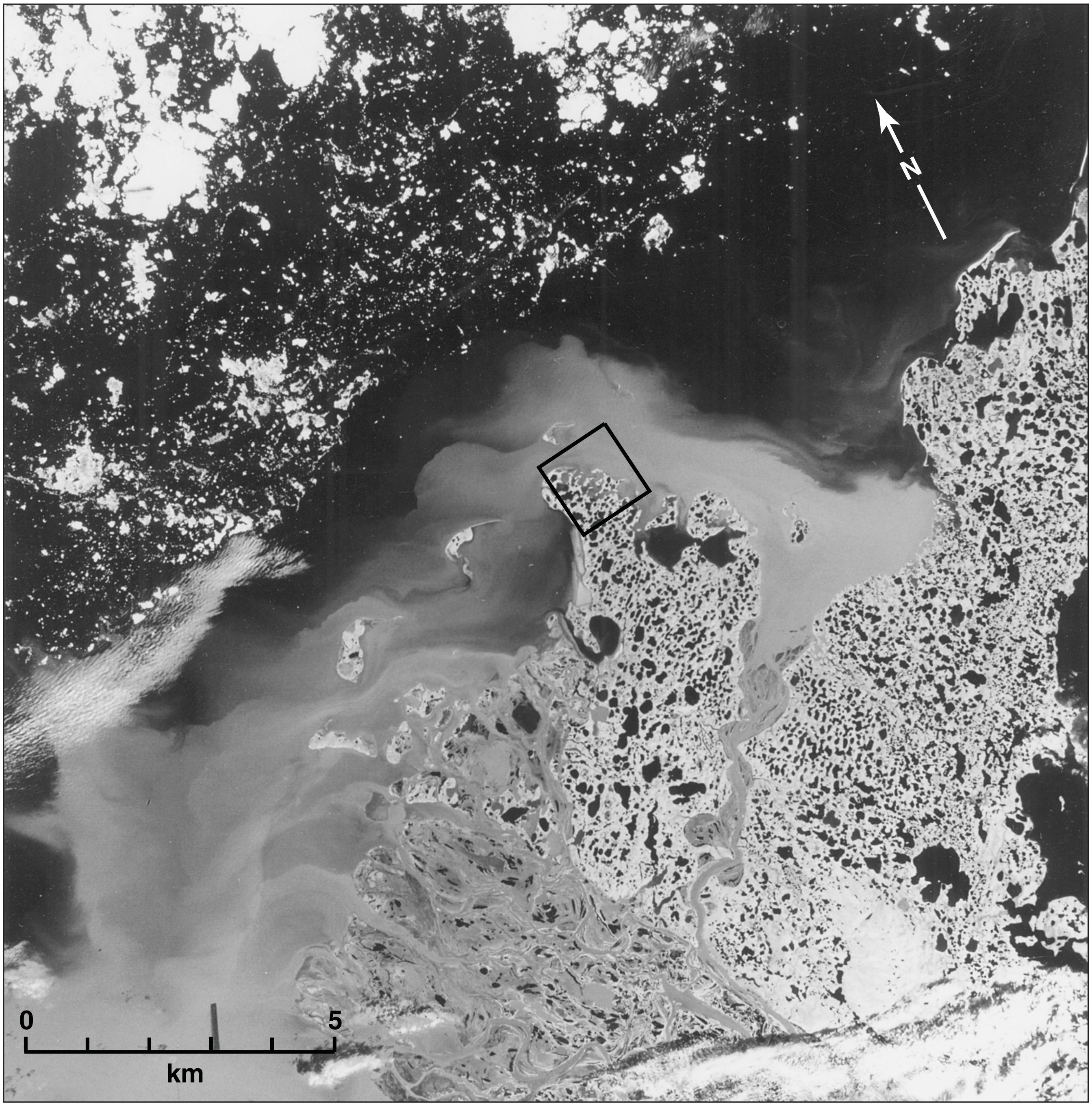

Figure 44. *Landsat 5 image of part of the highly sensitive Beaufort Sea coast, dated 23 July 1986, showing the Mackenzie Delta (bottom centre), the turbid freshwater plume of the Mackenzie River, and sea ice (top left). East of the delta (right side of the image), older Pleistocene terrain is pitted with thermokarst lake basins. Marine transgression across this surface has resulted in the development of a highly irregular shoreline with numerous shallow embayments formed by the breaching of thermokarst lakes. The area outlined is shown in greater detail in Figure 45.*

