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Coastal Environments of Canada : The Impact and Cleanup of Oil Spills

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COASTAL ENVIRONMENTS OF CANADA:
THE IMPACT AND CLEANUP OF OIL SPILLS.

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A Report Submitted to:

Research and Development Division
Environmental Emergency Branch
Ottawa, Ontario.

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ABSTRACT

A review of the shoreline and process characteristics of Canada's coasts involved definition and description of 34 coastal environments and shows that littoral processes operate at relatively low-energy levels in many regions due to (a) the small fetch areas on most coasts, and (b) the significant role of ice in all littoral environments, except for the British Columbia and southern Nova Scotia coasts. The shorelines are predominantly rocky coasts or coarse-sediment beaches. The major deltas of the Mackenzie and Fraser Rivers and sandy barrier beaches account for only a very small proportion of the total coastline. The expected impact and persistence of a major spill on Canada's coasts is a function of (i) the type of oil, (ii) weathering processes, and (iii) littoral zone energy levels. Cold climates in most regions and the predominance of low wave-energy levels indicate that oil from a major spill would not be rapidly dispersed or degraded. Existing clean-up methods could be employed, if necessary and if properly executed, to restore contaminated shorelines. Cleanup is usually difficult and time-consuming but can be effective. No major new methods or techniques are likely in the near future and offshore protection will remain a critical aspect of spill response for many years. Improvements

in offshore protection (from the development of acceptable chemical dispersants) and onshore protection (from new, effective and acceptable surface treatment agents) are possible in the near future and these would provide valuable options with which to combat oil spilled in Canada's coastal waters.

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RESUME

Une étude des caractéristiques des rivages canadiens et des processus s'y déroulant a comporté la définition et la description de 34 environnements côtiers et a révélé que les niveaux d'énergie des processus sont relativement faibles dans de nombreuses régions, à cause: a) des petites aires génératrices des vagues de la plupart des côtes et b) du rôle important de la glace partout, sauf sur les côtes de la Colombie-Britannique et du sud de la Nouvelle-Ecosse. Les rivages sont surtout des côtes rocheuses ou des plages à sédiments grossiers. Les principaux deltas des fleuves Mackenzie et Fraser et les cordons littoraux de sable ne constituent qu'une petite proportion de la côte du pays. Les conséquences prévues d'un déversement massif et la persistence des hydrocarbures sur les côtes canadiennes est fonction: i) du type d'hydrocarbure; ii) des processus d'altération et iii) des niveaux d'énergie de la zone littorale. Le climat froid de la plupart des régions et la prédominance des faibles niveaux d'énergie des vagues indiquent que les hydrocarbures ne seraient pas rapidement dispersés ni dégradés. Les méthodes existantes de nettoyage pourraient être employées, si nécessaire, afin de mettre en état les rivages contaminés. Le nettoyage est ordinairement difficile et long mais peut être efficace. Aucune méthode ni technique importante nouvelle n'est prévue dans l'immédiat, et la protection des zones hauturières demeurera un aspect critique des interventions dans les cas de déversement, pendant de nombreuses années. Une meilleure protection des zones hauturières (grâce à la découverte d'agents chimiques acceptables de dispersion) et côtières (grâce à la découverte d'agents de nettoiement nouveaux, efficaces et acceptables) est possible dans un avenir prochain, et ces nouveaux produits pourraient constituer des moyens précieux de lutte contre les hydrocarbures déversés dans les eaux côtières du Canada.

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PART 1 - FOREWORD

1.1 INTRODUCTION

The impact of a major oil spill on Canada's shorelines would vary considerably, depending primarily on the shoreline types and on the character of the coastal environment of the affected area. Effective response and clean-up operations for contaminated shorelines depend largely on the preparation of adequate contingency plans and on the implementation of suitable methods for restoring particular shoreline types. Because of the great variety of shoreline types and coastal environments in Canada, a variety of contingency plans are necessary. These plans require information on the nature and variability of the major coastal environments of Canada and on an assessment of restoration techniques.

This report presents the first attempt to discuss and examine the coastal environments of Canada. In dealing with such a long coastline (approximately 250,000 km) many generalizations are unavoidable. The approach used in this discussion provides a first-approximation of the characteristics of the major coastal environments and is based on division of the coastline in terms of geologic and oceanographic parameters.

In addition to the great variety of coastal environments and shoreline types, there is an uneven distribution of available information. Certain areas, particularly the Maritime

Provinces and the lower Great Lakes, have a good data base. For these areas the discussion synthesizes the major points, however, more detailed information can be obtained from the cited references. Many other sections of coast have been rarely visited and are largely unexplored. For these regions where information is lacking, the character of the coastal zone is largely inferred. Despite this great variability in the information base, it is possible to examine the major elements of each of the coastal environments in terms that can be applied to the preparation of regional oil-spill contingency plans.

1.2 OBJECTIVES

The primary objectives of this report were as follows:

(1) to define the major coastal environments of Canada, including the Great Lakes,

(2) to explain the significant geological characteristics and processes in each environment,

(3) to discuss the expected nature and behaviour of oil residues in the different environments,

(4) to discuss the expected distribution of oil residues in the littoral environment,

(5) to discuss the expected persistence of oil residues in different littoral environments,

(6) to assess available clean-up techniques in terms of their applicability and effectiveness,

(7) to present guidelines for the implementation of the most suitable clean-up techniques in each coastal environment, and

(8) to present a bibliography of relevant geological and clean-up information sources.

The report was prepared from: (a) first-hand regional reconnaissance surveys and research programmes in different parts of Canada, (b) a literature survey of results published by other workers, (c) a brief aerial reconnaissance of the southern coast of British Columbia, (d) experience gained by studies associated with previous major spills, in Canada (Chedabucto Bay and the Baie des Chaleurs) and in analogous coastal environments (Straits of Magellan, Chile), (e) a literature survey of the effects of previous spills and clean-up programmes in different coastal environments, and (f) discussions with other workers who have studied the coasts of Canada or who have been involved with coastal oil spills or clean-up programmes.

1.3 FORMAT

The information presented in this report falls into two halves. The first deals with the coastal environments of Canada, the second with the impact and cleanup of oil spills.

The coasts of Canada are initially divided into four major units on the basis of geomorphology and shoreline processes. The characteristics of each unit are then examined at a general scale (Part 2). These four primary units are subdivided into a total of 34 coastal environments, each of which is defined on the basis of process and/or morphological characteristics (Parts 3 to 6).

Using this base-line information, the expected impact of a major spill is discussed with reference to the significant process and morphology parameters of the coastal zone (Part 7). Additional information related to regional aspects of a major spill on Canada's coasts is then briefly discussed (Part 8). Consideration of restoration decisions and the applicability and effectiveness of clean-up methods (Part 9) includes a discussion of the present state-of-the-art and guidelines for the implementation of a response programme.

The bibliography, organized according to each part of the text, provides references for more detailed information, as well as listing those sources cited in the text.

An appendix following the main body of the text provides a definition of terms used in this report.

PART 2 - THE COASTS OF CANADA

2.1 INTRODUCTION

Canada's coastline is almost a quarter of a million kilometres in length, it borders on three oceans and extends from 44°N to 83°N (Fig. 1). In addition to its ocean shoreline, Canada borders on the Great Lakes system, the largest surface area of freshwater in the world (245,000 square kilometres).

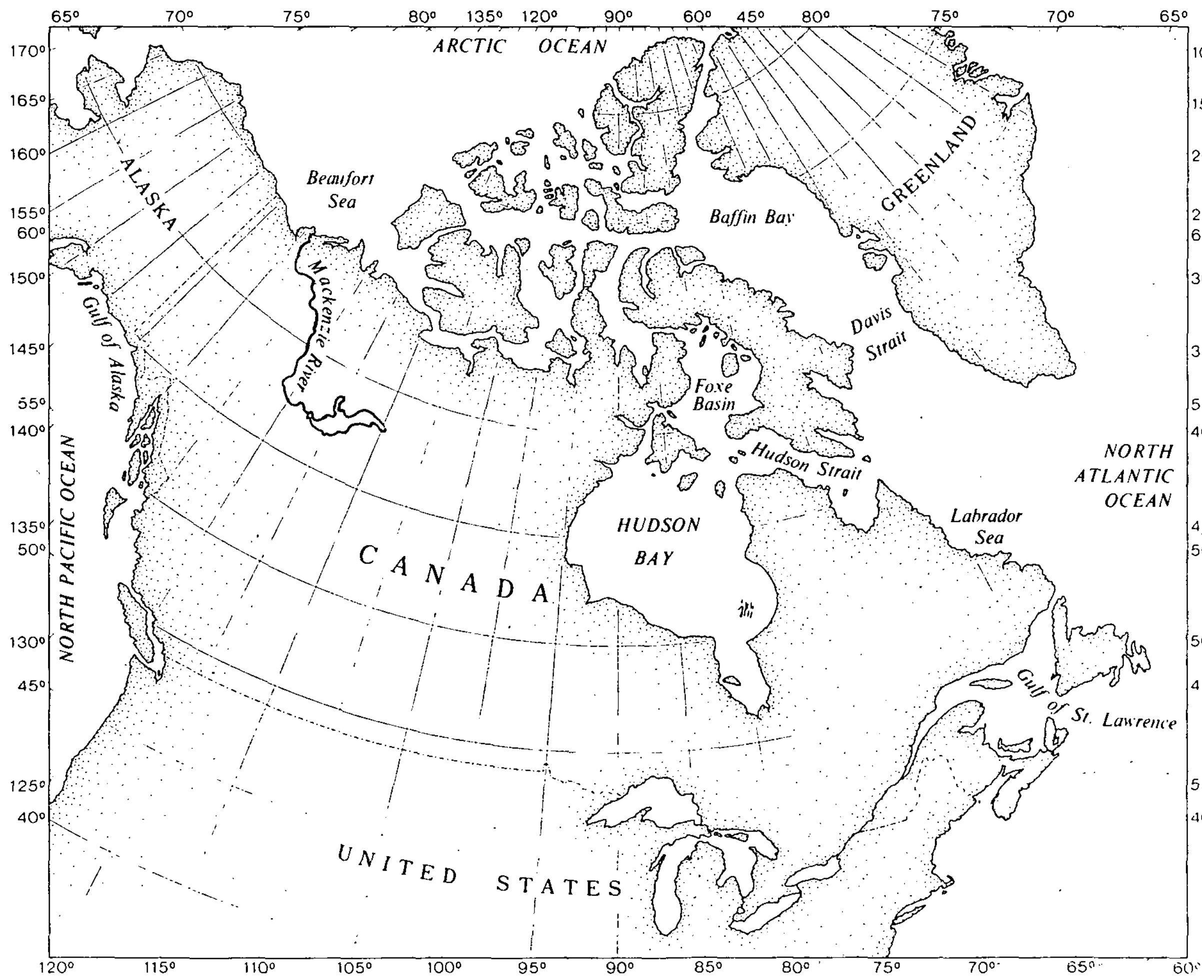


Figure 1. Location diagram of Canada.

The general structure of Canada resembles a large basin, centred on the Laurentian or Canadian Shield. This old resistant core area comprises 50% of the total land area and the central area of this basin is filled by the large inland sea of Hudson Bay. The Shield is fringed by upland or mountain regions with the Cordillera in the west, the Appalachians in the southeast, the Labrador-Baffin mountains in the east, and the Innuitian mountains in the north.

As the coastline of Canada is so long and covers a wide range of geologic and oceanographic environments it is not surprising that the coastal zones include every major shoreline type, except for those associated with coral or mangrove coasts. The character of the coastline is predominantly rocky with the major exceptions to this generalization being the Mackenzie and Fraser deltas, the barrier beaches of the southern Gulf of St. Lawrence, and the muskeg shorelines of southern Hudson Bay.

2.2 SUBDIVISION OF COASTAL ENVIRONMENTS

The primary division of the coast of Canada is based on the physical processes that act on the shoreline and on the geology and relief of the coastal zone (Table 1, Fig. 2). Within each of the four major units, secondary subdivision is based on a more detailed examination of geologic and oceanographic criteria to define 34 coastal environments. Considerable variation may exist in the types of shoreline within each of the 34 coastal

TABLE 1. Characteristics of Primary Coastal Units of Canada

	WAVES/TIDES	CLIMATE	GEOLOGY/RELIEF	COASTAL ZONE
PACIFIC COAST	Exposed environment; high wave energy levels on exposed coasts: wave heights >1.5 m, 40% to 50% of the year: tidal range 2-5 m.	Warm summers, cool winters: winds generally out of the west in winter and southeast in summer.	High mountainous coast (Cordillera), resistant rocks: coast follows northwest to southeast structural trends.	Complex rocky coast of islands, inlets, and fjords; sediments scarce except for a few areas (e.g., Fraser and Skeena deltas, Argonaut Plain).
ARCTIC COAST	Sheltered environment; very low wave energy levels and short open-water period: wave heights >1.5 m less than 20% of the open water period: tides <3 m except in Hudson Strait region.	Short cold summers, very long cold winters: ice present on the sea and on the beaches for 6 to 12 months each year.	Generally low relief in west and Hudson Bay: mountain coast on eastern fringes: predominantly an archipelago.	Very varied shorelines ranging from MacKenzie Delta and Ellesmere Ice Shelf to fjord coasts: generally rocky shorelines.
ATLANTIC COAST	Storm-wave environment: wave heights >1.5 m for 30% to 40% of open-water season: ice present up to 4 months each year: tidal range <2 m except in Bay of Fundy, St. Lawrence estuary and N. Labrador	Warm summers, cold winters: ice on the shoreline for minimum 3 months each year except in S. Nfld, outer N.S. and Bay of Fundy.	Northern segment of Appalachian mountains: relief generally low except in N. Labrador: predominantly resistant rocks.	Rocky coastline except for barrier beaches of Gulf of St. Lawrence and intertidal mud or sand flats of Bay of Fundy and St. Lawrence estuary.
GREAT LAKES COAST	Sheltered low wave energy environment: wave heights >1.5 m for 20% to 30% of open water period: non-tidal environment, lake levels vary up to 0.8 m during a year.	Warm-hot summers, cold winters: ice on lakes and beaches 3 to 4 months each year, lakes rarely frozen over.	Lake Superior and Georgian Bay border on resistant Shield; elsewhere less resistant rocks frequently covered by unconsolidated glacial deposits.	Predominantly low, cliffed coasts: few areas of large-scale sediment accumulation.

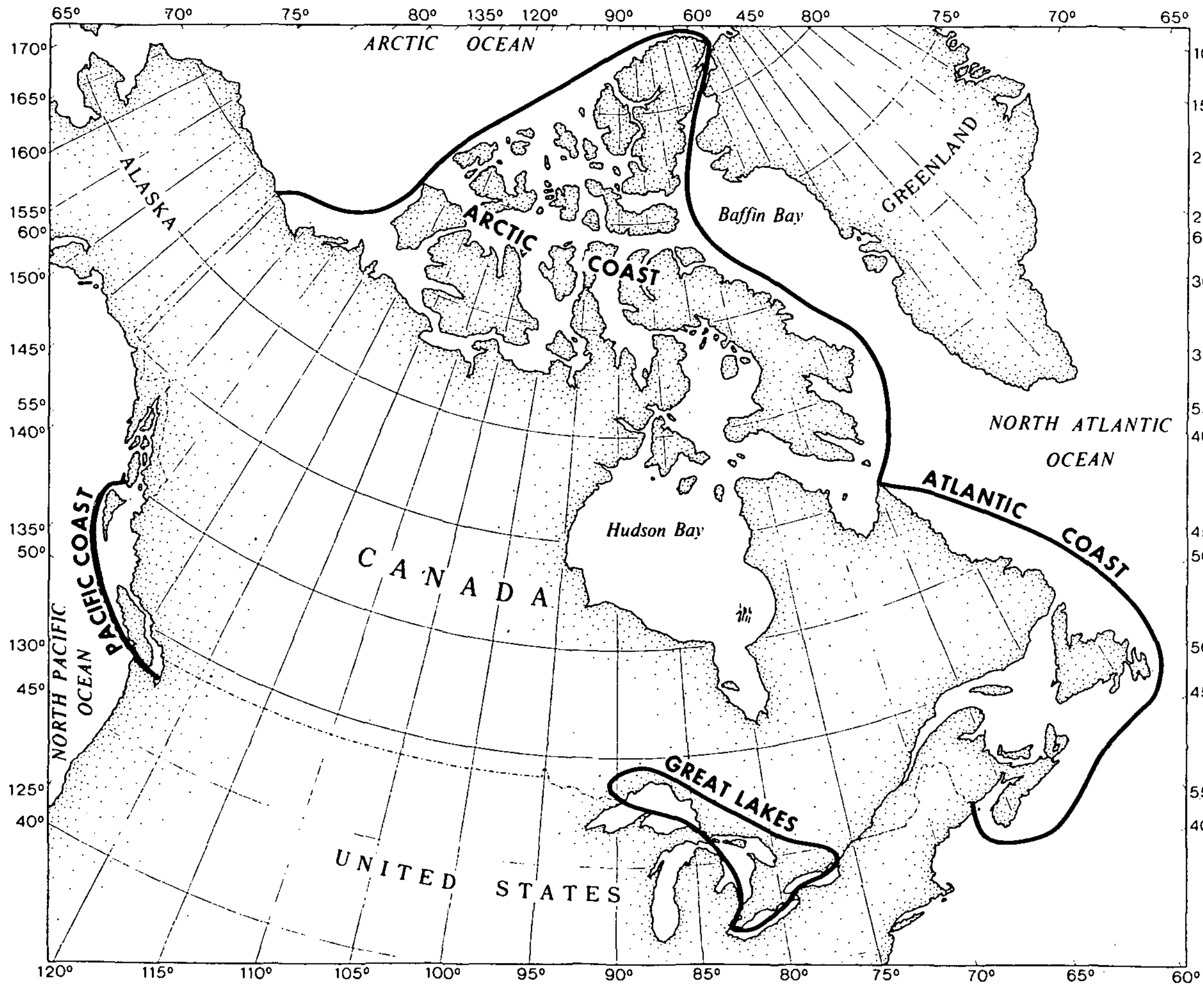


Figure 2. Primary division of the coasts of Canada.

environments, but at this level of discussion these differences are less important than the broader-scale homogeneities of the region. The approach presented in this report involves a subdivision that permits more detailed examination of each coastal environment and provides a framework for discussion of specific sections of coast within the context of the more general regional characteristics. This report presents only the general subdivisions of Canada's coastal environments. Each of the four major divisions is discussed and this is followed (Parts 3 to 6) by the detailed examination of the coastal environments within each of these divisions.

2.3 PACIFIC COAST

The Pacific coast of Canada accounts for 10.5% (25,717 km) of the total ocean coastline (Table 2). The dominant characteristic of this region is a structurally-controlled coastline of mountains and fjords. Maximum elevations up to 4000 m in the coastal mountain ranges and a complex shoreline of islands, inlets and fjords give the coast an irregular, rugged character. This is a west-facing coast, in a mid-latitude location and is exposed to waves generated in the North Pacific Ocean by the prevailing westerly winds. The exposed coast has a swell-wave environment (see definition in Appendix) with high wave-energy levels throughout the year. In contrast to the exposed shorelines, wave-energy levels are very low in sheltered coastal areas.

Winds

The primary wind directions of this region are from the northwest in summer and from the southeast in winter. In addition to this distinct seasonal variation in direction, wind velocities are greater during winter months due to the regular passage of low-pressure systems through the region. There is considerable variability in local wind directions due to topo-

TABLE 2. Canada's Coastline Measurements (in kilometres)

PACIFIC COAST		25,717	(10.5%)
Vancouver Island	3496		
Queen Charlotte Islands	2623		
ARCTIC COAST		172,950	(70.9%)
Queen Elizabeth Islands	34259		
Hudson Bay	13348		
Baffin Island	28302		
Ellesmere Island	10747		
Victoria Island	7089		
Devon Island	3588		
Melville Island	3107		
Axel Heiberg Island	3060		
Prince of Wales Island	2576		
ATLANTIC COAST		45,369	(18.6%)
Bay of Fundy	1413		
Gulf of St. Lawrence	7496		
Newfoundland (not including Labrador)	13656		
Cape Breton Island	1883		
Prince Edward Island	1260		
	TOTAL:	244,036 km	

Coastline north of the Arctic Circle	110,863	(45.4%)
Total mainland coastline	58,497	(24 %)
Total island coastline	185,539	(76 %)

(Source: after Cooper, et al, 1971)

graphic effects in most fjords and valleys, and the data for Victoria (Figs. 3 and 4, Table 3) reflect the funnelling effects of the Strait of Juan de Fuca on the winds in this area.

Waves

On the exposed coasts, offshore wave heights are greater than 3 m for 30% of the time in winter months, but for only 5% of the time in the summer months (C.H.S., 1974a). Most of the wave energy on the outer coast is in the form of long-period (up to 15 seconds) swell waves out of the west. The seasonal variation in wave height and wave-energy levels is due to the greater intensity of the Westerlies over the North Pacific Ocean during winter months. These higher wind velocities are caused by the increased pressure gradients between the low-pressure air mass over the Aleutians and the high-pressure system that is centred in the North Pacific. A secondary effect of this pressure difference in winter months is the generation of storm waves by winds associated with the cyclonic depressions that travel from west to east across the region.

In the sheltered coastal waters of Hecate Strait and the Strait of Georgia, waves are generated by local winds that approximately parallel these bodies of water. A seasonal difference is once again evident, associated with the increased frequency of storms in winter months. Wave heights greater than 3 m generally occur for 10% of the time in the winter, but for

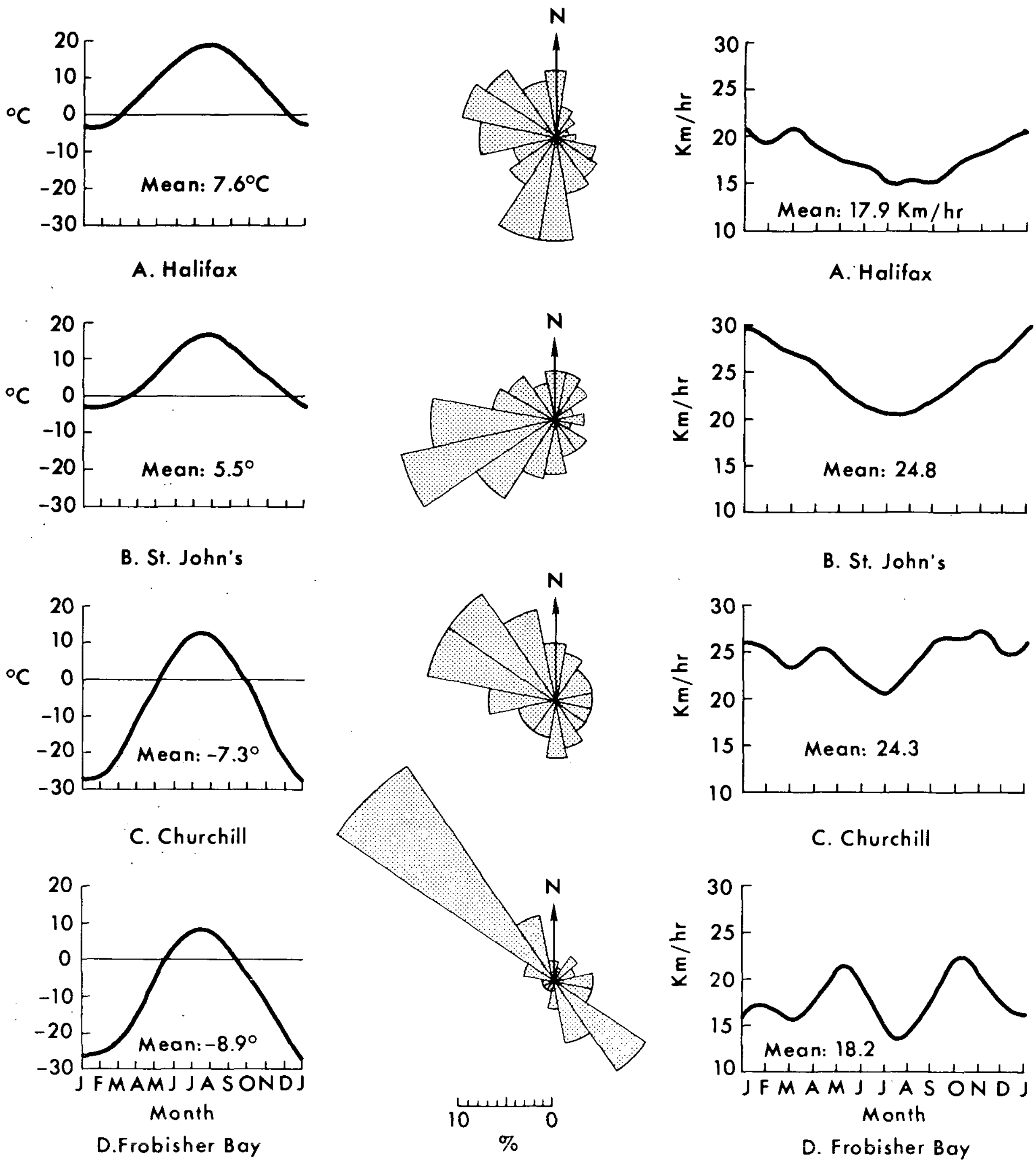


Figure 3. Selected meteorological data - mean daily air temperature for each month; annual wind frequency by direction; and mean monthly and annual mean wind velocity. The stations are located on Figure 4

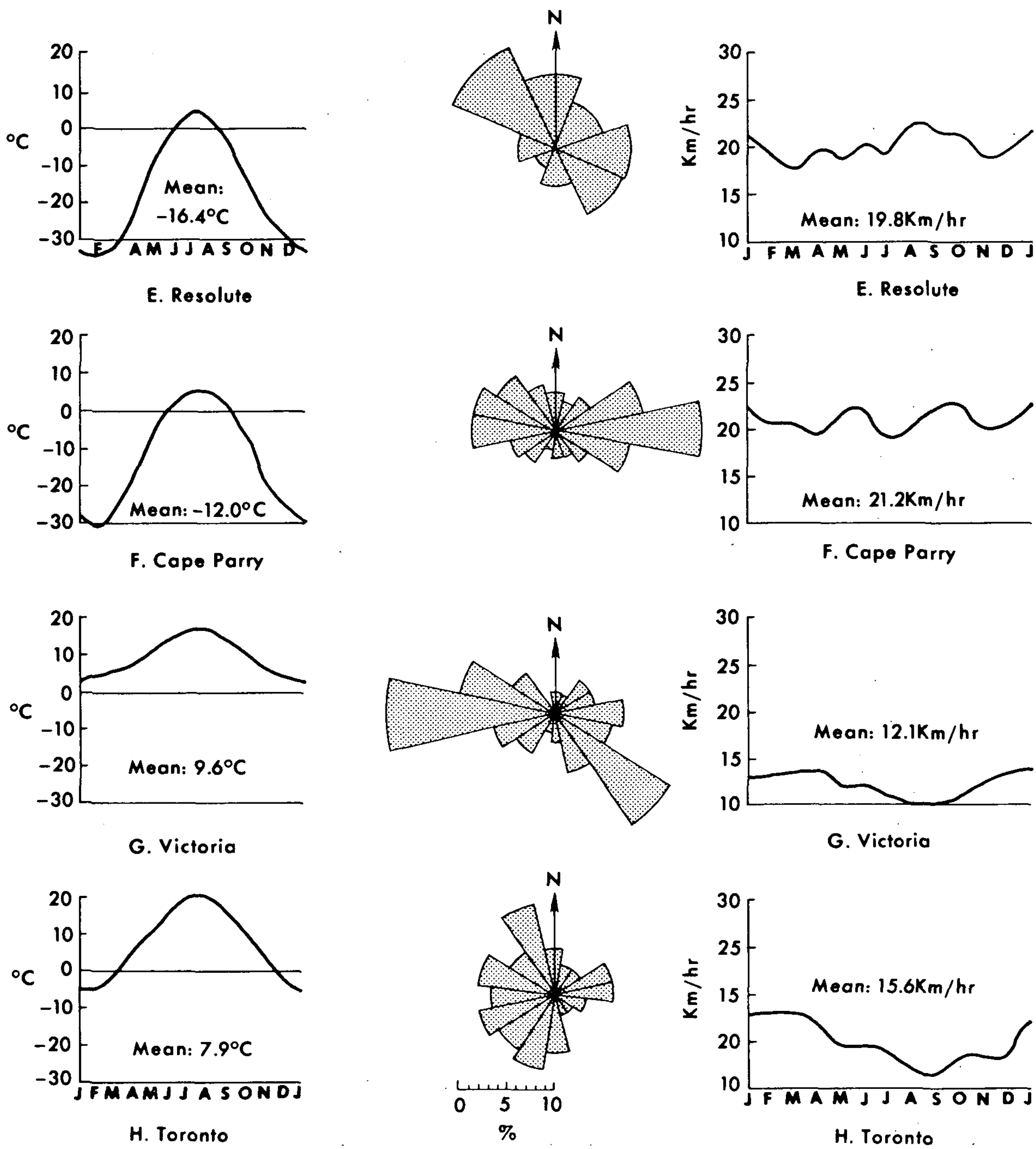


Figure 3. (cont'd) and other data for these stations are presented in Table 3 on the following pages. Sources: Canada, Department of Transport, 1968; Environment Canada, 1973.

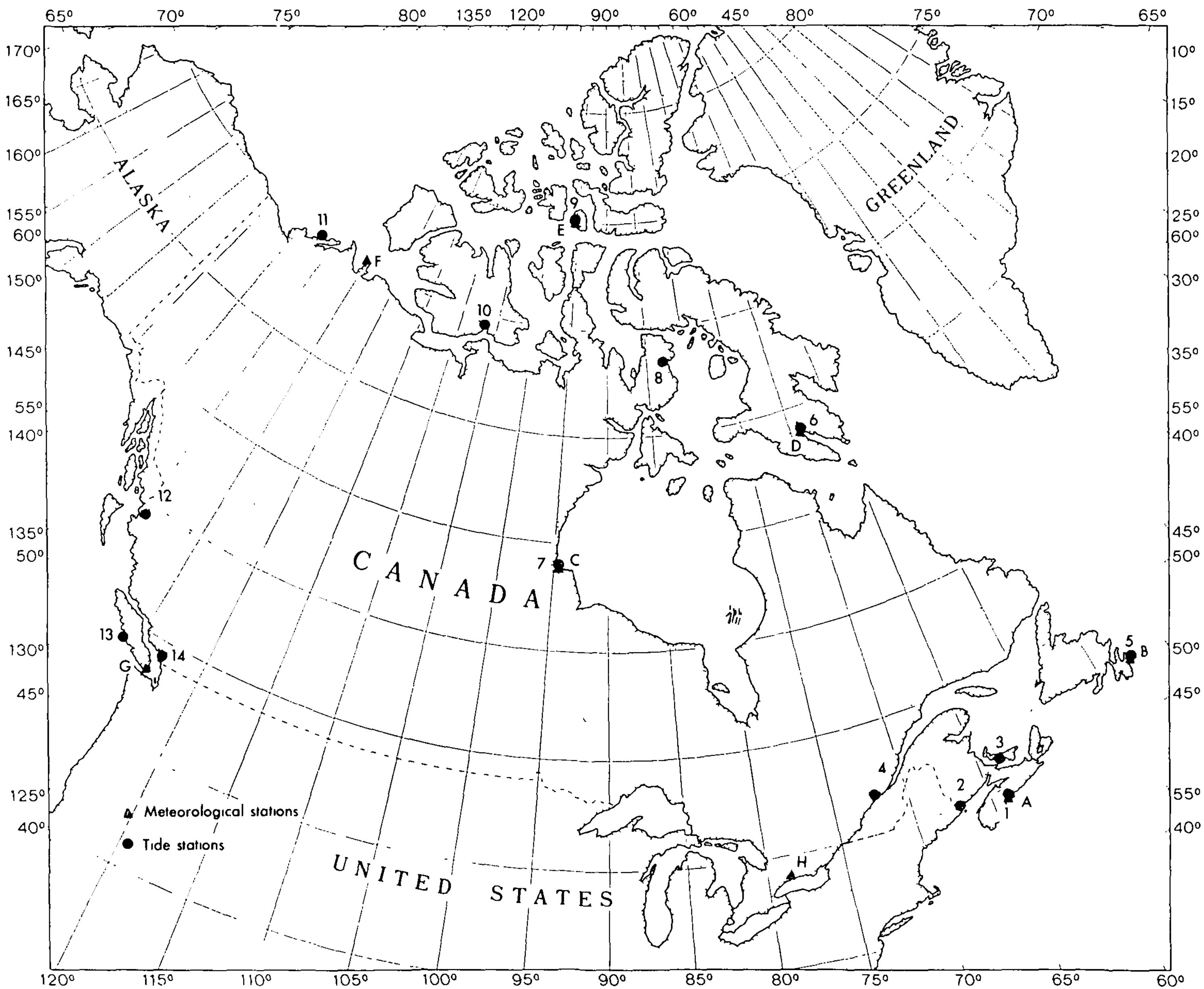


Figure 4. Location of meteorological stations for Figure 3 and tide stations for Table 4.

TABLE 3. Meteorological Data

a. Mean daily temperature (°C)
b. Prevailing wind direction

	LOCATION		JAN.	FEB.	MARCH	APRIL	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
A	Halifax, N.S.	a.	- 3.2	- 3.3	0.1	4.8	9.7	14.4	18.3	18.6	15.6	10.7	5.7	- 0.6
		b.	WNW	WNW	WNW	N/NW	S	S	S	S	SSW	S	NW	NW
B	Saint John's, Newfoundland	a.	- 3.2	- 3.8	-1.8	1.8	6.3	11.1	15.8	16.1	12.2	7.8	4.1	- 0.4
		b.	W	W	W	WSW	WSW	WSW	WSW	WSW	WSW	WSW	WSW	W
C	Churchill, Manitoba	a.	-27.6	-26.7	-20.3	-11.0	-2.3	6.1	12.0	11.5	5.7	-1.0	-11.9	-21.8
		b.	WNW	WNW	WNW	NW	NW	NW/NE	NW/NE	NNW	NNW	NW	NW	WNW
D	Frobisher Bay, NWT	a.	-26.2	-25.2	-22.3	-14.0	-3.3	3.5	7.9	6.9	2.4	-4.7	-12.4	-20.3
		b.	NW	NW	NW	NW	NW	NW	SSE	SE	NW	NW	NW	NW
E	Resolute, NWT	a.	-32.6	-33.5	-31.3	-23.1	-10.7	-0.3	4.3	2.7	-4.9	-14.7	-24.2	-28.8
		b.	NW	NW	NW	NW	N	NW	NW	NW	NW	NW	NW	NW
F	Cape Parry, NWT	a.	-28.5	-30.4	-26.1	-17.4	-6.1	1.7	5.7	5.3	0.8	-6.5	-18.2	-24.5
		b.	W	W	E	E	E	E	E	E	E	ESE	E/W	E/W
G	Victoria, B.C.	a.	2.9	4.7	5.8	8.6	11.9	14.5	16.4	16.1	13.9	10.0	6.2	4.2
		b.	W	W	W	W	W	SE	SE	SE	W	W	W	W
H	Toronto, Ontario	a.	-4.8	-4.8	0.0	6.3	11.3	17.2	20.2	20.0	16.6	10.5	4.8	-2.0
		b.	SW	WSW	NW/E	NW/E	NNW	NW/S	NW/S	NW/S	NW/SW	WSW	WSW	SW

Source: Canada, Dept. of Transport 1968, and Environment Canada, 1973.

less than 5% of the time in summer months. Local wave-energy conditions are very variable, depending on fetch distances (q.v.) over which waves approaching a given section of shoreline can be generated.

Ice

Ice plays a very minor, virtually negligible role in coastal processes in this region. Sea-water temperatures are always above freezing and ice only forms in inlets where inflowing fresh river-water freezes.

Tides

The mean range of the semi-diurnal tides (q.v.) on this coast decreases from 5 m in northern areas to a minimum of 2 m near Victoria (Table 4). A maximum range of 8.4 m has been recorded at Prince Rupert. An important effect of the tides in areas where the passage of water is constricted through narrow channels is the generation of strong tidal currents. In Discovery Passage and the Seymour Narrows, at the northwest end of the Strait of Georgia, tidal currents up to 7 m/s are common (C.H.S., 1974a and 1977). An additional characteristic of tidal currents in inlets is that the ebb frequently runs for longer, and is stronger, than the flood current, due to the effects of freshwater discharge and this is particularly noticeable during the spring run-off period.

TABLE 4. Selected Tidal Range and Tide Type Data

LOCATION	MEAN TIDAL RANGE	LARGE TIDAL RANGE	TIDE TYPE
1. Halifax, N.S.	1.4 m	2.1 m	SD
2. Saint John, N.B.	6.7	9.1	SD
3. Charlottetown, P.E.I.	1.8	2.9	MSD
4. Quebec City, P.Q.	4.1	5.8	SD
5. St. John's, Nfld.	0.9	1.4	SD
6. Frobisher Bay, NWT	7.3	11.6	SD
7. Churchill, Man.	3.4	5.2	SD
8. Hall Beach, NWT	0.8	1.3	MSD
9. Resolute, NWT	1.3	2.1	MSD
10. Cambridge Bay, NWT	0.4	0.6	MSD
11. Tuktoyaktuk, NWT	0.3	0.5	MSD
12. Prince Rupert, B.C.	4.9	7.6	MSD
13. Tofino, B.C.	2.7	3.9	MSD
14. Vancouver, B.C.	3.3	4.9	MD

SD - Semi-diurnal
MD - Mixed diurnal
MSD - Mixed semi-diurnal

Source: Canadian Hydrographic Service, 1977

Note: Stations are located on Figure 4, page 14.

Geology

In this Pacific coast region resistant mountains up to 4000 m in height occur adjacent to the ocean (Photo 1). This mountain belt (the Cordillera) is part of a system that fringes the entire length of the eastern Pacific Ocean from Chile to

Photo 1. Upland fjord coastal zone, looking seawards, southwest Vancouver Island, British Columbia. Relief is in the order of 1500 m. (December 1976)

Alaska. The Coast Range on the mainland is separated by the Hecate-Georgia Strait Depression from an insular range that rises to 1200 m on the Queen Charlotte Islands and to 2200 m on Vancouver Island. Seaward of the outer range the sea floor drops off rapidly and the continental shelf is less than 50 km wide in most areas.

The structure of the Cordillera system runs northwest-southeast and this controls the primary trend of the coast. The rocks are predominantly resistant volcanics or intrusives (q.v.) with relatively few exposures of less resistant sedimentary rocks. The rock outcrops are only occasionally covered by glacial deposits, and these are often thin and restricted in area except on the coastal plains.

The mountainous coastal zone was considerably modified by the effects of ice during the Pleistocene. Glaciers developed on the Queen Charlotte Islands and on Vancouver Island as well as on the Coast Mountains. The rugged relief of the mountains and the formation of a fjord coastline result directly from erosion by these glaciers. Dixon Entrance, Hecate Strait, Queen Charlotte Sound, the Strait of Georgia and the Strait of Juan de Fuca have been modified by the scouring effects of the ice.

Coastal Geomorphology

The form of the Pacific region coastline is attributed primarily to the structural control exerted by the Cordilleran Mountain system and secondly to topographic modifications by erosion of an extensive system of fjords by the Pleistocene glaciers. The coastal zone is characterized by high relief, resistant rock outcrops and a general scarcity of sediments. Although the coasts are generally steep, wave-eroded sea cliffs are not common, the notable exceptions occurring on the west coast of Moresby Island (in the Queen Charlotte group) and on the east coast of Vancouver Island. The numerous fjords extend inland up to 110 km and give a very indented coastline. These fjords are typically U-shaped (Photo 1) and result from the sea flooding into deep, narrow valleys that were eroded or deepened by the glaciers.

As the rock outcrops on the coast are predominantly resistant, little sediment is available for reworking by shoreline processes. Small deltas occur in sheltered areas at the heads of fjords (e.g., at Kitimat and Bella Coola) and two large prograding deltas have formed at the mouths of the Fraser (Photo 2) and Skeena Rivers. A few extensive beach systems have developed

Photo 2. Mouth of the Canoe Pass channel, Fraser River delta, British Columbia. (December 1976)

at several locations, notably at Long Beach on the west coast of Vancouver Island (Photo 3) and on the Argonaut Plain in northeast Graham Island, where local erosion of unresistant rocks or of glacial deposits has supplied sediment to the littoral zone. Other smaller beach systems have developed where sufficient amounts of sediment are provided by wave erosion and where there is a relatively shallow nearshore zone.

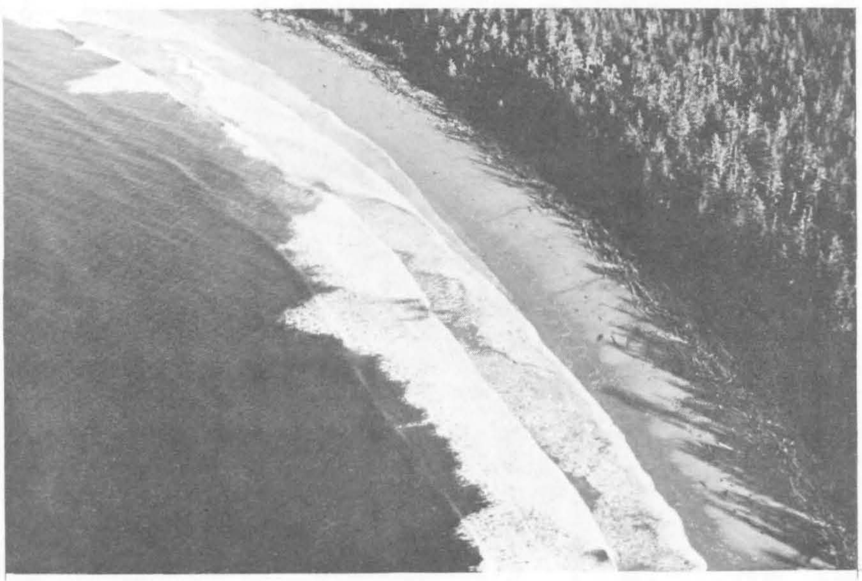


Photo 3. West coast Vancouver Island, British Columbia. Aerial view of a wide (c. 100 m) sand beach at low tide. Note logs above the high-water mark and the long-period swell waves breaking on the beach. (December 1976)

2.4 ARCTIC COASTS

This coastal environment includes almost three quarters (70.9%) of the ocean coastline of Canada (Table 2, p. 10). Everywhere within this environment ice plays an important role in modifying shoreline processes and morphology. Although 35.9% of the coasts of this unit lie south of the Arctic Circle (66°33'N), these shorelines are nevertheless affected by ice for more than 6 months each year. There is great variety in the shoreline characteristics (ranging from the large delta of the Mackenzie River to the cliffed fjord coasts of Baffin Bay), however, the coasts of this region are characterized by a sheltered wave environment in which sea and shore ice control the length of time during which littoral processes can operate.

Winds

All areas have prevailing winds out of the west or northwest, but in western sections (the Beaufort Sea coast) the lower frequency of cyclonic depressions results in approximately equal frequencies of southeast and northwest winds (C.H.S., 1970) (compare Frobisher Bay, Churchill and Cape Parry in Fig. 3 and and Table 3, p. 12 to 15). In winter months the Polar Continental air mass, a high-pressure system, is centred over the Mackenzie Basin and this produces winds out of the northwest quadrant over most of this region. As this high-pressure system moves to the north and east in summer months, cyclonic storms move across Hudson Bay towards the Davis Strait area. In the eastern Arctic during summer months winds are out of the southwest due to the influence of a large low-pressure system centred over Iceland and southern Greenland.

Surface winds are more variable in summer months, due to the greater frequency of cyclonic depressions, but there is little difference in average wind velocities between the two seasons. When compared to more southerly latitudes, wind velocities are lower due to the relatively low pressure gradients associated with the Polar Continental air mass. In summer, strong winds (>50 km/hr) occur on the average only one or two days each month (C.H.S., 1970). In areas of high relief, topography can considerably modify the normal wind pattern to produce strong local winds.

Waves

The primary controls on wave generation are the small fetch distances and the presence of sea ice. Waves are usually less than 1 m in height and have short periods (2-4 seconds). Except for Hudson Bay and Baffin Bay, fetch distances are generally less than 300 km. In those two areas wave-energy levels are highest due to the size of the water bodies and to the fact that these areas have the longest periods of open water. In Hudson Bay wave heights greater than 4 m can be expected for 1% to 2% of the time in summer months (July to September) and waves less than 2 m in height occur for approximately 80% to 90% of the open-water season (U.S. Naval Oceanographic Office, 1965). Wave-generated nearshore processes in this environment require (1) that the sea be free of ice, (2) that the wind direction coincide with the open-water fetch for sufficient time to generate waves, and (3) that beach and nearshore zones are ice-free.

Ice

The distribution of ice during the period 1 to 15 September is representative of the maximum open-water conditions. Figure 5 presents the expected distribution of ice during this period for heavy and light summer ice conditions. In winter months solid ice covers virtually all of the waters of the archipelago with a 6/8 to 8/8 cover over Lancaster Sound, Baffin Bay, Foxe Basin, Hudson Strait and Hudson Bay. As the ice is moved through the channels towards the east and south during late spring, breakup progresses slowly into the archipelago. The length of the ice-free season is at a minimum in the most northwest sections of the archipelago, and in these areas some years may have no open-water season at all (Fig. 5a). Littoral processes can only operate when the sea <u>and</u> the beach are ice-free. An ice foot (q.v.) on the shore forms before freeze-up and persists after breakup of the sea ice, so that the length of time that the shore is ice-free is less than the open-water period (Fig. 6).