inconclusive and highly variable estimates of the trend. These estimates vary from 0.1-1.0 m/century (Forbes, 1980, 1989; Forbes and Frobel, 1985), depending on which part of the data set was used. Radiocarbon dating of coastal peat deposits has demonstrated a 30 m rise of relative sea level (averaging 0.6 m/century) since 5000 BP (Hill et al., 1985), but reduced rates during the past 1000 to 2000 years (Forbes, 1980; Hill et al., 1993).

Low-level oblique, air-video imagery for most of the Canadian Beaufort Sea coast was obtained by Forbes and Frobel (1984). Physical shore-zone characteristics have been mapped at a variety of scales by Forbes and Lewis (1984), Harper et al. (1985), among others. These and other sources show that the coast is primarily recessional and dominated by ice-rich cliffs, barriers and spits, breached-lake embayments, and eroding deltas with localized progradation. Mean sensitivity scores for regions 10, 11, and 12 are 14.8 (n=24), 20.2 (n=12), and 11.7 (n=7) respectively. The statistical distributions of sensitivity values in the Beaufort Sea region are characterized by higher variance and lower kurtosis than those in other Arctic regions, where the values are more peaked. Most sections of the Beaufort Sea coast show moderate to high susceptibility to sea-level rise.

Liverpool Bay and Tuktoyaktuk Peninsula

Liverpool Bay has unconsolidated cliffs up to 40 m high, with widespread thermokarst erosion and continuous sandy beaches. Although relatively protected, it scores toward the top of the moderately sensitive category. The Eskimo Lakes at the head of the bay form a brackish body of water with an intricate coastline, higher relief than elsewhere in the region, and very low levels of wave activity. This area is moderately vulnerable. The primary impacts of a rise in sea level would be an increase in salinity and extension of brackish habitats into former freshwater ecozones. The eastern part of Liverpool Bay is dominated by receding ice-rich tundra cliffs interrupted by important waterfowl areas in the Anderson River delta, the Mason River delta, and the former estuary of the Horton River. Wave energy increases toward Cape Bathurst, and sensitivity increases from moderate to high accordingly.

Much of the outer coast of the Tuktoyaktuk Peninsula is an area of breached thermokarst lakes, forming an intricate coastline with high sensitivity (scores ranging up to 26.2). The irregular shoreline results from the landward passage of a transgressive erosional front across low, thermokarst-lake topography (Héquette and Hill, 1989; Héquette and Barnes, 1990; Ruz et al., 1992). Small breached lakes perched above sea level are drained, and lacustrine sediments formerly deposited in them are exposed to erosion. Along this coast, the larger and deeper sea-breached lakes are transformed into wide embayments. Sandy spits and barrier islands develop within, and to seaward of, these embayments, fed by erosion of low bluffs (generally <10 m high) containing varying amounts of ground ice. Nearshore bars are prominent features of the nearshore waters off much of this coast. Barrier islands, detached spits, and anchored spits are migrating landward at mean rates of 3.1, 2.0, and 1.7 $m \cdot a^{-1}$ respectively (Héquette and Ruz, 1991).

Accelerated sea-level rise would hasten coastal retreat, resulting (for example) in more frequent breaching of thermokarst lakes and more rapid erosion of ice-rich bluffs. Even allowing for spasmodic retreat resulting partly from accumulation of debris on beaches and partly from differential adjustments on the shoreface, erosion rates could be further increased (in a global warming context) by a combination of more extensive open water, higher wave energies, and warmer ground temperatures. At the same time, new or modified spits and barriers would develop, thus maintaining the essence of the present coastal landscape.