Tides

Tidal range is high in the southeast sections of this division, with maximum spring tidal ranges of 11.6 m (Table 4). The range decreases to the north and west, with values less than 0.5 m on the coasts of the Arctic Ocean.

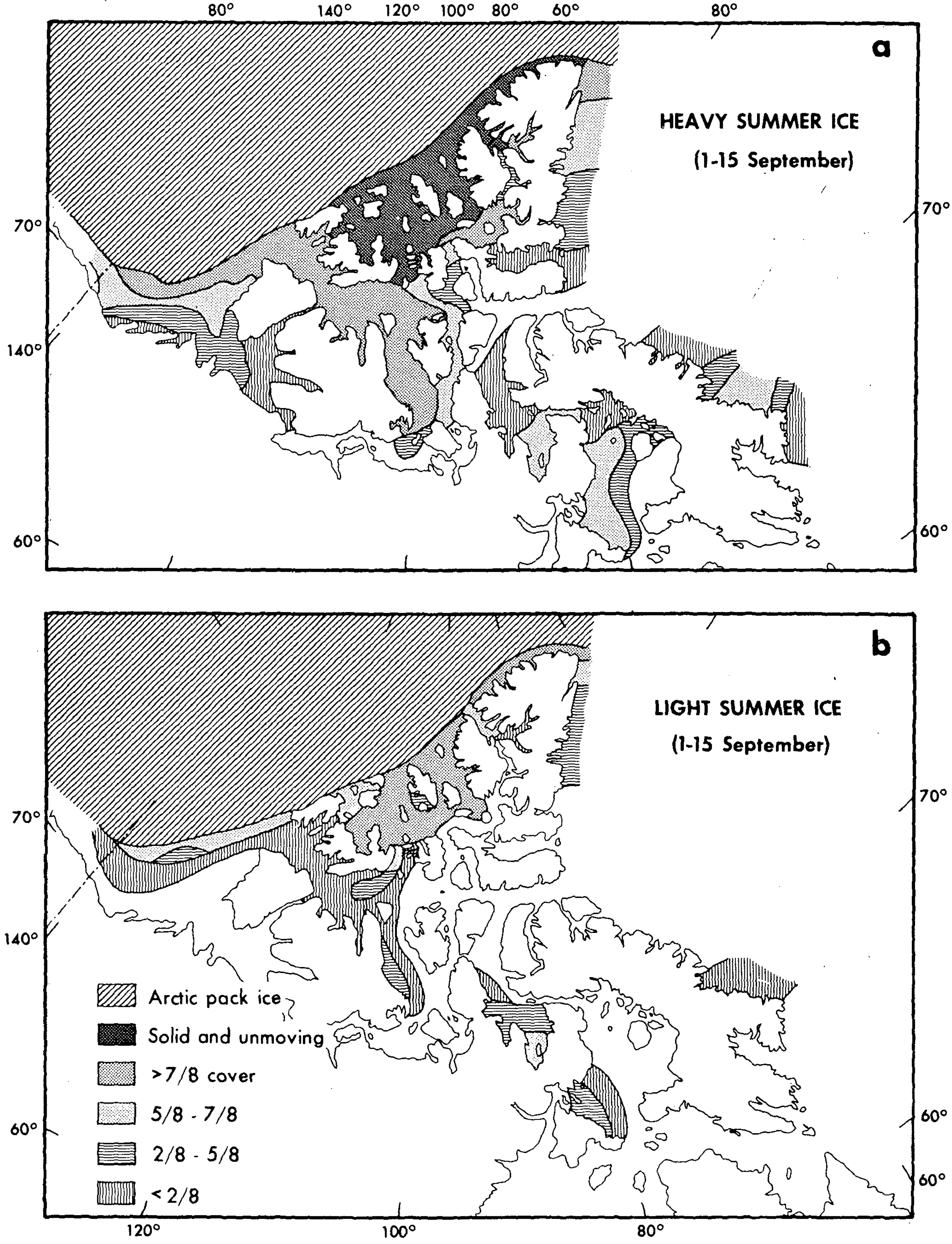


Figure 5. Distribution of ice on Canadian waters during summer: (a) heavy and (b) light years (after C.H.S., 1970).

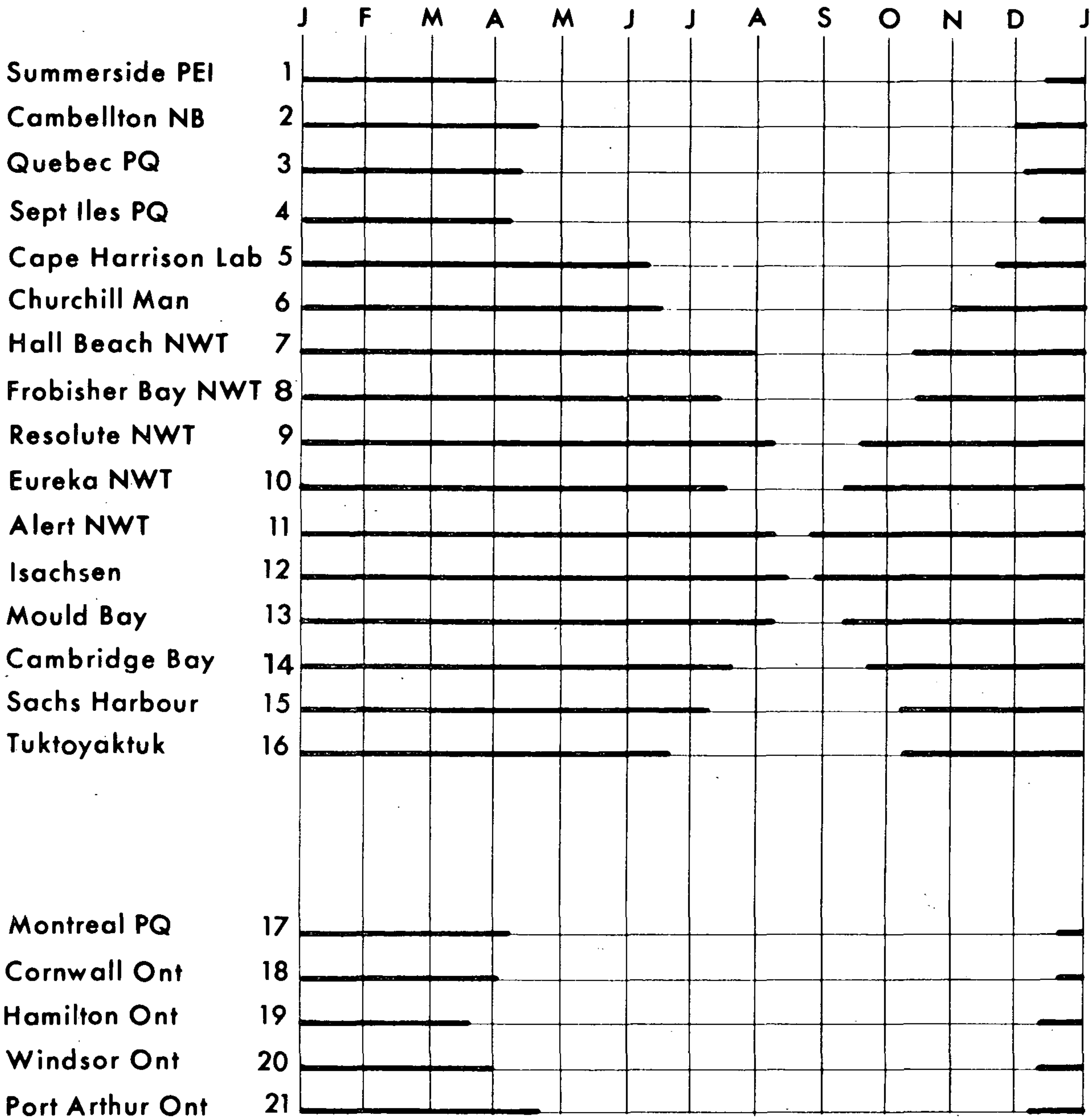


Figure 6. Duration of ice on beaches or in nearshore zones during average years (data from Allen, 1964). Stations are located by number on Figure 8 (page 34).

Geology

This environment can be divided into 4 geological units. The Canadian Shield (i) includes the majority of the mainland coast and in the east extends north into Baffin Island, east Devon Island and southeast Ellesmere Island (Fig. 7). The

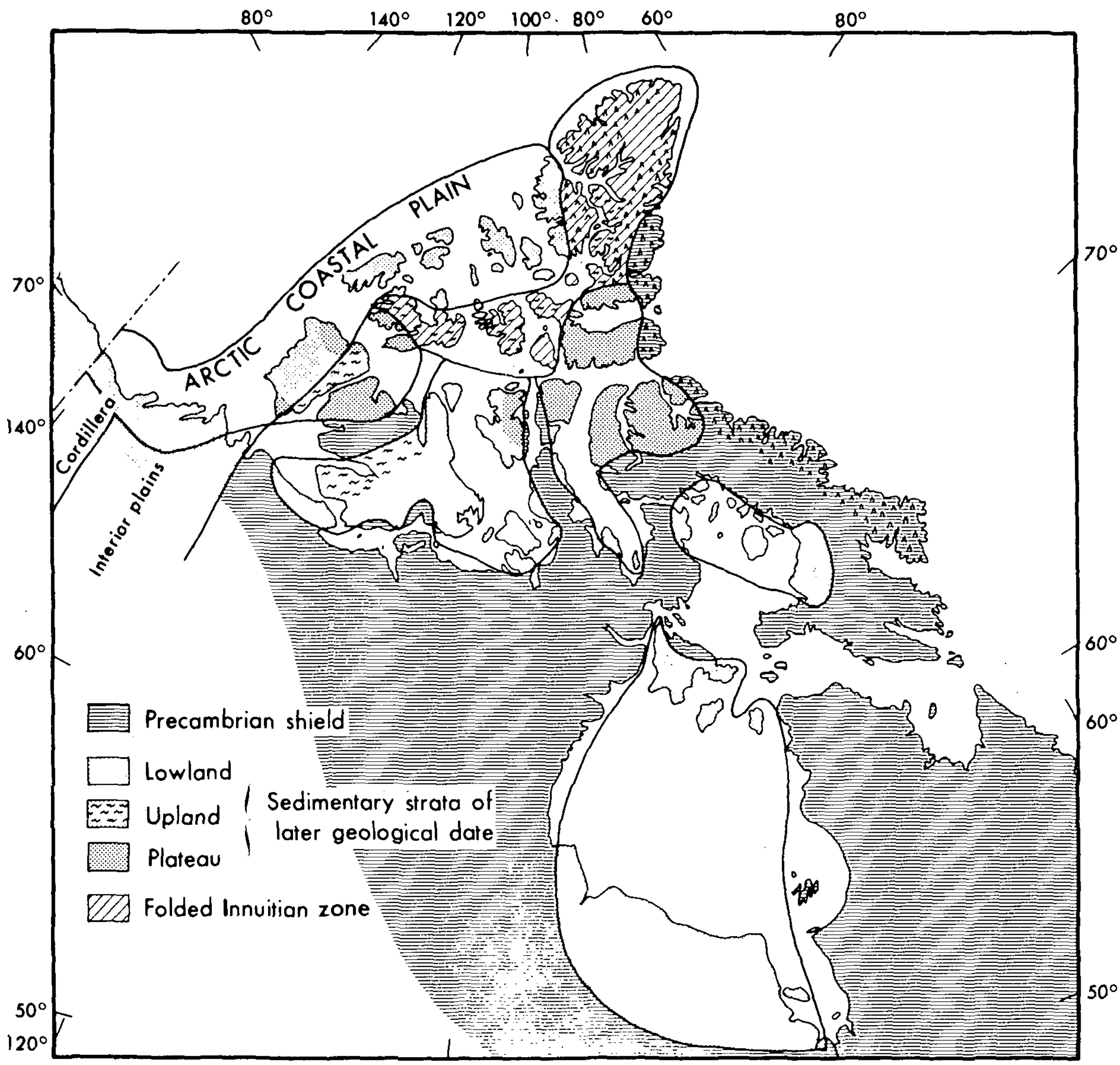


Figure 7. Generalized geologic map of the Canadian Arctic (after C.H.S., 1970).

Shield has a basin-like shape, with the low central area occupied by Hudson Bay and the eastern rim expressed by the mountains of east Baffin, Devon and Ellesmere Islands. In the northwest, the Arctic Ocean is bordered by a low coastal plain (ii) of undeformed sedimentary rocks. In the north, the Innuitian Mountain system (iii) consists of folded sedimentary rocks that trend north-south through Ellesmere Island, then trend east-west through northeast Devon, Bathurst and Melville Islands (Fig. 7). The final division (iv) is a series of sedimentary basins that have developed on the old resistant rocks of the Canadian Shield platform. These sedimentary rocks form uplands, plateaux and lowlands; the resistance of the rocks varies greatly in different areas.

Except for west and northwest sections, the region was affected by vast Pleistocene ice sheets and glaciers. In upland or mountain regions adjacent to the coast the ice gouged steep valleys that have been invaded by the sea to produce fjord coasts. As the ice retreated across lowland regions, south of Queen Elizabeth Islands, large areas were mantled with thick deposits of unconsolidated glacial sediments.

Coastal Geomorphology

The shorelines of the Canadian Arctic are predominantly rocky in character. A large depositional (deltaic) area occurs at the mouth of the Mackenzie River on the Beaufort Sea coast.

In other areas, the accumulation of sediments in the littoral zone is often related to the presence of small river deltas that feed material directly into the shore zone. Intertidal mud flats occur in the eastern part of Foxe Basin and on the southwest coast of Hudson Bay. Littoral processes and beach development are greatly limited by the very low levels of wave energy that result from the very short open-water season.

The resistant mountains of the Canadian Shield have been eroded to give a fjord coastline in the eastern Arctic on Davis Strait, Baffin Bay and Kane Basin (Photo 4). Elsewhere the

Photo 4. Inner part of Hare Fjord, Nansen Sound, west Ellesmere Island, N.W.T. Relief in this area is up to 3000 m and a series of valley glaciers cross the steep fjord walls. Small deltas occur where the valleys that do not contain glaciers enter the fjord. Photograph taken in mid-July; the fjord is completely covered by sea-ice (from Dunbar and Greenaway, 1956).

Shield coast generally forms a resistant lowland shoreline. Although the sedimentary basins have less resistant rocks, the slow rates of coastal erosion due to low wave-energy conditions have resulted in relatively little shoreline modification. Locally, accumulations of sediment have produced beaches, spits and deltas in some areas, but except for the Coastal Plain the coasts generally have either lowland or upland cliffs. Where the backshore relief is low, narrow pebble-cobble beaches have developed. The arctic region was covered by thick ice sheets during the Pleistocene and the weight of this ice caused the land to be depressed. Since the ice melted the land has risen, and in most areas, still is rising. In lowland sections this has given a series of raised or stranded beaches which extend up to several hundred meters above present sea level (Photo 5).

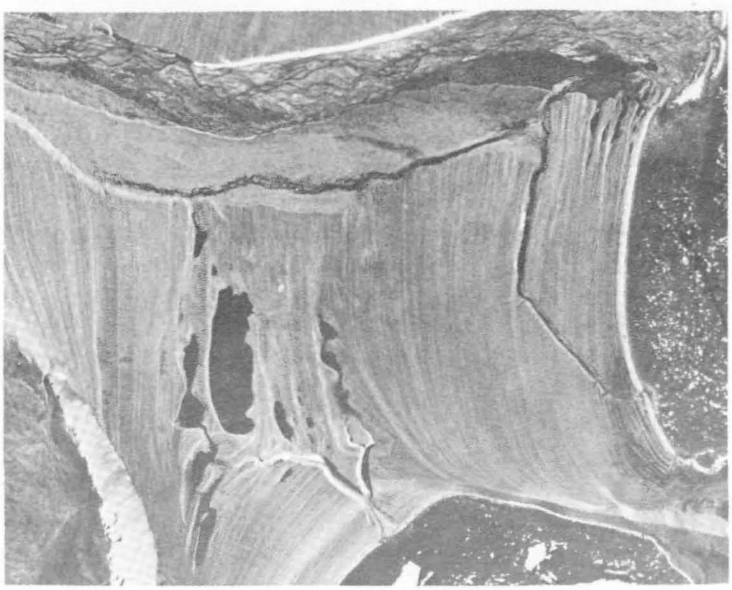


Photo 5. Vertical aerial photograph, raised beaches near Cape Storm, south Ellesmere Island, N.W.T. (National Air Photo Library, Ottawa, A16756-149, July 24, 1959).

The same processes occur in this environment as in lower latitudes, however, ice plays a significant role in reducing the level at which these processes operate. The characteristics of the shorelines of this environment are predominantly those of rocky cliffed coasts in a low wave-energy environment.

2.5 ATLANTIC COAST

The Atlantic coast of Canada is a predominantly exposed, rocky environment that extends from the United States border to Cape Chidley in northern Labrador (Fig. 2, p. 8). This unit is 45,369 km in length (Table 2, p. 10), represents 18.6% of Canada's ocean coastline and includes the large marginal sea of the Gulf of St. Lawrence (with a coastline of 7,500 km) and the smaller Bay of Fundy (1,400 km). Within this region there is a large variation in tidal range (Table 4, p. 17) and in levels of wave energy. The unifying characteristics of the region are the rocky shorelines, the predominance of storm-generated waves, and the general scarcity of littoral sediments.

Winds

The prevailing winds are out of the westerly quadrant (Fig. 3 and Table 3, p. 12 to 15). The edge of the Polar Continental air mass lies across this unit and the local characteristics of the winds are dominated by the west to east passage of cyclonic depressions along this Polar Front. These low-pressure systems are more frequent and intense during winter months when the pressure gradients along the Polar Front are greatest. Occasionally this coastal area is affected by extra-tropical storms that form in the southwestern North Atlantic and swing towards the north along the North American coast. These storms are most common during the period August to October, and between 1871 and 1963 fifty such storms crossed this region, although only 7 had hurricane-force winds (>120 km/hour) (Cry, 1965).

Waves

This mid-latitude east-facing coast is influenced by waves that are generated locally in the western North Atlantic. This is a storm-wave environment (q.v.), with wave periods usually between 4 and 10 seconds, as compared to the swell-wave environment that characterizes the Pacific coast of Canada (Davies, 1972). Within this unit there is a considerable variation in wave energy in both time and space. For instance, Neu (1971) notes that in offshore areas wave-energy levels in winter are 5 times greater than in summer. However, during winter months because winds are primarily out of the northwest, the seas off Nova Scotia are in a relatively sheltered location, so that wave-energy levels are 3 to 4 times less than over the exposed Grand Banks off Newfoundland. The yearly maximum wave heights range from 18 m on the Grand Banks, to 16 m off Labrador, 12.5 m on the Scotian Shelf, and to 7.6 m in the Gulf of St. Lawrence (Neu, 1972; Ploeg, 1971).

In the more sheltered coastal areas (the Gulf of St. Lawrence and the Bay of Fundy), significant wave heights (q.v.) are generally less than 2 m, with maxima occurring in winter months. Wave-energy levels vary locally with shoreline orientation and with fetch distances. For example, in the Magdalen Islands, located in the central part of the Gulf of St. Lawrence, significant wave-height values are greater on the exposed west coast by a factor of 2.25 in summer and 2.95 in winter when compared with the adjacent, but sheltered east-facing coast of the Islands (Owens, 1977b).

Ice

The importance of ice in the coastal zone increases from south to north (Fig. 6, p. 26). The southwest coasts of Nova Scotia are virtually ice-free (Fig. 8), whereas ice is present on the beaches and in the nearshore zone for up to 4 months each year in the Gulf of St. Lawrence and for up to 7 months each year in central Labrador (Allen, 1964). Ice on the sea prevents wave generation and dampens existing waves, but the primary effect of ice is its presence in the nearshore zone or on the coast, which prevents waves acting upon the littoral zone.

Tides

There is considerable variation in tidal range throughout this environment (Table 4, p. 17). From Cape Chidley in northern Labrador to Battle Harbour on the southeast coast of Labrador,

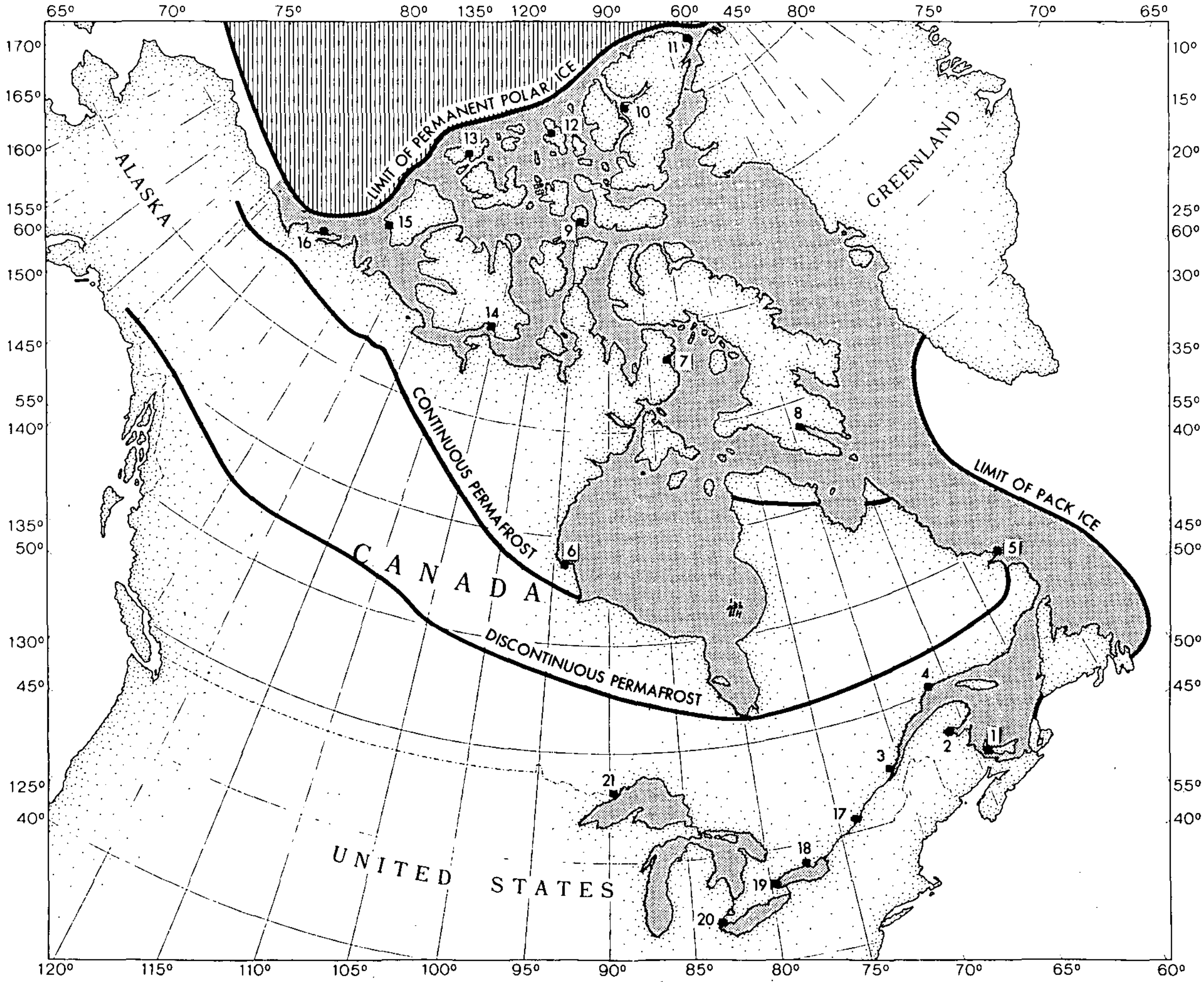


Figure 8. Limits of polar ice, pack ice (shaded area) and permafrost.

the mean range decreases from 8.0 m to 3.0 m (C.H.S., 1977). The outer coasts of Newfoundland and Nova Scotia have mean ranges in the order of 1 to 2 m , whereas in the Gulf of St. Lawrence the range is everywhere less than 2 m. In the St. Lawrence estuary the mean range increases from 2.3 m at Sept Iles to 4.1 m at Quebec City. The Bay of Fundy is notable for its high mean tidal range that increases from 5 m at the entrance of the Bay to a maximum of 12 m in the upper reaches.

Throughout the environment, the tides are mixed or semi-diurnal (q.v.), except for a small region of mixed diurnal tides (q.v.) in the Northumberland Strait within the southern Gulf of St. Lawrence.

Geology

The east coast of Labrador is part of the upland rim of the Canadian Shield. Coastal relief reaches a maximum of 1500 m in northern areas (the Torngat Mountains). This upland, resistant coastal range was eroded by glaciers during the Pleistocene to produce a fjord coastline. The resistant Shield rocks also form the north coast of the Gulf of St. Lawrence, although in this area relief is much lower and the shoreline is more regular.

South of Labrador, the remaining sections of this unit are the northern extension of the Appalachian mountain system. This old range of folded rocks has low relief (generally less than 500 m, with a maximum of 800 m), resistant rocks, and is characterized by southwest-northeast structural trends. These regional trends are particularly evident in the Bay of Fundy, Nova Scotia (Fig. 9) and Newfoundland. The southern Gulf of St. Lawrence is a broad basin of unresistant, unfolded rocks and is a relatively flat, lowlying region with relief less than 200 m. This entire region was glaciated during the Pleistocene but was primarily an area of erosion rather than deposition, so that surficial deposits are generally scattered and thin in most areas.

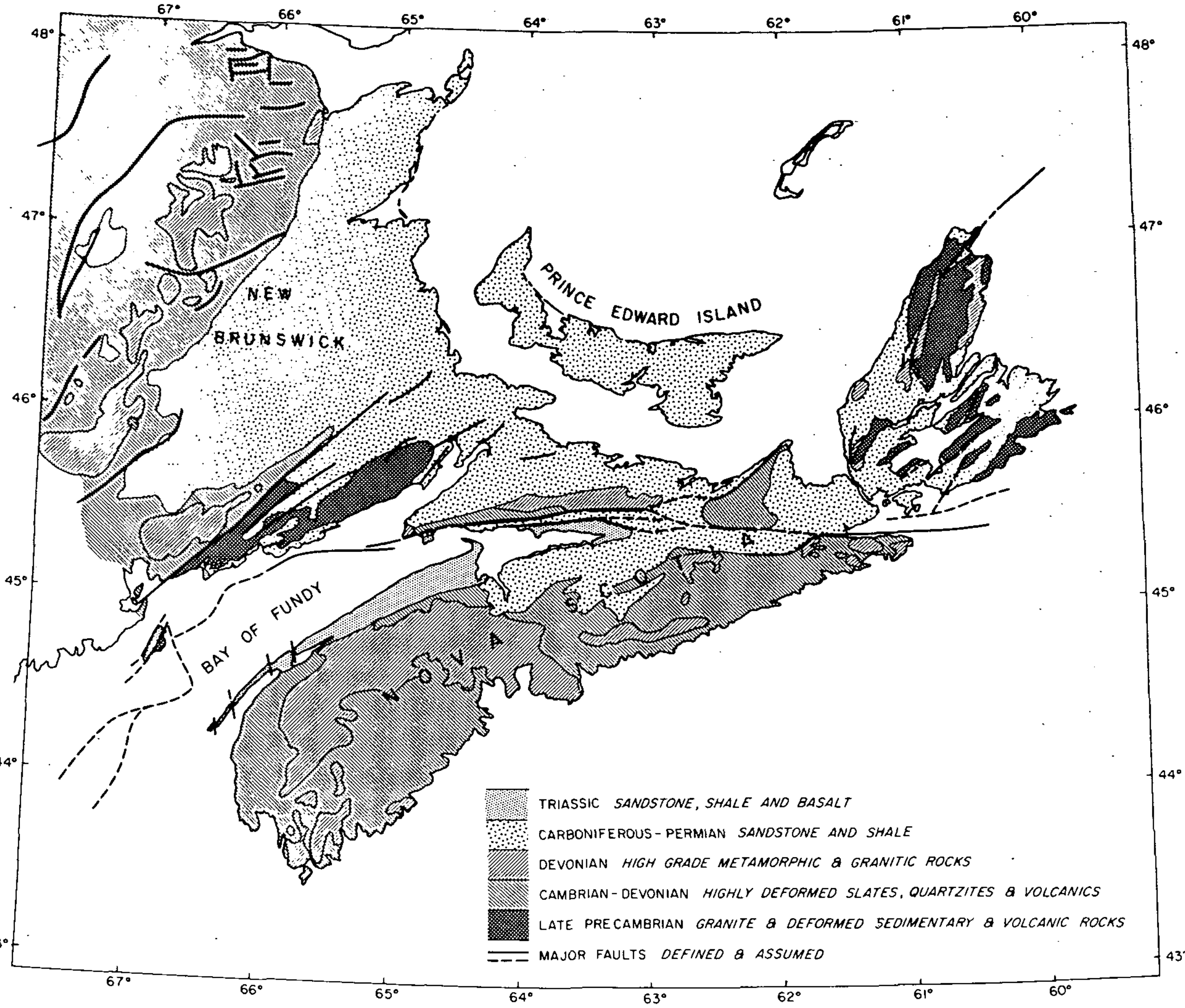


Figure 9. Geologic map of the Maritime Provinces (compiled from various sources).

Coastal Geomorphology

The basic form of the coastline is provided by the structural controls exerted by the Appalachian mountain system in the south and by the upland rim of the Canadian Shield in the north. This environment is characterized by rocky shorelines with occasional large accumulations of littoral sediments. The Atlantic coast of Labrador is one of fjords, with few beaches, and has an irregular rocky shoreline with many islands and large inlets (Photos 6 and 7). In northern areas, coastal relief is high and the shoreline has a bold, rugged character. Newfoundland, Atlantic Nova Scotia and the north shore of the Gulf of St. Lawrence have lowlying, irregular shorelines of resistant rocks that provide little sediment for reworking by coastal processes.

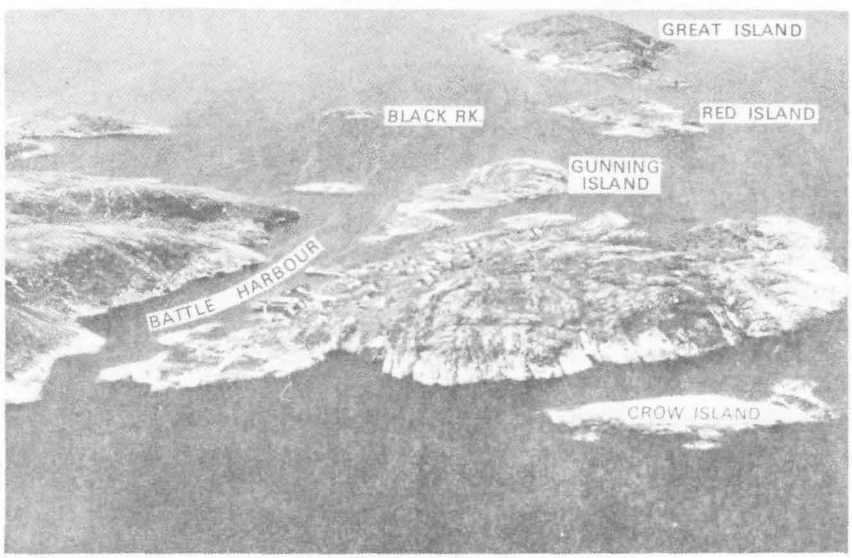


Photo 6. Aerial view of Battle Harbour, southeast Labrador. Note the rocky shorelines and lack of beaches. The settlement of Battle Harbour is on the east side of the harbour (to the right in the photo) (from C.H.S., 1974b).

An extensive system of barrier beaches and barrier islands has developed on the east coast of New Brunswick, the north coast of Prince Edward Island, and on the Magdalen

Photo 7. Occasional Harbour, a deep glacially-scoured fjord in an area with adjacent coastal relief up to 150 m (from C.H.S., 1974b).

Islands (Photo 8), in the southern Gulf of St. Lawrence (Owens, 1975). In this section material is provided to the littoral zone by the erosion and reworking of lowlying, unresistant sandstones and unconsolidated glacial deposits. Sable Island is an isolated depositional remnant of reworked glacial sediments, approximately 200 km southeast of the coast of Nova Scotia, on the outer margin of the continental shelf. The island is 37 km long and is composed entirely of sand (Photo 9). The only other depositional environments occur in sections of high tidal range that are sheltered from high levels of wave energy. These are the extensive sand/mud deposits that have accumulated in the intertidal areas of Minas Basin and Cumberland Basin, Bay of Fundy,

Photo 8. Barrier beach, west coast of the Magdalen Islands, P.Q., central Gulf of St. Lawrence. The barrier system is backed by dunes and encloses a large tidal lagoon (August 1972 by P. Haque).

Photo 9. Eastern end of Sable Island off the coast of Nova Scotia. The island is less than 1 km wide in this area and the dunes are replaced by a low overwash beach towards the eastern tip of the island.

and on the southern shore of the St. Lawrence estuary. In total, these depositional coasts account for less than 2% (approximately 900 km) of the coastline of Atlantic Canada.

2.6 GREAT LAKES

The Great Lakes system has the largest surface area of freshwater in the world (245,000 sq. km). Canada borders the northern shores of Lakes Superior, Erie and Ontario and the eastern and northern shores of Lake Huron, whereas Lake Michigan is entirely within the United States. No measurements are available on the length of Canada's Great Lakes coastline but it is estimated to be in the order of 15,000 km. The lakes form a step-like sequence from Lake Superior (184 m above mean sea level), through Lake Huron (177 m), and Lake Erie (174 m), to Lake Ontario (75 m), that drains into the North Atlantic Ocean through the St. Lawrence River (Fig. 10). The coastal processes that affect the shorelines of the Great Lakes are essentially the same as those that operate on open ocean coasts. The primary differences are that there are no astronomical tides and that the water bodies are relatively small in area, so that these are sheltered wave-energy environments.

Winds

The prevailing and dominant winds over the Great Lakes region are out of the westerly quadrant, between southwest

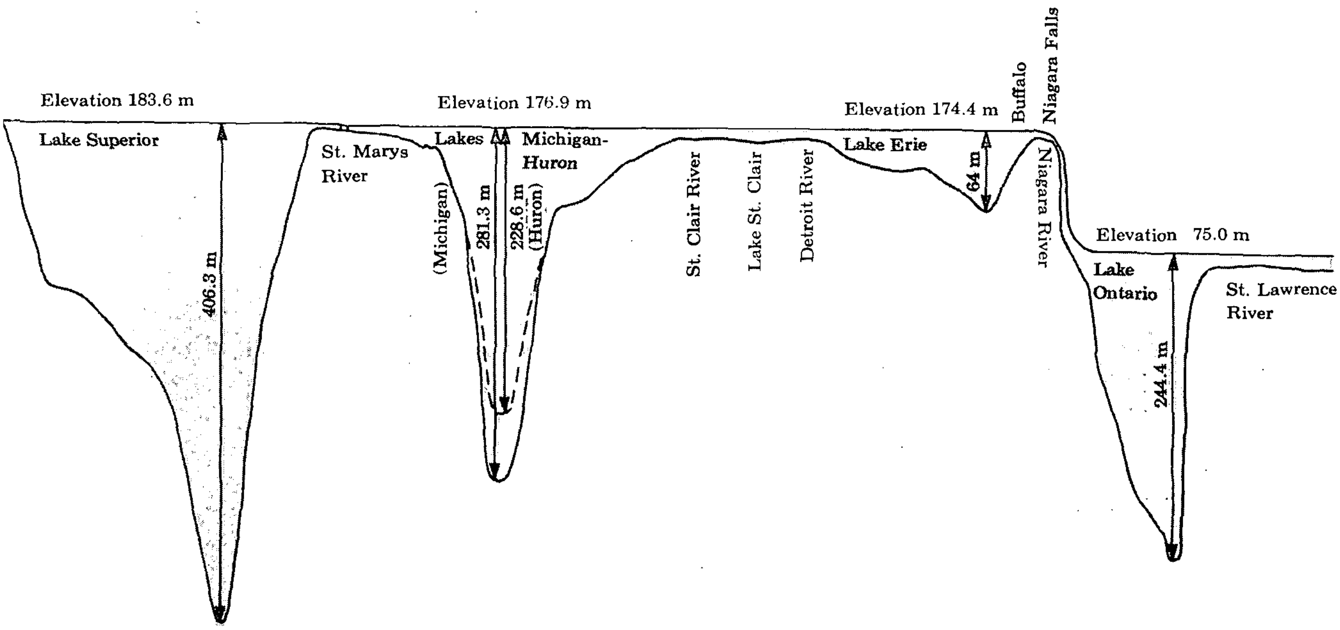


Figure 10. Idealized profile of the Great Lakes to illustrate their relative depths and elevations (note that the horizontal and vertical scales are considerably distorted) (From Ragotzkie, 1974).

and northwest (Fig. 3, p. 13). These winds are associated with cyclonic depressions that form along the Polar Front between the cold arctic air to the north and the warmer continental air mass of the central United States. The low-pressure systems cross the area from west to east and are more intense during winter months, when the pressure differences between the two air masses are greatest. This gives higher wind velocities during winter months (Fig. 3, page 13). Locally land and lake breezes can occur throughout the year due to temperature differences between the lake and the land. In summer months breezes towards the lakes occur at night and towards the land during the day. In winter the breezes are towards the lakes.

Waves

Wave heights are generally low (<2 m) and wave periods short (<5 seconds) due to the limited fetches; Lake Superior has the longest fetches, with a maximum of 500 km. Levels of wave energy vary seasonally as wind velocities are greatest in winter months. Energy levels at the shoreline are very variable, depending on the orientation of the coast with respect to the direction of wave approach. For example, strong winds out of the southwest would give low energy conditions on the coasts of southwest Lake Ontario and Lake Erie, but would lead to high energy conditions on the northeast shores.

Ice

Ice limits the generation and the effects of waves during the period from November to April (C.H.S., 1976). Although the lakes do not freeze over completely (except for Lake Erie), ice on the shoreline prevents sediment redistribution by waves. In addition, pressure ridges may form in the nearshore zone and ice can be pushed up onto the beaches or onto the backshore areas.

Water Levels

The Great Lakes are non-tidal, but lake levels vary due to (1) river and groundwater inflow, precipitation, evaporation, and outflow, (2) the regulation of the inflow and outflow by man, and (3) the effects of wind-generated storm surges. Lake elevations change from year to year as the balance between water supply and loss varies. Long-term fluctuations of this type up to 2 m have been recorded (Hough, 1968) (Fig. 11).

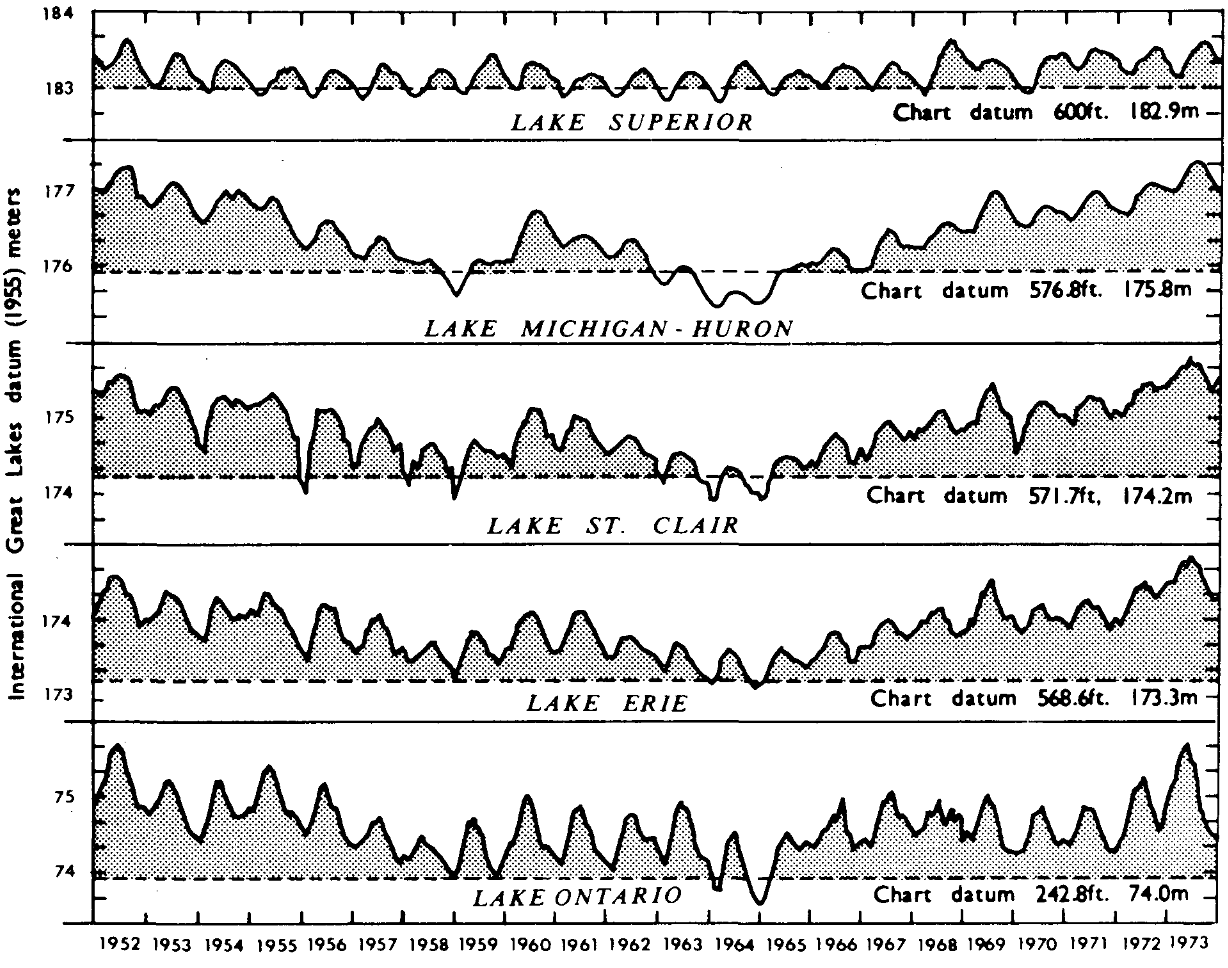


Figure 11. Hydrographs of mean monthly Great Lakes water levels, 1952-1973 (after Boulden, 1975).

The seasonal or monthly variations in lake levels due to hydrologic factors are in the order of 0.5 m to 0.6 m, although a maximum of 1.24 m has been recorded for Lake Ontario. Lake levels are usually highest in early summer and lowest in early winter (Environment Canada, 1975). Short-term (daily) lake level variations that result from barometric pressure, storm surges and wind set-up are common. An extreme example is of one storm in Lake Erie in February 1967 that caused the water level at Buffalo to rise to 176 m (the normal lake level is 173.3 m), whereas at the same time the level dropped to 171.6 m at the other end of the lake at Toledo. This set-up and set-down led to a seiche effect (q.v.) of alternating high and low water levels at Buffalo and Toledo. Figure 12 illustrates a similar situation as an equilibrium condition was restored following a major storm surge (Clemens, 1976).

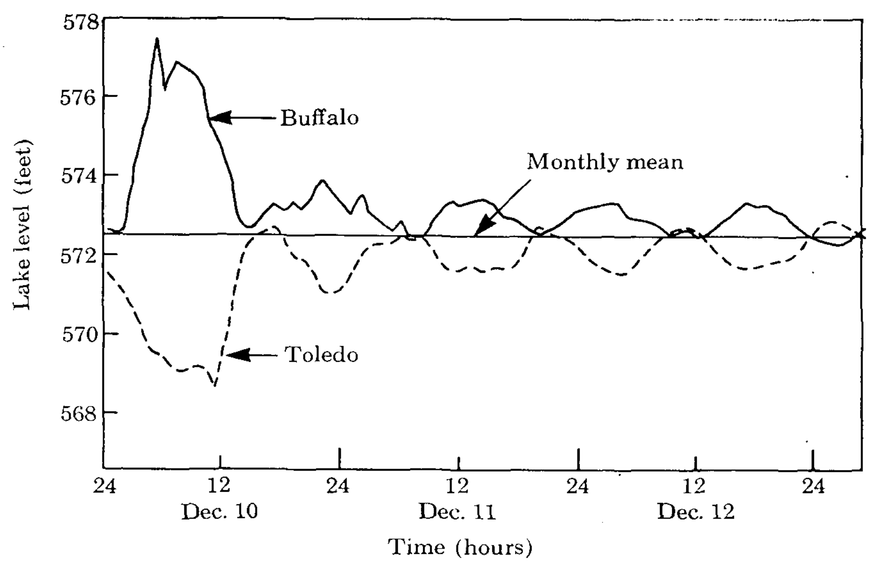


Figure 12. Water levels at Buffalo and Toledo, Lake Erie, showing storm surge followed by seiche (q.v.) (from Ragotzkie, 1974).

Geology

The Great Lakes were formed as ice sheets scoured along pre-existing river valleys during the advances and retreats of the Pleistocene glaciation. The lakes began to form at the margins of the retreating ice, approximately 15,000 years ago, and by 2,000 years ago had achieved their present form (Hough, 1968). The lakes are located across the southern boundary of the exposed resistant Shield rocks. Outcrops of the Shield in the Sault St. Marie area and at the eastern end of Lake Ontario act as bedrock dams to form Lakes Superior and Ontario (Fig. 13).