Mackenzie Delta

The coastline of this region has two distinct parts. The first is the seaward margin of the modern Mackenzie Delta, characterized by an active distributary channel network, a low, flat, flood plain surface between channels (Mackay, 1963b), and a wide subaqueous delta platform that slopes very gently to the 2 m isobath about 15 km offshore (Hill et al., 1991). The outer delta plain is flooded by the river during the snowmelt-breakup season (Marsh and Hey, 1991), and by storm surges during the summer and fall (Mackay, 1963b; Henry, 1975; Marsh and Schmidt, 1993). The seaward margin of the delta plain is retreating rapidly in many areas (Hill et al., 1991; Solomon and Forbes, 1993a). These rates average about 2 $m \cdot a^{-1}$ east of Shallow Bay and 6 $m \cdot a^{-1}$ on the western side of the delta, where rates as high as 29 $m \cdot a^{-1}$ have been reported (Harper et al., 1985). Local progradation occurs in the vicinity of some channel outlets, particularly in the Olivier Islands region on the east side of Shallow Bay (Jenner, 1989; Jenner and Hill, 1991). Another large area of silt aggradation along the west side of Richards Island is marked by occurrences of extensive tidal flats (Forbes and Frobel, 1985). Rates of sedimentation are undetermined, but the broad erosional character of the delta coast suggests that much of the 1.8×10^6 tonnes of sediment delivered annually by the Mackenzie River may be by-passing the delta to accumulate in coastal basins (Solomon and Forbes, 1993b) and on the Beaufort Shelf (Harper and Penland, 1982).

Under accelerated sea-level rise, the outer Mackenzie Delta is liable to experience more frequent and severe flooding, inundation of emergent bars in depositional areas, and more rapid retreat of the interdistributary shoreline. It is possible that marsh surfaces on the Mackenzie Delta and elsewhere in the Beaufort Sea region would not aggrade rapidly enough to keep pace with relative sea-level rise (this is in contrast to the expected natural maintenance of marsh habitats in southeastern Canada).

The coasts of Kugmallit Bay, Richards Island, and other islands north of the delta (notably Pullen, Hooper, Pelly, and Garry) are developed in older Pleistocene sediments characterized by limited clay, extensive sands, and thin glacial diamicts, and large volumes of ground ice (Kurfurst and Dallimore, 1989). These higher relief coasts are also subject to rapid erosion (e.g. Forbes and Frobel, 1985; Mackay, 1986; Dallimore et al., 1988), despite the broad, shallow, shoreface and extensive nearshore bar complexes that cause significant dissipation of incident wave energy (Hill et al., 1986, 1991).