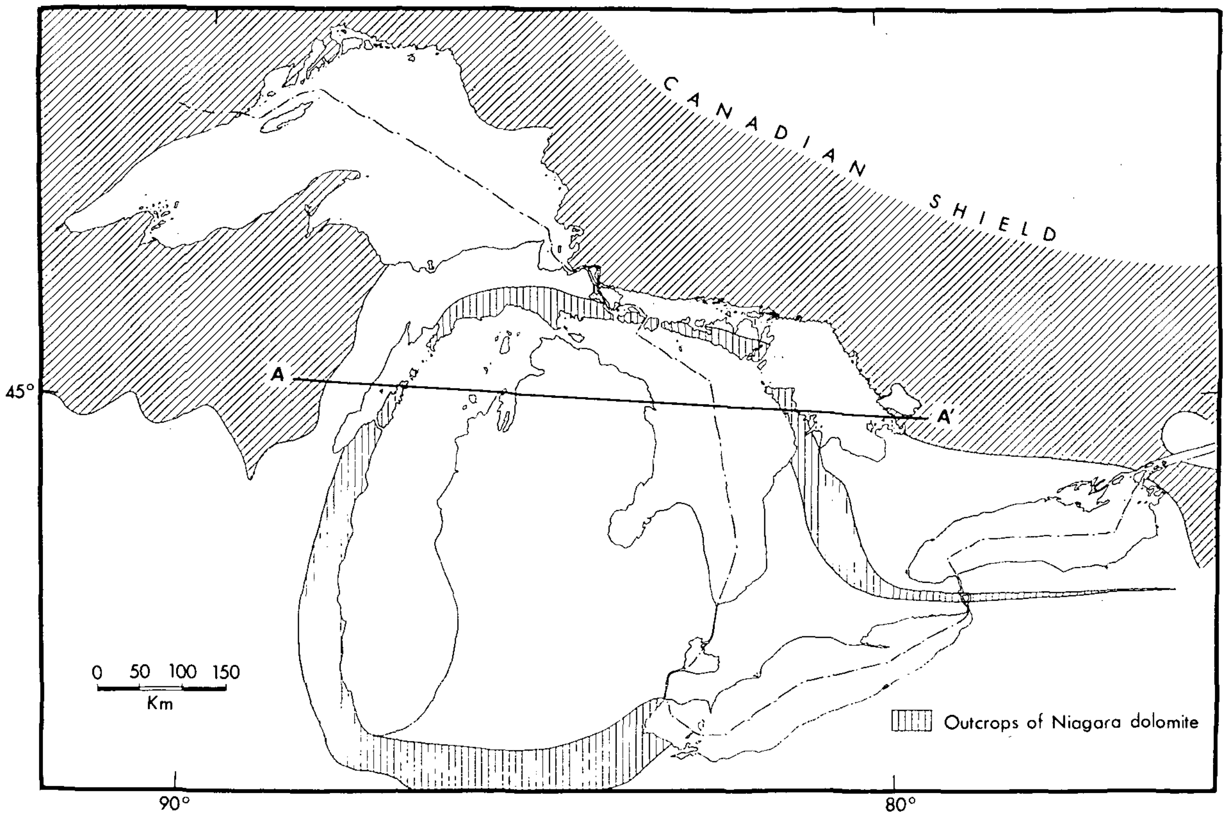


Figure 13. Simplified geology of the Great Lakes region to show the distribution of Shield rocks and the Niagara dolomite outcrops. The cross section A-A' is given in Figure 14.

Lakes Michigan, Huron and Erie are at approximately the same level (Fig. 10), the two latter join through Lake St. Clair and the St. Clair and Detroit Rivers that are cut in relatively unresistant sandstones and shales. The Niagara Escarpment, a resistant limestone outcrop, dams Lake Erie (Fig. 13), and the falls of the Niagara River are eroding back into the Erie basin at a rate of about 2 m/year. From the Niagara River the escarpment runs west then north through the Bruce Peninsula and Manitoulin Island, which result from erosion of less resistant rocks adjacent to the escarpment (Fig. 14).

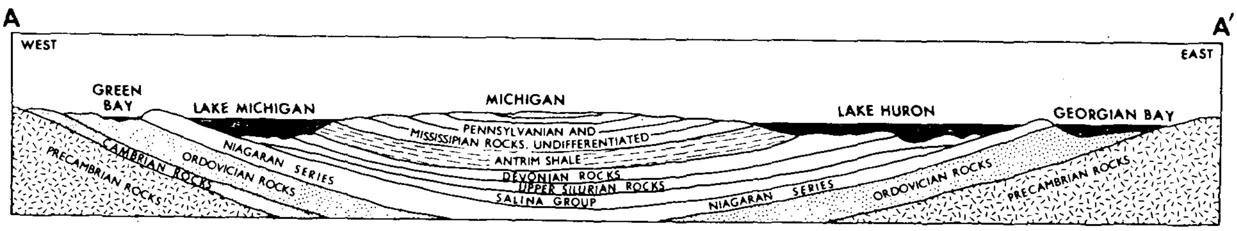


Figure 14. Cross section across the Michigan Basin (located on Fig. 13). The escarpment formed by the Niagara dolomite separates Georgian Bay from Lake Huron (the Bruce Peninsula) and Green Bay from Lake Michigan (the Door Peninsula) (from Pincus, 1962).

Most of the Great Lakes environment is an area of low relief, with a maximum elevation of 680 m near the northwest coast of Lake Superior. South of the Shield, the ice deposited considerable volumes of sediments that in most areas cover the bedrock outcrops. These unconsolidated clays, sands and gravels are easily eroded and form much of the shorelines of southern Lake Huron and Lakes Erie and Ontario.

Coastal Geomorphology

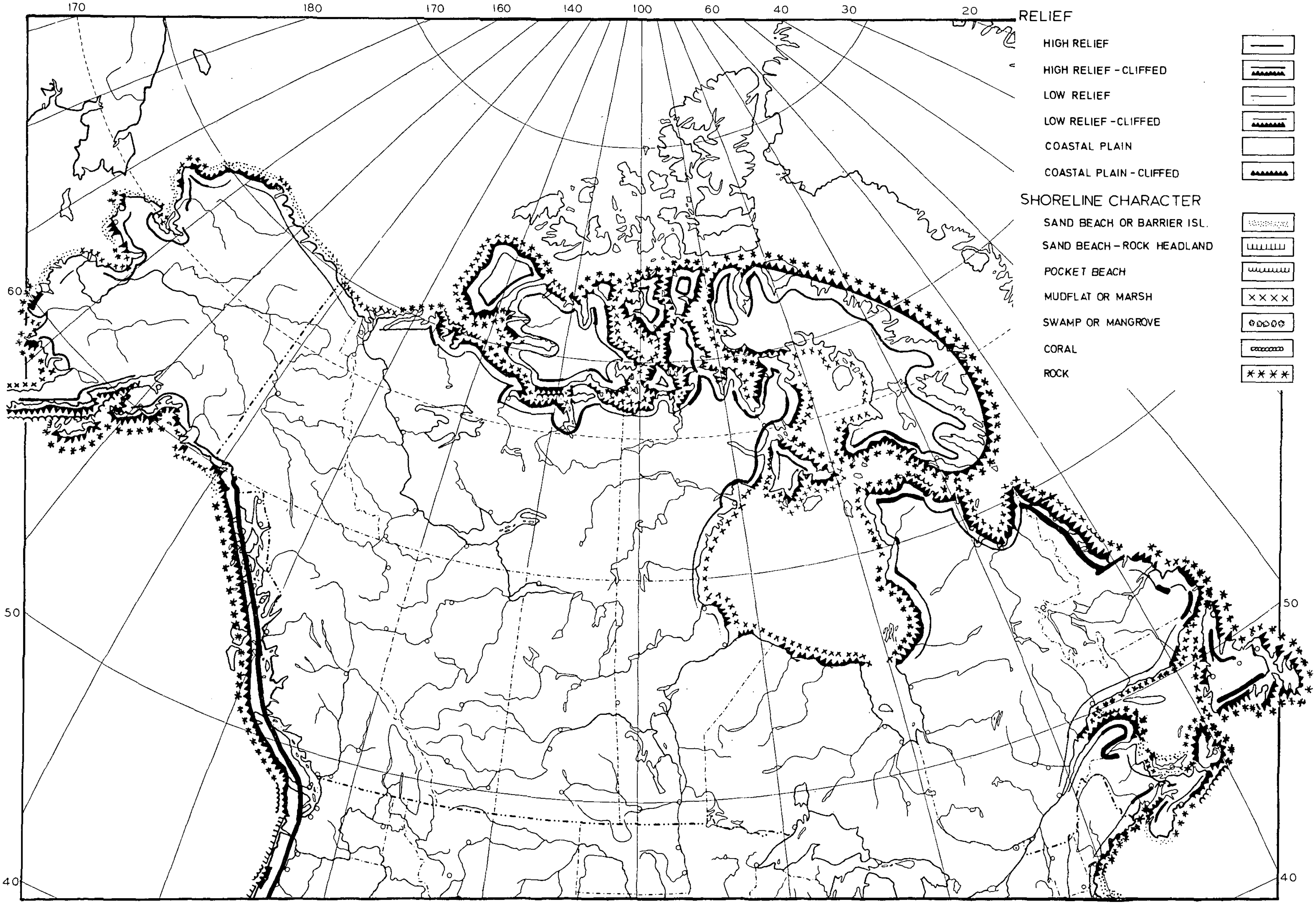
The coasts of the Great Lakes are predominantly rocky or cliff shorelines. Relief is generally low (<20 m) and in Lakes Erie and Ontario and in southeast Lake Huron the coastline is relatively straight as the cliffs are cut into unconsolidated glacial deposits. Erosion in these areas supplies material for the development of extensive beaches, particularly on the north shores of Erie and Ontario. Elsewhere only local accumulations of beach sediment occur and the sediment supply to the littoral zone is very limited due to the resistant nature of the coastal outcrops. On these rocky coasts the shoreline is frequently very irregular, with numerous headlands, bays and islands. Although the lakes are non-tidal, variations in lake levels due to annual, seasonal and meteorological factors produce water-level changes up to 4 m. High lake levels can have a marked effect in the littoral zone, particularly on the erosion of unconsolidated cliffs (Pincus, 1962, p. 131) and on beach overwash and erosion processes. This is a relatively low wave-energy environment because of the small fetches and because ice plays an important limiting role on the effects of waves for 3 to 5 months each year.

2.7 SUMMARY

Canada's coastal zones encompass a wide range of climatic, oceanographic and geologic environments. However, close examination of these environments indicates that *rocky coasts* are the dominant shoreline type. This is shown in a generalized map of coastal landforms presented in Figure 15.

The process environment is characterized by the fact that approximately 90% of the total coastline is affected by the presence of *ice* on the beaches or the adjacent waters. British Columbia is the only ice-free region, whereas northern areas of the Arctic Archipelago may remain ice-locked for several successive years (Fig. 5, p. 25).

Figure 15. Coastal landforms of Canada and adjacent areas of the U.S. (from Dolan *et al.*, 1972).



170
180
170
160
140
100
60
40
30
20
RELIEF
HIGH RELIEF
HIGH RELIEF - CLIFFED
LOW RELIEF
LOW RELIEF - CLIFFED
COASTAL PLAIN
COASTAL PLAIN - CLIFFED
SHORELINE CHARACTER
SAND BEACH OR BARRIER ISL.
SAND BEACH - ROCK HEADLAND
POCKET BEACH
MUDFLAT OR MARSH
SWAMP OR MANGROVE
CORAL
ROCK
60
50
40
50
40

PART 3 - COASTAL ENVIRONMENTS OF THE PACIFIC COAST

The Pacific coast of Canada is divided into 6 environments on the basis of exposure to waves and on the geological character of the coastal zone (Fig. 16, Table 5). There are many local variations in the shoreline types within each coastal environment but at this level of discussion these are less significant than the more general characteristics of the coast.

Information used for definition of these coastal environments was derived primarily from an aerial reconnaissance of the coasts of Vancouver Island south of 50°N and of the Fraser River delta; from the Sailing Directions (C.H.S., 1974); from Holland (1976); and from J.L. Luternauer (Geological Survey of Canada, pers. comm.). Relatively little work has been carried out on the coasts of this region, so that the available data base is very limited for most areas.

3.1 FRASER RIVER DELTA

This is a river-dominated environment characterized by a large prograding delta system. The modern (western) delta is 37 km wide and faces the Strait of Georgia; an abandoned delta (13 km wide) faces south into Boundary Bay (Luternauer and Murray, 1973). These two deltaic systems are separated by the Point Roberts Peninsula, a deposit of unconsolidated glacial sediments. The Fraser River bifurcates at New Westminster to

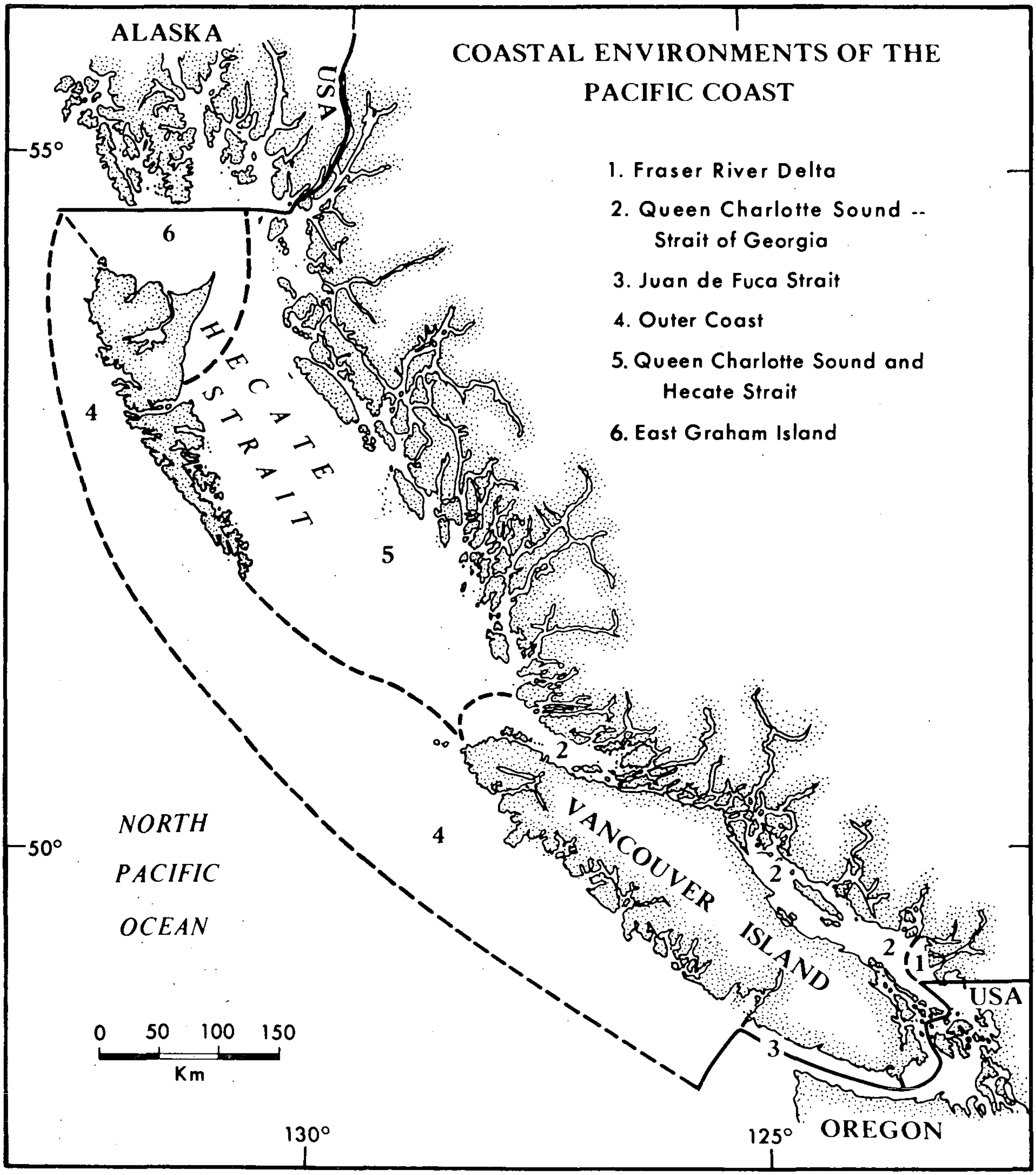


Figure 16. Coastal environments of the Pacific coast (see Table 5).

TABLE 5. Characteristics of Pacific Coastal Environments

	GEOLOGICAL CHARACTER	COASTAL ZONE		FETCH AND WAVE EXPOSURE	MEAN TIDAL RANGE	SEDIMENT AVAILABILITY
		BACKSHORE RELIEF	BEACH CHARACTER			
1. Fraser River Delta	Unconsolidated fine-grained sediments; accumulation of river-borne material.	Low: marshes, usually dyked.	Flat intertidal zone of sand and mud up to 6 km wide at low tide: no beaches.	<50 km, very sheltered.	3 m	Very abundant.
2. Strait of Georgia	Resistant igneous rocks on mainland: volcanics and sedimentary rocks on Vancouver Is.	Low coastal plain backed by fjords cut into mountains: cliffs in less resistant rocks or glacial deposits.	Absent or narrow, with pebble-cobble sediments: occur near glacial deposits on low-lying coasts.	Up to 200 km; outer coasts exposed, elsewhere very sheltered.	3 m	Scarce: some local concentrations.
3. Juan de Fuca Strait	Resistant lavas.	Low coastal plain: cliffs up to 10 m.	Pebble-cobble and narrow in east; absent or narrow in west: rock intertidal platforms.	Progressively more sheltered to the east: west shore very exposed.	2.5 m	Scarce: some local concentrations.
4. Outer Pacific Shore	Resistant volcanics or lavas.	Mountains or uplands incised by steep-sided fjords: narrow coastal plain on Vancouver Is.	Absent or narrow with pebble-cobble sediments: isolated wide sand beaches near eroding glacial deposits.	>1000 km, exposed very high energy; sheltered inner coastal zone.	3 m	Very scarce: a few local concentrations.
5. Queen Charlotte Sound and Hecate Strait	Resistant igneous rocks on mainland lavas or volcanics on Q. Charlotte Islands.	Coastal lowlands give way to mountains or uplands cut by fjords.	Absent or narrow with pebble-cobble sediments: deltas at heads of fjords.	300 km to >1000 km, exposed outer shores, sheltered inner coastal zone.	3 to 5 m	Very scarce: some local concentrations.
6. East Graham Island	Unconsolidated glacial drift or outwash sands and gravels.	Cliffs up to 100 m high: relief <200 m.	Wide sand or sand/gravel beaches.	Up to 300 km, exposed.	3 to 5 m	Abundant.

give two major channels, North Arm and Main Channel, that enter the Strait of Georgia just to the north of the United States border. The delta area is a lowlying marsh that has been dyked and reclaimed in many areas. Seaward of the marsh the delta-front is prograding at a rate of 2.5 m/yr (Glass, ed., 1972) by deposition of the river-borne sediments. Low-gradient mud and sand flats, in the order of 6 km wide, are exposed at low tides (Photo 10). On the intertidal flats there is a general gradation from sands in the lower intertidal zone to muds in the upper flats. The muds in turn give way directly to the vegetated marshes. The channel margins (Photo 11) are characterized by deposits of medium to fine sand (Luternauer and Murray, 1973).

Photo 10. Intertidal mud flats backed by dyked and reclaimed marshes; Sturgeon Bank, Fraser Delta, British Columbia (December 1976).

Photo 11. Mouth of the Middle Arm Channel, Fraser Delta, British Columbia (December 1976).

Redistribution of the surface sediments by river, wave and tidal currents results in sand waves that are less than 1 m in height and that have a crest-to-crest spacing between 50 and 100 m. Frequently these sand waves have deposits of mud in the troughs (Medley and Luternauer, 1976). The construction of jetties and breakwaters has altered the natural processes locally. In many of the sheltered sections created by these constructions, extensive eel-grass beds have developed. In addition, these man-made structures may have induced local erosion or extension of the marsh edge (Luternauer, 1976a), although in general the marsh is relatively stable in position (Medley and Luternauer, 1976).

The basic form and character of the unconsolidated deltaic deposits is primarily controlled by the discharge of the river. The local distribution and form of the sediments on the intertidal flats between the major channels results from wave- and tide-induced processes. River discharge is at a minimum during the period from January to March, increasing to a maximum from the end of June to mid-August, with about 80% of the yearly runoff during May through July (Luternauer and Murray, 1973). During this latter period, river currents are in the order of 3 m/s and the river outflow prevents seawater from entering the channels during the flooding tide. Often the plume of sediment from the delta is clearly visible and extends up to 30 km into the Strait of Georgia. The delta is largely sheltered from waves and any incoming wave energy is dissipated on the shallow delta margins in the low-tide zone. The mixed semidiurnal tides (Fig. 17) have a mean range of 3 m, with a maximum range of 4.7 m during spring tides.

The character of the shore zone of this environment is dominated by the wide, flat intertidal sand and mud deposits and by the extensive marshes in the backshore. The North Arm of the Fraser River enters the sea along the northern fringe of the delta, whereas the Main Channel bisects the delta to produce two large tidal flats (Sturgeon Bank in the north (Photo 10), Roberts Bank in the south) that are of almost equal area. The flats are dissected by numerous small creeks and channels and there are large areas of migrating sand waves or megaripples (Photo 12). The dyked marshes are rarely inundated, whereas

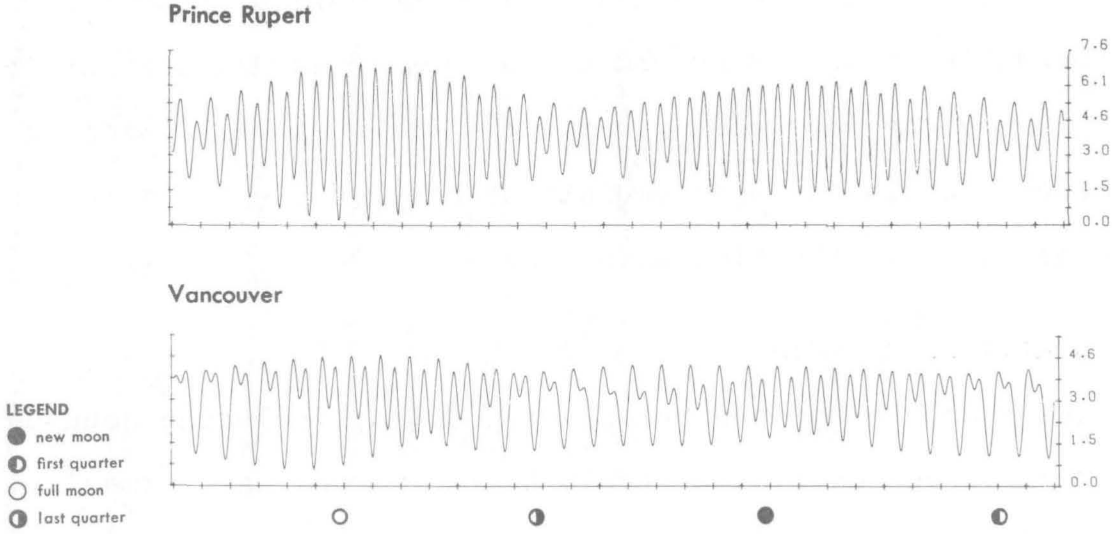


Figure 17. Typical tidal curves for Prince Rupert and Vancouver, British Columbia for a one-month period (in metres) (from C.H.S., 1977). See also Table 4 (page 17) and Figure 4 (page 14) for further data and the location of these stations.