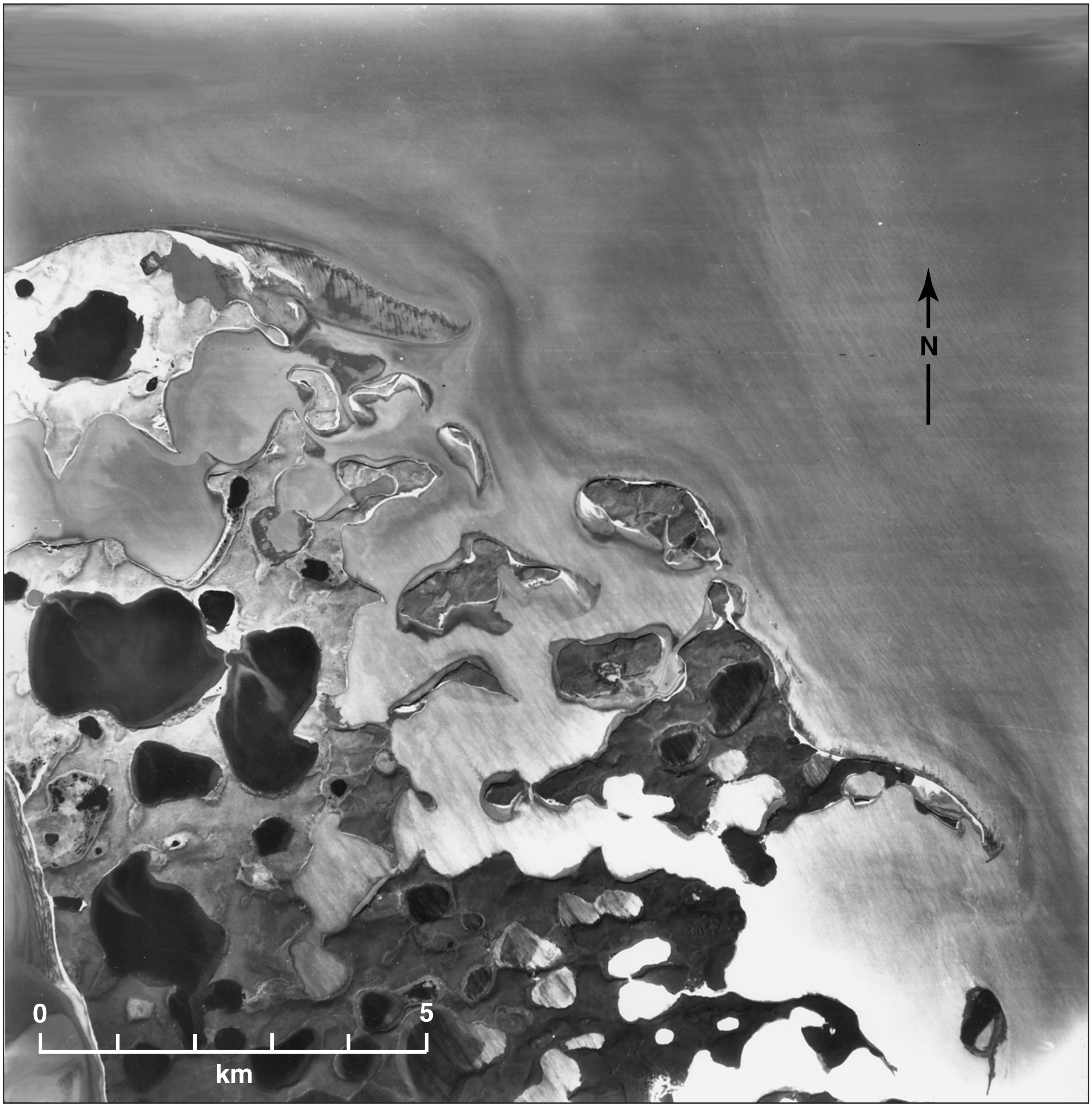

Figure 45. *Expanded view of sensitive shoreline on northern Richards Island (see Fig. 44) showing complex network of breached lake embayments. Unbreached freshwater lakes contain clear water (dark), in contrast to turbid water of the Mackenzie River plume (grey), which dominates the circulation along the outer coast and in the tidal embayments. Cliff erosion along the outer coast supplies sandy beaches, spits, and spit platforms with sediment. Accelerated sea-level rise may induce more rapid coastal erosion and further breaching of lake basins. National Air Photo Library photograph A26754-197.*

Thaw consolidation resulting from melting of transgressed permafrost may contribute to adjustment of shoreface profiles in this area (Kurfurst and Dallimore, 1989). Parts of the coast, particularly in northeastern Richards Island, show the highly embayed topography resulting from the breaching of thermokarst lakes (Fig. 44, 45), as described for the Tuktoyaktuk Peninsula (region 10).