Photo 12. Intertidal sand bars exposed at mid-tide between North Arm Jetty and Iona Causeway, Fraser Delta, British Columbia (December 1976).

non-protected areas are flooded during the maximum runoff period and during high spring tides. An abandoned delta front in Boundary Bay has intertidal flats that are up to 4 km wide at low tide. Considerable accumulations of logs are found in many areas at or above the high-water mark.

3.2 STRAIT OF GEORGIA

The coastline of the Strait of Georgia, including Johnson Strait and Queen Charlotte Strait in the north, was formed by the inundation of the northwest-southeast trending Georgia Depression. This Depression lies between the intrusive igneous rocks of the Coast Mountains and the volcanic and sedimentary rocks of the Vancouver Island Mountains. An arch of resistant igneous rock extends into the Depression, in the area of Johnson Strait, to separate the Strait of Georgia from the Queen Charlotte Strait. In many sections of the Strait of Georgia the coastal zone is a low, narrow plain that gives way inland to uplands or mountains, with relief up to 2000 m within 30 km of the coast.

The region was repeatedly glaciated by ice flowing from the adjacent mountain ranges on each side. On the eastern coast of the Depression, erosion by the ice along former rivers gouged deep, steep-sided valleys which were later flooded to become fjords, as sea level rose following the retreat of the glaciers. The longest of these fjords cuts back more than 70 km into the Coast Mountains. The drowning of the complex pattern of fjords has led to the formation of many islands along the coast. On the west side of the Georgia Depression, the coastal plain is larger and few fjords have developed. On the southeast coast of Vancouver Island differential erosion of relatively unresistant sedimentary rocks has led to the formation of a series of linear, parallel islands (the Gulf Islands). In many parts of the Strait area, glacial sediments were deposited in the present coastal zone.

The tides of this environment range from the mixed mainly semi-diurnal type in the south (Fig. 17, page 57), with a mean range of 3 m, to mixed semi-diurnal tides in the northern areas, which have a mean range of 3.5 m. Strong tidal currents occur in the passages between islands where the tides are constricted. Passes in the Gulf Islands have currents up to 4 m/s, whereas in Seymour Passage in the Johnson Strait area, currents up to 7 m/s are common (C.H.S., 1977). Winds in this environment are characteristically out of the northwest or west in summer months (Fig. 3, Table 3; pages 12 to 15), with stronger easterly and southeasterly winds in winter months. During the period October to March, storms with winds greater than 60 km/hr occur on the average 3 to 4 days each month. Although the Strait area is protected, winds blowing along the axis of the Strait can generate high waves. In winter months wave heights up to 3 m occur for approximately 5% of the time (Table 6). Due to the very short fetches in most areas, the

TABLE 6. Wave Height Data for the Pacific Region

	SEA				SWELL			
	Summer		Winter		Summer		Winter	
	>1m	>3m	>1m	>3m	>1m	>2m	>1m	>2m
Open Coast	50%	8%	70%	20%	50%	10%	80%	30%
Strait of Georgia	15%	2%	35%	5%	30%	5%	40%	10%
Hecate Strait	25%	8%	No Data		20%	5%	8%	0%

Source: Canadian Hydrographic Service, 1974

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majority of the shorelines are not exposed to high wave-energy levels (Photo 13).

The backshores of this environment are predominantly wooded, low, resistant and rocky (Photo 14). The mainland coast has many steep-sided fjords that cut back into the mountains, and these frequently have small deltas with marshes and intertidal mud flats at their heads (for example, at Squamish). Wave-cut cliffs have developed by erosion of unconsolidated sediments, particularly along the southeast coast of Vancouver Island and in the Gulf Islands where the rocks are less

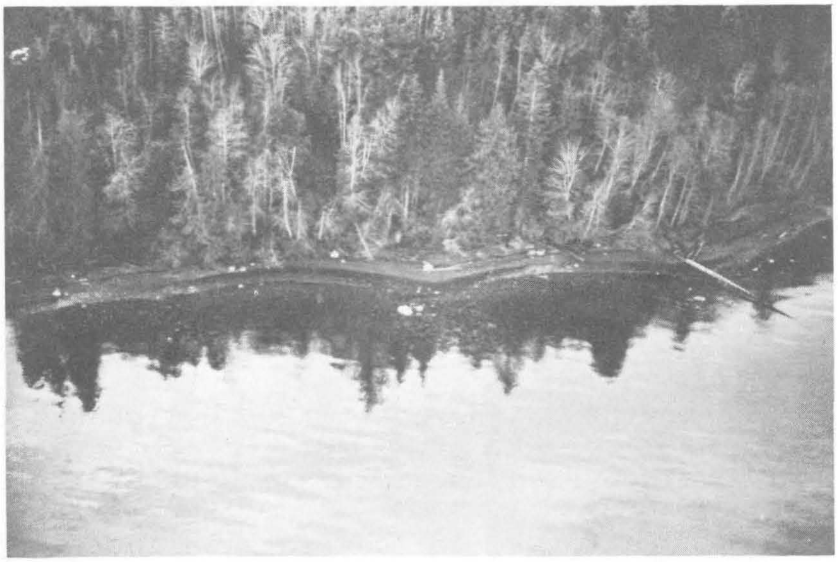


Photo 13. Sheltered littoral environment with pebble-cobble-boulder sediments on beach, near Courtenay, Vancouver Island, British Columbia (December 1976).

Photo 14. Low rocky coast in the Gulf Islands, Strait of Georgia, British Columbia (December 1976).

resistant. Because marine erosion is limited, the many small pocket beaches have developed only where unresistant rocks or unconsolidated glacial deposits occur along the coast. Beaches in sheltered sections are usually a mixture of sand to cobble-size material (Photo 13), with large accumulations of logs at or near the high-water mark. Relatively large deltas have developed at the mouths of the Courtenay, Cowichan and Nanaimo Rivers; but in other areas sediments are generally scarce. Intertidal rock platforms, or mud flats in sheltered sections, up to 300 m wide at low tide, are exposed due to the large tidal ranges in areas of low coastal relief. Kelp beds frequently occur in these sheltered, shallow areas.

3.3 JUAN DE FUCA STRAIT

This long, narrow strait was eroded between the resistant lavas of southern Vancouver Island and the Olympic Mountains to the south. The structural trends in this environment are west-northwest to east-southeast, parallel to the Strait, and the preglacial valley that followed these trends was over-deeped by subsequent glacial erosion.

Tides are mixed semi-diurnal with a mean range of 2.5 m in the west, changing to mixed diurnal tides (Fig. 17, page 57) with a mean range of 2 m in the east. Tidal currents are generally less than 1 m/s at the entrance to the Strait increasing to 3 m/s on the coast near Race Rocks in the east (C.H.S., 1974). Winds in this environment are considerably modified by the topography but are predominantly out of the southwest or west in summer (with occasional southeast and west storms), and out of the northwest in winter months with a greater frequency of southeast storms. Between October and March winds greater than 60 km/hr occur for 10 to 15 days each month, but for only 1 or 2 days each month in the summer. The western coast is exposed to high levels of wave energy, but wave heights decrease rapidly towards the east within the shelter of the Strait.

The coastal geomorphology of the Juan de Fuca Strait is relatively uniform, characterized by a low rocky shoreline, with cliffs up to 20 m, and a wide (200 m), rocky intertidal wave-cut platform (Photo 15) that is frequently surrounded by kelp. Littoral sediments are scarce due to the resistant

Photo 15. Pachena Point, west Juan de Fuca Strait (December 1976). Note the wide, rocky intertidal platform and the low cliffs.

nature of the rocks but have accumulated as a series of small beaches that in eastern sections are of pebble-cobble material with logs in the upper intertidal zone. In the west there are many pocket beaches of coarse sediments and a few narrow, sand beaches. The only major shoreline irregularity that interrupts this straight coast is the wide fjord in the Port Renfrew area. Elsewhere rivers or streams are small and frequently have wave-formed bars across their mouths.

3.4 THE OUTER COAST

The exposed Pacific coasts of the Queen Charlotte Islands and Vancouver Island are a very high wave-energy environment, exposed to the full force of waves generated in the North Pacific. This resistant, rocky coast follows the northwest-southeast regional structural trends, with the west coast of Moresby Island being a straight, fault-line coast (Sutherland Brown, 1968). The continental shelf in the north is non-existent off Moresby Island or extremely narrow (<5 km), widening to a maximum of 100 km in the south off Vancouver Island. The island mountain ranges rise to maximum elevations of 1200 m in the Queen Charlottes and 2200 m on Vancouver Island. The resistant lava or volcanic mountains are directly adjacent to the coast, with elevations up to 1000 m within 10 km of the shoreline (Photo 1, page 18), except in the central part of west Vancouver Island where there is a narrow coast plain up to 20 km wide. Glaciers from the island mountains eroded steep-sided fjords to give this rugged coast a spectacular character. The drowning of the extensive fjord system by the sea after the retreat of the ice has produced a complex upland shoreline of inlets and islands (Photo 16). The distribution of glacial sediments on this coast has not been fully mapped, but they are found on the central coastal plain on west Vancouver Island.

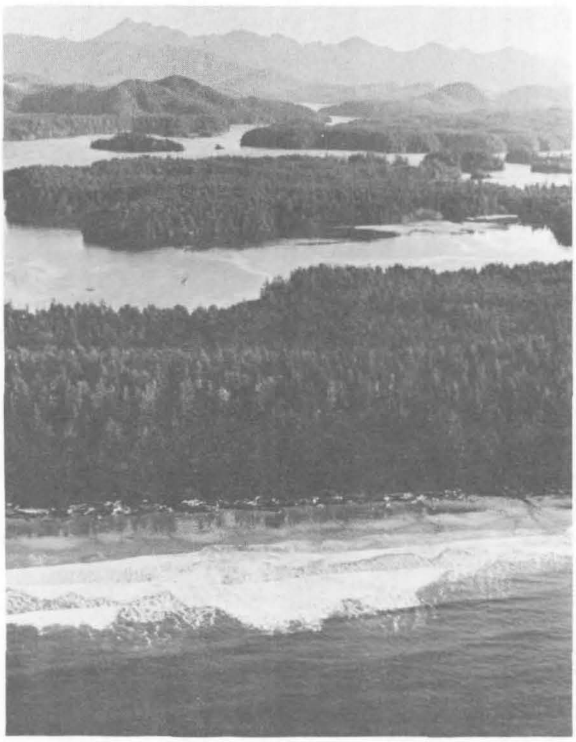


Photo 16. View inland near Tofino, west Vancouver Island, British Columbia. A sand beach on the outer, exposed coast gives way landward to a sheltered environment of islands and channels.

Tides are of the mixed semi-diurnal type everywhere and have a mean range of 3 m. Winter winds along the coast are dominantly out of the southeast, with prevailing northwest winds in southerly areas and southwest winds in northern sections during summer months. Wave-energy levels are very high throughout the year, with maxima during fall and winter months. Offshore wave heights (Table 6, page 60) of locally-generated waves are greater than 3 m for 8% of the time in summer months and 20% in the winter. Swell-wave heights can be expected to be greater than 2 m for 10% in summer and 30% in winter months.

The coastal geomorphology of this exposed, rugged coast is locally varied but overall very similar. This is a fjord coast with many islands and low rocky shorelines on the outer fringe (Photos 15, 16 and 17). Cliffs are rare, with the exception of west Moresby Island where they rise vertically to 150 m. The west coast of the Queen Charlotte Islands is generally much steeper than that of Vancouver Island. In the sheltered fjords and on the lee sides of the many small outer islands, trees extend down to the high-water mark. In sections of low relief the intertidal zone is rocky and usually has a narrow sand or pebble-cobble beach at the high-water mark. On west Vancouver Island a few isolated, but extensive (up to 10 km long) beaches have developed on the exposed coast adjacent to exposures of unconsolidated glacial deposits (Photo 3, page 21). At Long Beach, in Wickinannish and Florencia Bays, the wide, flat sand beach is backed by a debris line of logs at the high-water mark and by low, vegetated dunes or cliffs (Photo 18). In the

Photo 17. Buttle Lake, a former fjord, now cut off from the sea, near Campbell River, east Vancouver Island, British Columbia. Although this example is from the Strait of Georgia environment it is typical of fjords on the outer coasts.

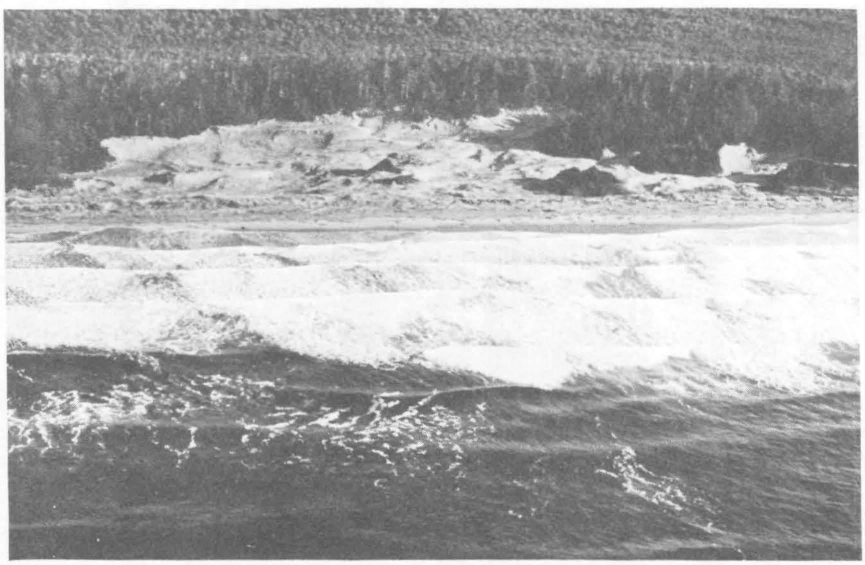


Photo 18. A section of Long Beach, Pacific Rim National Park, west Vancouver Island, British Columbia (December 1976). This wide sand beach is backed in this area by a small dune field. Note the regular pattern of the incoming swell waves and the width of the surf zone (approx. 200-250 m).

sheltered area of Grice Bay, adjacent to Long Beach, wide mud flats have developed in a small, shallow embayment. Small deltas with intertidal mud flats are found at the heads of most fjords, but in general there is a scarcity of sediments in the coastal zone. The exposed and rocky outer shoreline gives this coast its character, but the complex system of islands and inlets also provides many low-energy sections sheltered from the force of the Pacific waves. In particular, the drowned lowland area of Barkley Sound is a maze of small islands set back from the main trend of the coast (c.f., Photo 16, page 65) and is in marked contrast to the cliffs of Moresby Island or the coastal fjords.

3.5 QUEEN CHARLOTTE SOUND AND HECATE STRAIT

The Hecate Depression is a continuation of the regional structural trend that includes the Georgia Depression. This northwest-southeast depression is flanked by the Coast Mountains on the mainland, rising to 2800 m, and by the Queen Charlotte Mountains that reach elevations of 1200 m. The outer rim of the insular mountains is broken south of the Queen Charlotte Islands by the Queen Charlotte Sound, where ice covered the relatively lowlying areas north of Vancouver Island. The mainland mountains are resistant igneous rocks that give relief up to 1000 m within 50 km of the coast. These mountains have been deeply dissected by glaciers that eroded along former river valleys. These were overdeepened to produce a maze of fjords. The resistant basalts and lavas of the Queen Charlotte Islands have been eroded by ice to produce a complicated mountain coast of fjords and islands. In many sections of this environment, the coasts that border directly on the Hecate Depression are areas of low, flat relief that inland rise rapidly to mountains and fjords. This type of flat coastal plain that fronts a high fjord coast is referred to as a strandflat.

The mean range of the mixed semi-diurnal tides increases from 3.4 m at Bella Bella to 4.9 m at Prince Rupert (Fig. 17, page 57) and 5.0 m at Queen Charlotte City. The tides are constricted in the many channels and currents up to 2.5 m/s are common in narrow passages. Winds in the region are primarily from the southwest in winter and from the northwest in summer. This general pattern is considerably modified by local topography, so that in the Portland Inlet, for example, strong winds are funneled towards the shoreline out of the northeast. Offshore wave heights are greater than in the more protected areas of the Strait of Georgia, but are considerably less than on the outer Pacific coast (Table 6, page 60). Wave-energy levels decrease both to the north, as the coast becomes more sheltered from incoming Pacific swell, and inland where the passages and channels are protected by the islands. Occasionally ice forms in the rivers or in inlets where freshwater on the sea surface freezes, but ice does not play an important role in littoral processes.

On the outer islands of the mainland coast, such as Banks Island, the western shorelines are rocky and lowlying. This gives the outer shoreline many rock islets and islands. A similar situation occurs on the east coast of the Queen Charlottes where the relief of the islands bordering Hecate Strait decreases towards the east. This low rocky outer shoreline gives way inland in all areas to a complex system of narrow, steep-sided channels in low wave-energy environments (Photo 19).

Photo 19. South entrance, Hiekish Narrows, Finlayson Channel, in the Inner Passage. The steep, wooded coasts are tree-covered and this is a sheltered wave-energy environment (from C.H.S., 1974).

Wave-cut cliffs are rare and vertical fjord cliffs result from glacial rather than marine erosion. The shorelines are steep but in some sections have trees growing down to the high-water mark. The intertidal zones are generally rocky and narrow with few accumulations of beach material. Beaches, usually of pebble-cobble size material, are more common though not extensive on the outer coasts, where sediments can accumulate more readily due to the shallower nearshore gradients.

Small deltas are common at the heads of fjords (e.g., at Bella Coola and Kitimat). These are usually characterized by sand and mud intertidal flats backed by marshes that are inundated during the spring runoff period. The deltas are dominated by fluvial rather than by marine processes. The Skeena River has a large prograding delta, that has extensive intertidal sand flats and migrating sand waves. Near the channels, mud deposits are more common than sand and in sheltered areas there are extensive eel-grass beds (Luternauer, 1976b). The character of the coastal zone of the Hecate Strait-Queen Charlotte Sound unit is dominated by two major shoreline environments: (i) the lowlying, high wave-energy, rocky outer shorelines that border Hecate Strait and Queen Charlotte Sound, and (ii) the steep-sided, low energy, inland channels and fjords (Photo 20).

3.6 EAST GRAHAM ISLAND

This flat, lowland plain is composed of glacial drift and of sands and gravels that were deposited by outwash streams (q.v.) from former glaciers on the Queen Charlotte Mountains (Sutherland Brown, 1968). Elevations are less than 200 m and much of the plain consists of muskeg. Offshore gradients are low, as marine processes have eroded a wide platform.

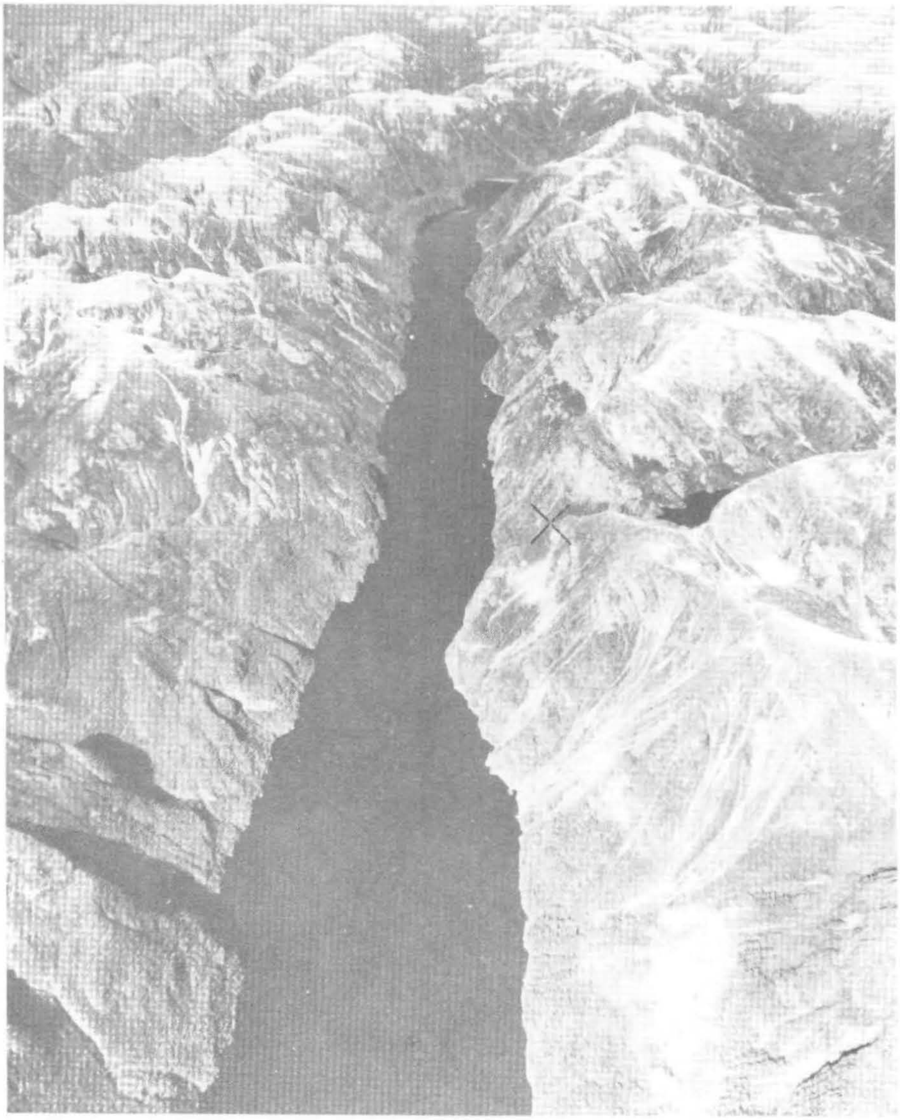


Photo 20. Cascade Inlet, near Ocean Falls, British Columbia. A long (25 km), straight, steep-sided fjord that cuts into the Kitimat Range (from Holland, 1976).

Mean tidal range decreases from 5.0 m at Queen Charlotte City, to 3.2 m at Rose Harbour and 2.7 m at Masset on the Dixon Entrance coast. The north coast is affected by Pacific swell waves that enter through Dixon Entrance and the east coast has a wave-energy environment related to locally-generated waves formed along the axis of Hecate Strait.

This large depositional plain is undergoing considerable marine erosion on the north and southeast-facing coasts. The east coast is primarily one of erosion and transportation with cliffs, up to 60 m high at Cape Ball, which are being cut into the unconsolidated glacial deposits by wave action. The sediments are being transported to the northeast by littoral drift towards Rose Point. There is a general decrease in the grain size of the sediments from pebble-cobble material near the cliffs to sands at the spit itself. The beaches of the north shore are in a depositional environment and are generally wide (up to 150 m at low tide), sandy, and in some sections are backed by dunes (c.f. Photos 3 and 18, pages 21 and 67). The east-facing beaches are narrower, steeper and consist of coarse sediments (gravel). Sand is transported around the depositional feature of Rose Point and then is moved westward along the north coast towards Masset Inlet (Holland, 1976). Virego Sound and Masset Inlet are the only major irregularities in this coastline. In Virego Sound, mud flats up to 6 km wide are exposed at low tide and these give way to extensive marshes in the backshore. The head of Masset Inlet has a fjord coast but, although the inlet is tidal, the inlet is more like a small inland sea as it is connected to the ocean by a long (30 km), narrow channel.

TABLE 7. Characteristics of Arctic Coastal Environments

	GEOLOGICAL CHARACTER	COASTAL ZONE		FETCH AND WAVE EXPOSURE	MEAN TIDAL RANGE	SEDIMENT AVAILABILITY
		BACKSHORE RELIEF	BEACH CHARACTER			
1. Hudson Strait-Southeast Baffin	Resistant Canadian Shield rocks.	Upland coast, cliffs 50-500 m (max. 1000 m in east); fjords in all upland areas; S. Ungava-lowland.	Pebble-cobble beaches backed by raised beaches in lowlying areas; wide tidal mud or sand flats in Ungava Bay; deltas at fjord heads, often boulders in intertidal zone.	Eastern areas exposed to Labrador Sea storms; elsewhere sheltered. Ice-free season is 3-4 months.	3 - 9 m (max. 15 m spring range in Ungava Bay).	Scarce, locally abundant at heads of fjords.
2. Hudson Bay	a. Unfolded, unresistant sedimentary rocks. b. Predominantly resistant Shield rocks.	a. Very low rocky coast (<20 m), often swamp or muskeg and raised beaches. b. Hilly or upland coasts, max. cliff heights 500 m in Richmond Gulf.	a. Beaches absent or narrow pebble-cobble; wide intertidal flats & nearshore shoals with mud or sand cover in southern areas. b. Narrow pebble-cobble beaches at base of cliffs.	Sheltered inland sea. Ice-free season is 2-4 months.	0.3 - 4 m	Scarce.
3. Fjord Coasts	Canadian Shield, with less resistant folded sedimentary rocks in N. Ellesmere (Innuitian Mts.).	Mountain coast, relief up to 2000 m (cliffs up to 1000 m); greatly indented by fjords, many tidewater glaciers.	Beaches rare except in lowlying areas, peb/cobble sediments, mud or sand flats at heads of ice-free fjords.	Sheltered coasts, fetch & energy levels decrease to the north. Ice-free season: 0-1 month in north, 1-3 months in south.	0.5 - 3 m	Scarce.
4. Jones Sound-Lancaster Sound-Prince Regent Sound	Unfolded, relatively unresistant sedimentary rocks, mainly limestones.	Upland plateau (relief 300 to 400 m). Steep cliffs with talus at base; some fjords.	Narrow at cliff bases; raised beaches in lowlying areas.	Very sheltered, low energy environment. Ice-free season 1-3 months.	1 - 2m	Abundant, but little redistribution.
5. West Ellesmere and Axel Heiberg Islands	Folded sedimentary rocks (Innuitian Mts.); structural trends NE-SW to N-S.	Upland or mountain coasts, relief 500-1000 m; large fjords follow structural trends.	Beaches generally narrow or absent. Raised beaches in lowlying areas; deltas & intertidal mud or sand flats in fjords.	Very sheltered, little wave activity. Ice-free season is 0-1 month.	<1m	Abundant, but little redistribution.
6. Ice Shelf	Innuitian Mts.	High relief, ice fields, occasional rock cliffs (50-200 m).	Ice shelf extends onto adjacent sea; beaches absent except at base of cliffs-usually w/ permanent ice foot.	Virtually no wave activity, rarely ice-free except for narrow leads.	<1m	Scarce, coastline predominantly ice.

	GEOLOGICAL CHARACTER	COASTAL ZONE		FETCH AND WAVE EXPOSURE	MEAN TIDAL RANGE	SEDIMENT AVAILABILITY
		BACKSHORE RELIEF	BEACH CHARACTER			
7. Coastal Plain	Unfolded, unresistant sedimentary rocks or unconsolidated sands and gravels.	Relief decreases from east to west; predominantly very low coasts.	Beaches narrow except in SW Banks Is.; wide, shallow nearshore zone often with mud and boulder sediments; many deltas, braided streams & raised beaches; barriers & spits in SW Banks Island.	Very sheltered; little or no wave activity in north; SW Banks Island is ice-free for 0-1 month (max. fetch is 100 km).	<1m	Abundant, but little redistribution, except on SW Banks Island.
8. Ria Coasts	Folded sedimentary rocks (Innuitian Mts.); structural trends approx. west-east.	Generally lowland relief; few cliffs except in SW Melville Island; alternating bays & headlands.	Beaches, deltas, braided streams, & raised beaches in lowlands; sand or peb/cobble sediments, with mud in sheltered areas.	Very sheltered, little wave activity; ice-free season is 0-2 months.	1 - 2 m	Abundant, but relatively little redistribution
9. S. Archipelago - Mainland	Resistant Shield rocks with less resistant sedimentary rocks (mainly limestones) in the Islands; area of glacial deposits.	Lowland region, relief <500 m; cliffs 5 - 20 m; high cliffs rare.	Peb/cobble beaches, shallow nearshore areas, mud flats in sheltered locations & in SE Foxe Basin.	Very sheltered, little wave activity in many areas. Ice-free season is 0-2 months.	<1 m except in SE Foxe Basin (5m).	Abundant in most areas.
10. Tuktoyaktuk Peninsula-Liverpool Bay	Unconsolidated sediments (sand and gravel).	Low relief, irregular shorelines, many lakes in backshore; some low cliffs (<10 m), mainly lagoons and dunes; rapid coastal retreat.	Low barriers and spits of sand or sand-pebble material.	Very sheltered, particularly Liverpool Bay. Ice-free season is 1-4 months.	<1m Storm surges up 3 m.	Abundant.
11. Mackenzie River Delta	Unconsolidated deltaic sediments.	Low, marsh; levees up to 3 m; relief higher in eastern areas with some low cliffs.	Narrow sand/silt beaches on outer delta margin.	Deltaic environment. Ice-free season is 1-4 months.	<1m Storm surges up to 3 m.	Abundant.
12. Yukon Coast	Unconsolidated sediments.	Unresistant low cliffs generally <20 m (max. 50 m); rapid coastal retreat.	Low barriers, spits and deltas.	Very sheltered environment. Ice free season is 1-4 months.	<1m Storm surges up to 3 m.	Abundant.

The dominant characteristic of this unit is the role of ice that affects coastal processes for at least 6 months each year throughout the region.

The primary sources of information used for this region were Bird (1967), Dunbar and Greenaway (1956), the Pilot of Arctic Canada (C.H.S., 1968, 1970 and 1974), and Taylor (1973). In particular, Taylor presents maps of the coastal geomorphology of the Queen Elizabeth Islands. It must be noted, however, that many coastal areas of the Canadian Arctic are relatively unexplored. The overall data base from which this discussion is derived is very variable, both in detail and in regional coverage.

4.1 HUDSON STRAIT AND SOUTHEAST BAFFIN ISLAND

This environment is predominantly an upland coast characterized by high tidal ranges. This is a region where the eastern rim of the Canadian Shield forms a resistant upland area that is cut by Hudson Strait. In southeast Baffin the regional structural trends are northwest-southeast, and are followed by the large fjord-bays of Frobisher and Cumberland Sound. On the south shore of Hudson Strait, Ungava Bay is a large re-entrant formed in a lowlying part of the Shield that has a relatively thick mantle of glacial sediments. Elsewhere surficial deposits are scattered and thin.

A major characteristic of this environment is the large range of the semi-diurnal or mixed semi-diurnal tides (Fig. 19, Table 8). Along the south shore of the Strait the mean range is everywhere greater than 3.4 m (5.6 m spring range) and is greater than 6.6 m (10.2 m spring range) in Ungava Bay. On the north shore ranges are greater than 4.1 m (6.4 m spring range) and are greater than 5.0 m on the open coast of Davis Strait and the Labrador Sea. An important feature of the tides is that the spring range is often twice as great as the neap range (Table 8, Fig. 19: Frobisher). Tidal currents greater than 2.6 m/s are common, reaching up to 6 m/s in channels such as the Smokey Narrows of Ungava Bay (C.H.S., 1974). The prevailing winds are out of the northwest (Fig. 3, page 12), with more

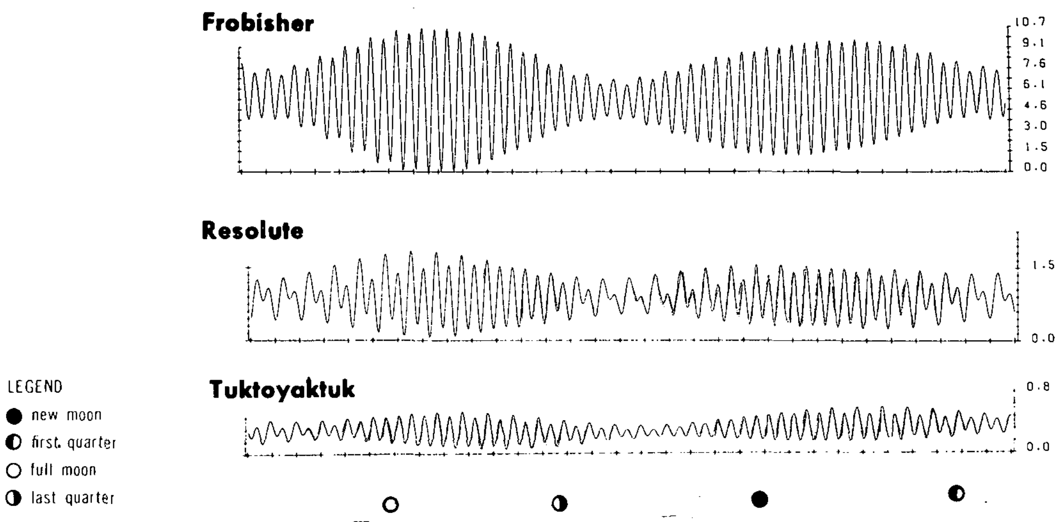


Figure 19. Typical tidal curves for Frobisher, Resolute and Tuktoyaktuk, N.W.T., for a one-month period (in metres) (from C.H.S., 1977). See also Table 4 (page 17) and Figure 4 (page 14) for further data and the location of these stations.

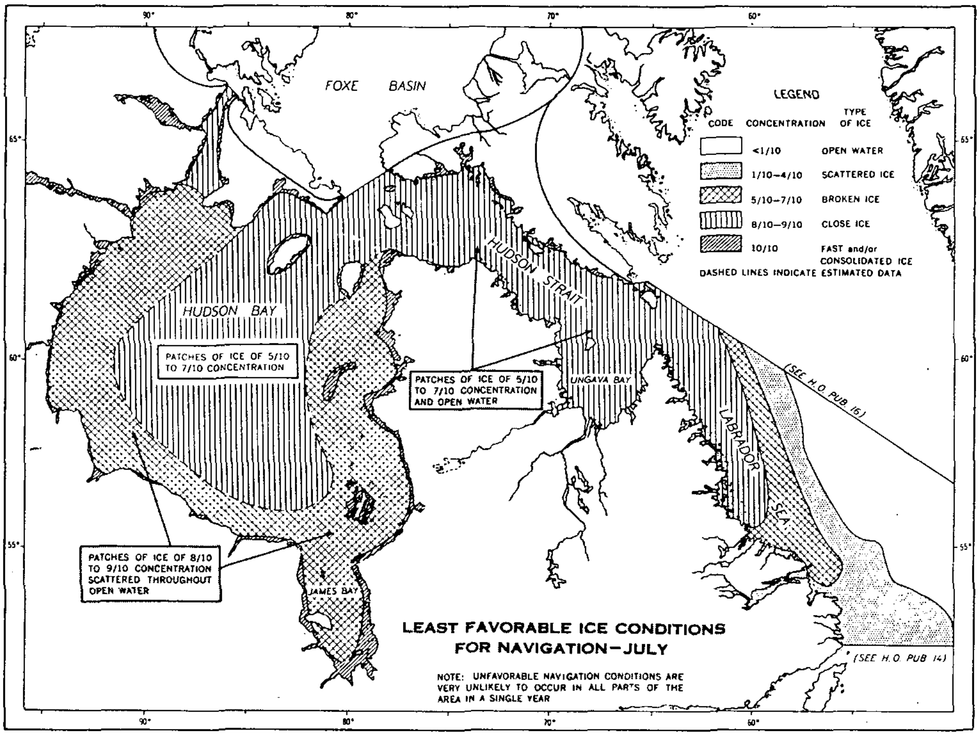
TABLE 8.

Tidal Ranges: Southeast Baffin Island and Hudson Strait

Hudson Strait	Mean	Large	(in metres)
South Shore:			
Ungava Bay - Leaf Basin	9.3	14.8	
Diana Bay	6.4	10.2	
Sugluk	3.4	5.6	
North Shore:			
Lake Harbour	7.7	12.7	
Frobisher Bay:			
Frobisher	7.3	11.6	
Cumberland Sound:			
Imigen Island	4.9	7.0	

Source: Canadian Hydrographic Service, 1977 variable winds and usually lower velocities in summer months due to weaker pressure gradients. Gales (winds >50 km/hr) are most frequent in autumn and winter, increasing from an average of 5 days each months in August to a maximum of 10 days in November and December (C.H.S., 1974). The period of storms coincides with the open-water season, giving a high wave-energy environment during the ice-free period. Wave-energy levels are greatest on the exposed southeast coast of Baffin Island but much of this unit is within a sheltered wave environment. Breakup begins during June and by late July ice remains only in Ungava Bay, Frobisher Bay, and Cumberland Sound. During a heavy ice year the Straits may not be clear until August (U.S. Naval Oceanographic Office, 1965) (Fig. 20a). Freeze-up commences in late October and most coastal areas have a 10/10 fast-ice cover by late November (Fig. 20b). The open-water season at Frobisher is usually in the order of 90 days (Fig. 6, page 26).

The coastal geomorphology of this environment provides a contrast between precipitous cliffs and wide intertidal mud flats. Along the Ungava Bay coast, the eastern shore is a lowland rock area with occasional cliff and fjord sections. To the south, this gives way to an area of very low relief with a very shallow nearshore zone and wide mud flats exposed at low tide. The west coast is low, rocky, with wide bays and inlets and mud flats in the intertidal zone. The remainder of the a



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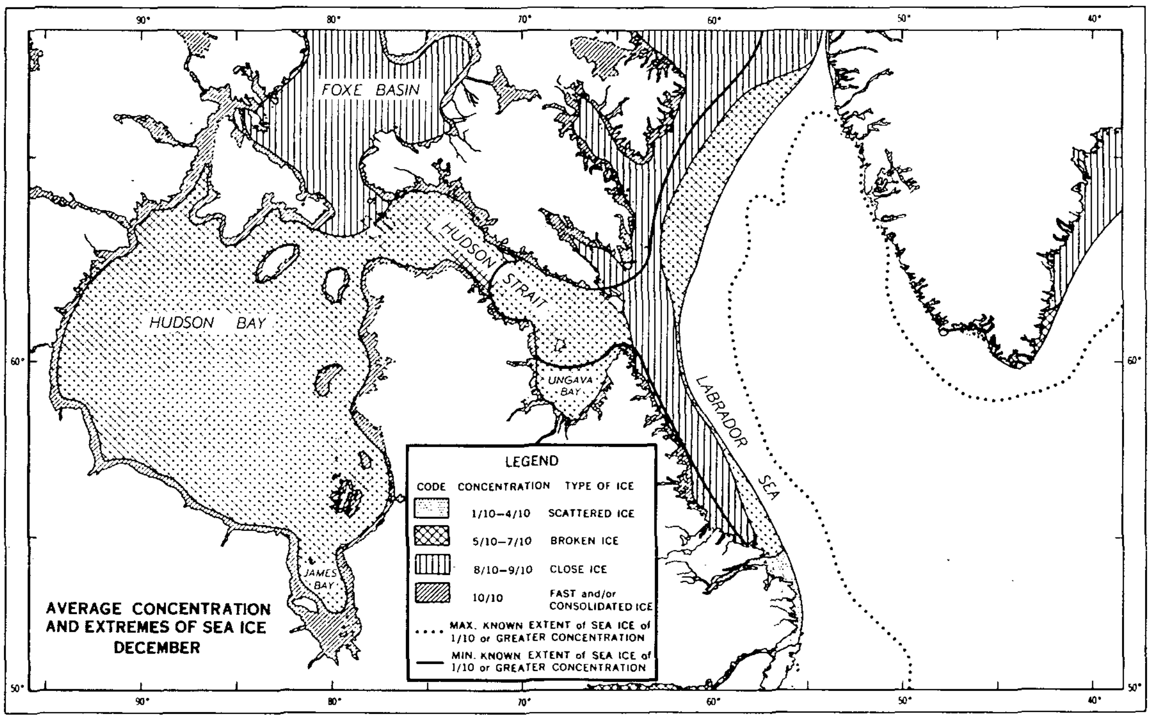


Figure 20. Southeast Arctic and Labrador Sea; (a) heavy July and, (b) average December ice distribution (from U.S. Naval Oceanographic Office, 1965).

south shore of Hudson Strait is predominantly a cliff coast, with heights up to 600 m in some areas (Photo 21). This relatively straight coast is broken by lowland rocky sections,

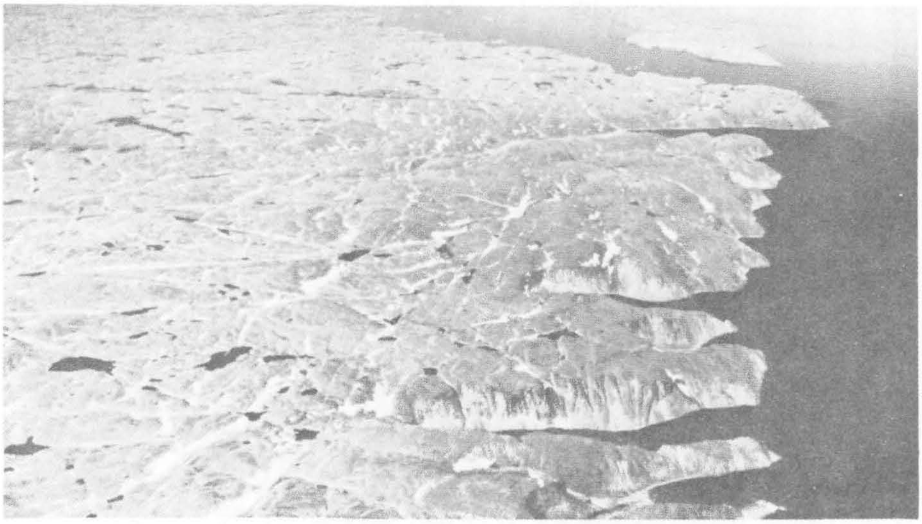


Photo 21. South coast of Hudson Strait, view towards Cape Wolstenholme. Coastal relief is 300-500 m and this section of the Strait is indented by numerous steep-sided fjords. Photograph taken in late July (from Dunbar and Greenaway, 1956).

small deltas and by steep-sided fjords. The north shore of Hudson Strait is a high rocky coast with many islands, bays and fjords. Frobisher Bay and Cumberland Sound, separated by the Hall Peninsula that rises to 1160 m, are large glacially-scoured re-entrants whose coasts are indented by subsidiary fjords and bays. Cliffs in this part of southeast Baffin rise to 1000 m locally. Not all sections have such high coastal relief and many sections are a complicated system of islands and channels (Photo 22). Many sheltered lowland areas have shorelines of deltaic or barrier beach deposits. The upper sections of the fjords have wide intertidal mud or sand flats, that are often strewn with boulders. Although these local sediment deposits are common, the basic shoreline character of

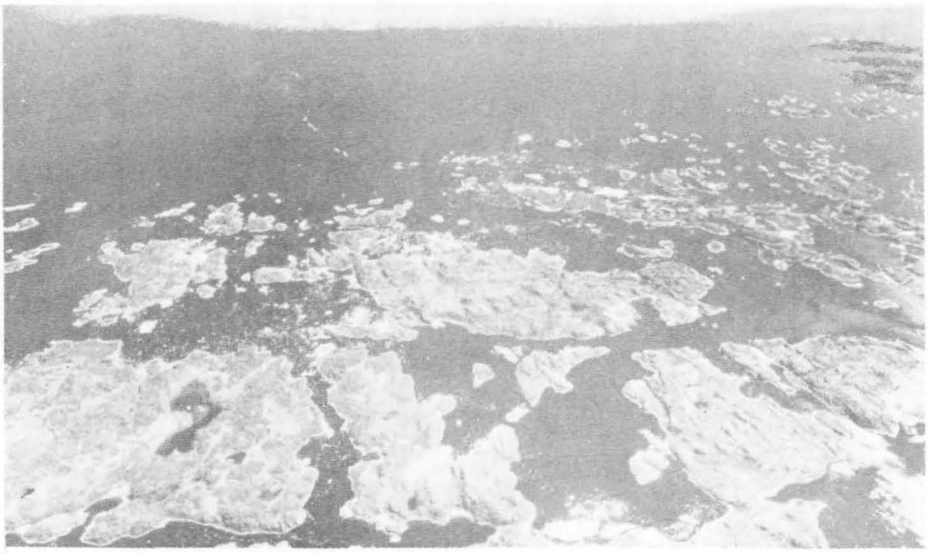


Photo 22. South shore of Cumberland Sound, N.W.T., near Nettilling Fjord in early July; a low, rocky coast with many islands and channels (from Dunbar and Greenaway, 1956).

most of this environment is either steep cliffs, with a narrow pebble-cobble beach at their base, or wide rock platforms and shallow nearshore areas dotted with rocky islands and reefs. Not all the cliffs fall directly into the sea, frequently the lower face of the cliff is buried by large accumulations of talus (q.v.). Cliff erosion results primarily from frost action (as the rocks freeze and thaw), rather than by direct marine erosion.

4.2 HUDSON BAY - JAMES BAY

The coasts that border the large inland sea of Hudson Bay are primarily low rocky shorelines. The low coastal zone of the James Bay area is a region of muskeg. Hudson Bay is a large horseshoe-shaped basin in the low centre of the Canadian Shield, that has been flooded by the sea through the channels in the north. The rocks are primarily old, resistant sedimentary and metasedimentary outcrops, but younger less resistant sedimentary rocks have been deposited in the central part of the basin. These latter are exposed in southern Southampton Island and in southwest Hudson Bay (Fig. 7, page 27). Relief is generally very low (<60 m) but in the northwest and northeast, coastal relief rises locally to 500 m.