Coastal stability in this area has recently been the subject of detailed investigation in preparation for a proposed pipeline landfall from the Amauligak field offshore (cf. Lussenburg, 1988; Solomon et al., 1992). In southeastern Kugmallit Bay, coastal erosion has been an ongoing problem at Tuktoyaktuk (Rampton and Bouchard, 1975), which is the only permanent settlement on the coast and the major port of the western Canadian Arctic (Fig. 46). Although the coastal recession, which has caused significant property losses and demolition of a large school complex, has been temporarily halted by protection works (Fig. 47), changes in the shoreface profile seaward of the beach may be ongoing as a result of various scour processes and possible thaw consolidation (Shah, 1978, 1982). The settlement of Tuktoyaktuk remains a highly sensitive location. The most exposed part of the community will eventually have to be abandoned if sea-level rise continues.

Yukon coast including Herschel Island

This is a small region, encompassed by only 7 NTS sheets. Detailed descriptions of the coastline can be found in reports by McDonald and Lewis (1973) and Lewis and Forbes (1975). The Yukon coast is developed on a coastal plain of low to moderate relief, 10-100 km wide, along the northern flanks of the Richardson, Barn, and British mountains. No bedrock outcrop occurs along the coast, which consists primarily of cliffs in unconsolidated ice-bonded sediments, fronted by sand and gravel beaches. Extensive retrogressive thaw failures occur near King Point, Kay Point, Stokes Point, and on Herschel Island, with more modest examples elsewhere. Erosion also occurs by thaw slumping, gullying, undercutting, ice-wedge meltout, and block collapse. Largely

Figure 46.

Tuktoyaktuk, the only permanent settlement on the Beaufort Sea coast and the major port of the western Canadian Arctic, is in a highly vulnerable location. Photograph by D.L. Forbes, 1991. GSC 1995-288A

Figure 47.

Plastic bags containing gravel were dumped on the beach at Tuktoyaktuk in an attempt to arrest coastal retreat. The most exposed part of the community will probably have to be abandoned if sea level continues to rise . Photograph by D.L. Forbes, 1991. GSC 1995-288B stable and vegetated backshore slopes occupy a large part of the coast in Babbage Bight, and these slopes may be susceptible to renewed erosion if sea level rises significantly.

The average sensitivity score is 12 (moderate sensitivity). Nevertheless, the Yukon coast (at least the part east of Herschel Island) is thought to be no less sensitive than regions 10 and 11. This illustrates a flaw in our method of scoring relief, which in this case has been influenced by the proximity of the mountain front, despite relatively low relief along the coast.

The two largest rivers east of Herschel Island are the Blow and the Babbage. The Blow River has built a lobate delta (McDonald and Lewis, 1973) that merges on its eastern margin with the Mackenzie Delta. The Babbage and its tributary, Deep Creek, have formed a thin deltaic veneer over valley-floor sediments as the sea has flooded up the valley (Forbes, 1981). A shallow lagoon estuary occurs to seaward. The other two major rivers of the Yukon coast, the Firth and the Malcolm, have formed braided fan deltas that are fronted by narrow lagoons lying behind a long, narrow barrier west of Herschel Island (McDonald and Lewis, 1973).

Herschel Island is an exposed area of ice-rich tundra cliffs with trailing spits at both eastern and western ends. East of Herschel Island, a low barrier coast of mixed sand and gravel extends to the mouth of Babbage River. A large barrier foreland with beach ridges is developed at Stokes Point, and a large double spit complex has formed downdrift from the mouth of Spring River in Phillips Bay. Kay Point anchors a major sand and gravel spit complex (McDonald and Lewis, 1973; Lewis and Forbes, 1975; Forbes, 1981; Forbes and Frobel, 1985), to the east of which are ice-rich tundra cliffs fronted by nearly continuous sand and gravel beaches (Lewis and Forbes, 1975). The sand and gravel barrier at King Point developed from an earlier spit that grew eastward across a former thermokarst lake basin (Hill et al., 1986; Hill, 1990). All of this coast is sensitive to impact if sea level rises.

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