The mean range of the semi-diurnal tides varies from 0.3 m at Point Harrison on the northeast coast, to 2.1 m in James Bay, and 3.8 m at Port Nelson on the southwest coast (C.H.S., 1977). Within Hudson Bay the waters have a predominantly anti-clockwise circulation. Winds are generally out of the north-northwest (Fig. 3, page 12) and cyclonic depressions cross the region in late autumn. Gale force winds (>50 km/hr) can be expected for an average of 6 days during November. Wave heights are generally low and data from Churchill indicate that from July to September 30% of the wave heights are greater than 1 m, but that only 8% are greater than 2 m (U.S. Naval Oceanographic Office, 1965). Ice begins to form in coastal areas during October in most of the Bay, and in James Bay during November (Fig. 20b, page 82). Breakup commences in James Bay in late May and in Hudson Bay during July, so that most areas are usually ice-free by early August (Fig. 6: Churchill, page 26).

The coastal geomorphology of the west coast of Hudson Bay changes from a hilly, rocky coast in the north to a low, swampy shoreline with a wide intertidal platform in the south. North of Chesterfield Inlet the undulating, indented coast has relief generally less than 30 m. The low shoreline extends offshore as a shallow, wide rock platform with many offshore islands (Dunbar and Greenaway, 1956). South of Chesterfield Inlet (Fig. 18, Unit 2a) relief is much lower and the gently sloping, often swampy, coastal plain gives way to tidal flats that are up to 9 km wide (Shilts and Boydell, 1974). These wide flats are exposed at low tide and in places have a cover of mud or sand and boulders. South of Churchill the low coast continues to be swampy, but the wide tidal flats have only a scattered sediment cover. A narrow pebble-cobble beach in the upper intertidal zone extends only 1 m above normal high-water mark (Beals, 1968). During summer months the maximum depth to which the beach sediments thaw is approximately 90 cm (Shilts and Boydell, 1974). In some areas the nearshore platform is up to 30 km wide. On the west side of James Bay the relatively straight coast has a low muskeg backshore and the wide flats have a sand or mud veneer.

The east shore of James Bay (Fig. 18, Unit 2b) has a low (<20 m), irregular coast with many islands. Wide sand flats, backed by marshes and muskeg, are fed with sediment by deltas such as that of La Grande Rivière. North of James Bay the coast forms a large arc and the shoreline is fringed by a series of parallel islands that are outcrops of resistant sedimentary and volcanic rocks which dip below the Bay towards the west. In northern areas of this arcuate section, relief increases from 60 m to a maximum of 500 m in the Richmond Gulf, which is a rocky section of coast with steep cliffs. The offshore islands, including the Belcher Islands, are predominantly low and rocky and have indented shorelines due to the arcuate shape of the resistant outcrops. North of this section the coast becomes more irregular with cliffs up to 300 m at Ivugivik Point.

The south shore of Southampton Island is a lowland coast (<150 m) with a shallow offshore area that has many reefs. Rocky tidal flats, up to 6 km wide, give way in bays to intertidal mud deposits with marshes in the backshore (Dunbar and Greenaway, 1956).

The coasts of Hudson Bay are predominantly low and rocky, with wide, shallow nearshore platforms. The intertidal flats have a cover of sand or mud in the south but elsewhere are rocky or are strewn with boulders. Large sections of this coast have not been explored due to the difficulties of access from the sea.

..3 FJORD COASTS

This environment extends from central Baffin Island to the northeast corner of Ellesmere Island (Fig. 18) and is a mountain coast indented by steep-sided fjords. Glaciers extend down to the sea at many localities and are a source of icebergs that are carried to the south by coastal currents. Except for the northern half of Ellesmere Island, the area is the eastern rim of the resistant Canadian Shield (Fig. 7, page 27). Northern Ellesmere Island is part of the Innuitian Mountain system that trends southwest-northeast in this area. Relief is high near the coastal zone reaching up to 2133 m on Baffin Island, 1828 m on Bylot Island, 1886 m on east Devon Island, and 2133 m on Ellesmere Island.

On Baffin Island the mean range of the semi-diurnal and mixed semi-diurnal tides varies from 1.9 m (2.8 m at spring tides) at Cape Dyer on the east coast, to 0.9 m (1.4 m at spring tides) on the northeast coast. Southeast Ellesmere Island has a high tidal range (2.9 m mean, 4.8 m spring) that decreases to the north with values of 0.6 m and 1.0 m at the northeast extremity of the island (C.H.S., 1977). Coastal currents, south of Smith Sound, are from north to south and parallel the coast, with velocities of 0.3 m/s in Smith Sound and 0.05 to 0.2 m/s off Baffin Island (C.H.S., 1970). Wind directions are predominantly out of the western quadrant along this coastal environment, but there is considerable local channeling due to the topography in the high, steep-sided fjords. The east coast of Baffin Island is exposed to a fetch of 500 km, but wave-energy levels decrease rapidly in the northern half of this unit as the coast becomes more sheltered and as the ice-free season becomes shorter. Parts of central, northern Baffin Bay remain open all year but the ice does not clear from the coasts of east Devon Island and northeast Baffin Island until mid- or late July. Freeze-up commences in late September and October, so that this region of north Baffin and east Devon Island is only open for 2 to 3 months each year (Fig. 5, page 25). The northern parts of Baffin Bay and Kane Basin may remain completely closed some years and Mackinson Inlet is open for only about 30 days (Taylor, 1973). Alert, at the northern tip of Ellesmere Island, is usually ice-free for only 10 to 15 days each year (Fig. 6, page 26).

Throughout this environment the coastal geomorphology is dominated by high relief, long narrow fjords, and glaciers that extend down to the sea (c.f. Photo 4, page 29). Many sections of coast have cliffs up to 1000 m but often the base of the cliff face is buried by talus deposits, as wave action is insufficient to remove this material. The fjords are generally steep-sided and have either a glacier or a delta with mud or sand intertidal flats at their heads. Where coastal relief is low, pebble-cobble beaches and boulder platforms are common. In central east Baffin Island, the area of Home Bay is a low coastal plain that interrupts this otherwise bold coast. This Bay is relatively shallow and has many rocky islands and reefs.

The east coast of Devon Island is a high fjord shoreline with many glaciers that calve into Baffin Bay. Coburg Island, in eastern Jones Sound, has vertical rock or ice cliffs on all of its coasts.

The eastern coast of Ellesmere Island has many tidewater glaciers and the entire coast is either high cliffs or calving glaciers. Inland relief is up to 2000 m. In the Kennedy Channel-Robeson Channel area the coast is much straighter and the fjords follow the southwest-northeast structural trends of the Innuitian Mountains, for example, Lady Franklin Bay. Elsewhere the coast of Ellesmere Island is deeply indented by fjords. Many of the cliffs have a cover of talus over the lower face and in northern areas (north of 80°) there is often a permanent ice foot (q.v.) that extends from 4 to 10 m above the water level. In the upper fjords some lowlying areas have beach deposits, and small deltas with intertidal flats are common where the fjord heads are ice-free (Taylor, 1973).

4.4 JONES SOUND-LANCASTER SOUND-PRINCE REGENT SOUND

This area of the central eastern archipelago (Fig. 18, page 75) has high, straight coastlines interrupted by occasional fjords. Geologically this is a region of sedimentary rocks (Fig. 7, page 27) that in most areas are relatively unresistant, horizontally-bedded limestones. This is an old plateau area with relief in the order of 300-400 m (Bird, 1967). The deep water bodies that separate the islands were enlarged by glacial erosion along the valleys of pre-existing rivers (Craig and Fyles, 1960). As a result, the channels are relatively straight and steep-sided, and resemble very large drowned fjords. The area was largely eroded by the ice sheets and there are few areas of unconsolidated glacial deposits.

Mean tidal ranges vary between 1.3 and 2.2 m, with spring ranges between 2.1 and 4.0 m; the highest values occurring in Jones Sound (C.H.S., 1977). Wind data from Resolute (Fig. 3, page 13) indicates that the prevailing winds are out of the northwest. Collin (1962) notes that wind values from Resolute are subject to topographic influences and may not truly reflect the regional conditions. This is a sheltered wave environment and high wave-energy conditions occur only at the infrequent times when strong onshore winds coincide with open water (McCann and Taylor, 1975; Taylor, 1975; Taylor and McCann, 1976). The ice begins to break up in eastern areas in late June and is moved to the east and south, but Barrow Strait, Wellington Channel, and west Jones Sound are not usually clear until mid-August. Freeze-up commences in September and is usually complete by mid-October, so that the ice-free season is only 1 to 2 months. In Jones Sound, fast ice remains in coastal areas throughout the summer in some years. The delay in the melting of the ice foot following breakup and its formation prior to freeze-up reduces the length of the open-water season in all areas (Fig. 6: Resolute, page 26) (Owens and McCann, 1970; Taylor and McCann, 1976). Taylor (1973) notes that the coast of northern Somerset has an average of 68 ice-free days but that Resolute has an average of only 44. In Radstock Bay, on southwest Devon Island, the ice foot remained on the beach throughout the summer in 1972 (McCann and Taylor, 1975).

The coasts of this environment are typically high and straight with predominantly cliffed shorelines. The steep cliffs, that rise to maximum heights of 600 m, usually have a talus deposit that protects the lower face (Photo 23). The

Photo 23. East coast of Prince Regent Sound, Brodeur Peninsula, in late July. The shoreline is a mixture of cliffs with large talus slopes and raised beaches in lowlying areas.

pebble-cobble beaches on this type of coast are usually narrow. The straight coasts are interrupted by fjords, particularly on southern Ellesmere and northeast and southern Devon Islands. Lowland sections, such as the Cape Storm area on southern Ellesmere Island (Blake, 1975), Radstock Bay on southwest Devon Island, and northern Somerset Island (Taylor, 1974) have low beaches, deltas, spits and barrier islands that are backed by raised beach sequences (Photos 5 (page 30) and 23). The fjords usually have small bay-head deltas and tidal flats where glaciers do not extend to the water level. Although the bedrock is relatively unresistant, rates of erosion and littoral sediment transport are very low due to the inability of waves to redistribute the sediments during the very short periods of open water. Cliff erosion is related primarily to frost action on the cliff faces, and frequently large rock falls are removed by ice rafting during breakup rather than by wave-related processes (Photo 24).

4.5 WEST ELLESMERE AND AXEL HEIBERG ISLANDS

This fjord coast has lower relief, less resistant rocks and a much lower wave-energy environment than the coasts of Baffin Bay and Davis Strait (Region 3, page 88). This area is part of the Innuitian Mountains, a system of folded sedimentary rocks that trend northeast-southwest in Ellesmere and approximately north-south in Axel Heiberg Island (Fig. 7, page 27).

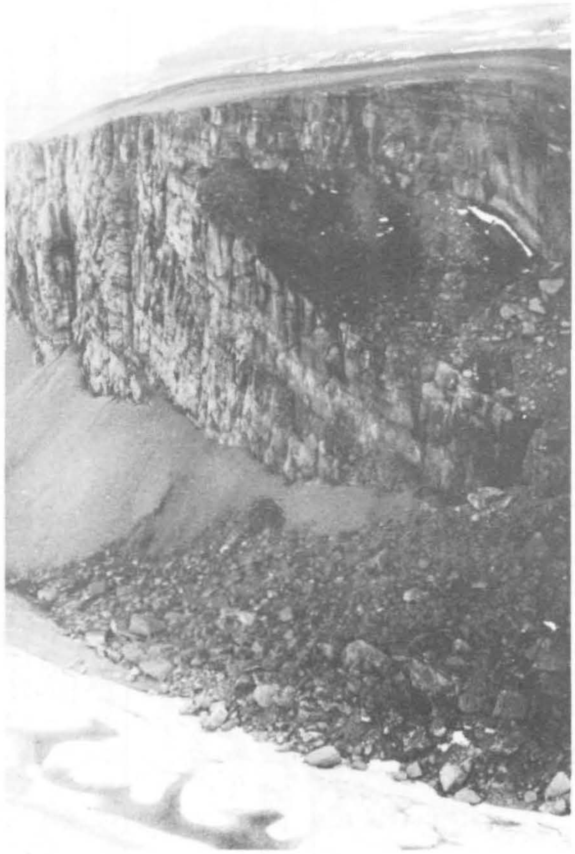


Photo 24. North coast, Griffith Island, Barrow Strait, in July. During the preceding winter months a large rock fall from the cliff face (approx. 200 m high) was deposited on the beach and the adjacent nearshore ice. The material on the ice would be removed by the ice during breakup. Note that to the east (left) of the rock fall the lower cliff face is buried by an older talus accumulation.

Relief is up to 2000 m inland, but is generally less than 500 m near the coasts.

Mean and spring tide ranges are everywhere less than 0.2 m and 0.5 m respectively (C.H.S., 1977). During the summer months winds are predominantly out of the northwest and these help to clear the broken pack ice through the channels towards more open water to the south and east. During a heavy ice year the coasts of this region may remain ice-locked, even in the most southerly areas adjacent to Norwegian Bay (Fig. 5, page 25). In a good year, southern areas can be ice-free by mid-August and may remain clear until early September. In the northern sections, the sea is very rarely open (Fig. 6: Eureka, page 26) and if the ice does break up there is rarely less than a 5/8 ice cover. During the period 1946-1950 the ice in Sverdrup Channel did not move for 5 consecutive summers (C.H.S., 1970). As a result of the short, or non-existent, ice-free season and the presence of fast ice on the beaches, the northern parts of this environment are at the low end of the wave-energy spectrum. In less sheltered areas, waves can act in the littoral zone for up to 40 days in a light ice year.

The coasts of this environment are a mixture of lowland coastal plains or steep cliffs and fjords. The fjords are particularly well-developed on Ellesmere and on west and southeast Axel Heiberg Island (Photo 4, page 29). To a large extent, the orientation of the fjords is structurally controlled; this is particularly evident in southeast Axel Heiberg Island. Due to the less resistant bedrock of this area the relief is lower and the fjords tend to be longer than those of the Shield coasts

(Taylor, 1973). The valley walls of Otto Fjord in northwest Ellesmere Island rise up to 900 m from the water level (Thorsteinsson, 1974), but in general, elevations are much lower. Cliff sections of coast are infrequent and in many areas contrast to the adjacent lowland regions, for example, the 300 m-high Svartevaeg Cliff on northern Axel Heiberg Island. The east coast of Axel Heiberg is generally low and has few fjords; this is a section of low coastal plains with deltas, pebble-cobble beaches and mud flats. The south and west coasts, however, have fjords and cliffs in a more upland topography (Dunbar and Greenaway, 1956).

4.6 ICE SHELF

This coastal environment, which is relatively short in length, is unique to polar regions. The ice shelf is up to 100 m thick in places and has a rolling surface topography, similar to a ridge and valley system (Taylor, 1973). The shelf is almost continuous along the coast and is up to 16 km wide in the Disraeli Bay area (Dunbar and Greenaway, 1956). The ice is covered with glacial debris in many areas. The ice front calves periodically and in 1961, approximately 50% of the Ward Hunt Ice Shelf broke away (Taylor, 1973). Tides in this environment are less than 0.5 m and normal coastal processes are virtually absent due to the presence of the polar pack ice that rarely leaves this coast open (Fig. 5, page 25).

4.7 COASTAL PLAIN

This environment is a lowlying plain with shallow nearshore zones and relief generally less than 150 m. Towards the east relief increases to maximum elevations of 300 m in some areas. Geologically this is a region of unresistant sedimentary rocks and unconsolidated deposits of sand and gravel (Fig. 7, page 27).

The tides of this environment are less than 1.0 m and the coasts north of Banks Island have a semi-permanent ice cover. During a light ice year the channels rarely have less than a 5/8 ice cover (Fig. 5, page 25). Western Banks Island clears during periods of southeasterly winds in summer and the polar pack ice may move as much as 80 km offshore as broken ice drifts to the southwest. The open-water season, if it occurs, it usually in August or September (Fig. 5). Elsewhere the coasts remain locked-in most years and littoral processes are at a minimum (Fig. 6: Isachsen and Mould Bay, page 26).

Ellef and Amund Ringnes Islands have low coasts with many bays and deltas. Beaches of pebble-cobble sediments give way to a very shallow nearshore zone. Northern Ellef Ringnes Island is very low and has extensive mud flats and swamps in the Cape Isachsen area. Borden, Mackenzie King and Brock Islands are very low in western areas, with wide shoals and mud flats, but relief increases slightly to the east. Prince Patrick Island has a similar coastline, with hills and bays on the east coast and low shoals with many islands on the Arctic Ocean coast. Western Banks Island has a coast of deltas and swamps (Photo 25) with many barrier beaches that enclose the lagoons (Dunbar and Greenaway, 1956). In this section of coast, which has open water most years, littoral processes have been able to rework sediments to form continuous beaches, (Stevens, 1976),

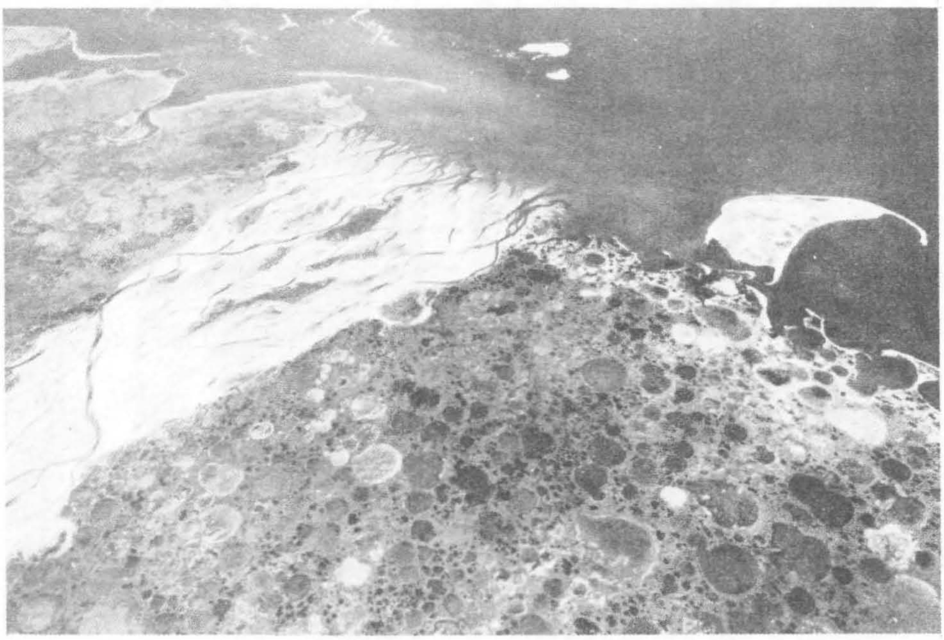


Photo 25. Coast of southwest Banks Island at the mouth of the Big River in August. Note the many lakes in the backshore and the braided river channels that have been unmodified by wave action at the shoreline. Some reworking of the littoral sediments is evident from the presence of barriers and spits in the nearshore area (from Dunbar and Greenaway, 1956).

for example, Cape Kellet in the southwest corner of Banks Island (Photo 26). Elsewhere in this environment, fluvial processes tend to dominate due to the lack of wave energy and to the inability of waves to redistribute the sediments supplied to the littoral zone.

The Coastal Plain environment is primarily one of lowland plains, deltas, braided streams and mud flats, with barrier beaches developed in the more open southwestern sections. Ice action plays an important role in redistributing sediments. Ice push can form gravel ridges on the shallow shoals, can form ridges up to 10 m high in the shore zone, and, due to the low relief, can push inland up to 1 km (Taylor, 1973).

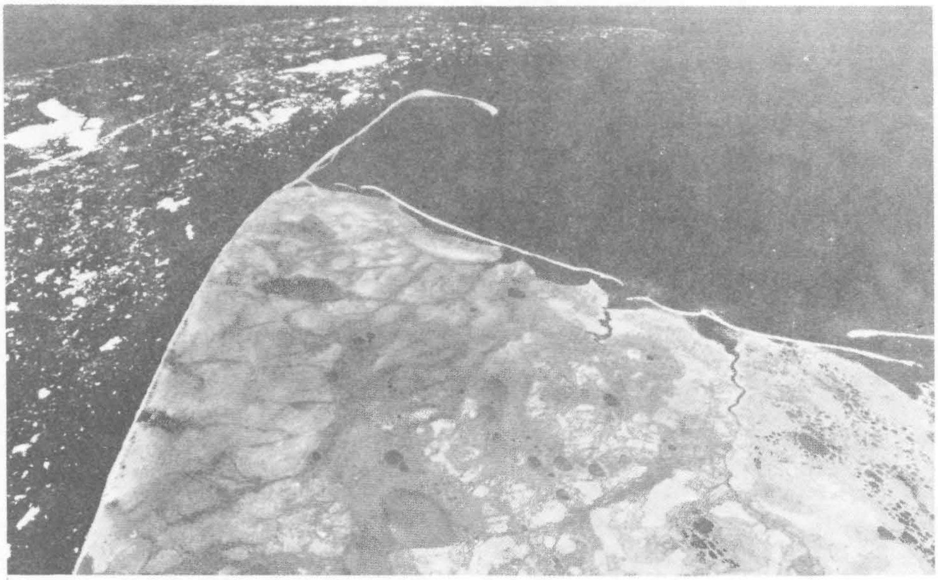


Photo 26. Cape Kellet, southwest Banks Island in August. This coast has well-developed barrier beaches and spits (of pebble-cobble sediments) and is an area of relatively high wave activity due to open-water conditions for up to 2 months each year (from Dunbar and Greenaway, 1956).

4.8 RIA COASTS

This environment is the southwest portion of the Innuitian fold mountains (Fig. 7, page 27). Unlike more northerly sections of this geologic region, relief is low (<700 m) and the relatively unresistant sedimentary rocks have been eroded to give many areas a very irregular and indented coastline. Differential erosion of alternating resistant and unresistant outcrops by fluvial and glacial processes, along the predominantly east to west trending fold axes, gives this environment its characteristic ridge and valley topography, that is expressed in the coast as a typical ria (q.v.) shoreline (Photo 27).

Photo 27. Bracebridge Inlet on the west coast of Bathurst Island in early August. A typical example of a ria coastline (from Dunbar and Greenaway, 1956).

Tidal range varies from 1 to 2 m and southeastern sections are exposed to wave activity during a 1 or 2 month period in most years. Taylor (1973) notes that Hooker Bay, in southwest Bathurst Island, is open for an average of 25 days each year, with a variation between 14 and 46 days. In northern sections, the open-water season is much less as the ice does not clear so rapidly from these more sheltered areas (Fig. 5, page 25). Southern sections are cleared following breakup by north-northwest winds that move the pack ice towards Lancaster Sound.

The primary characteristics of the coasts are provided by resistant rock outcrops that form peninsulas and off-lying islands and by less resistant rocks that have been eroded to form large embayments. This alternating ridge and valley system, referred to generally as a ria coastline, trends predominantly east-west, following the fold axes of the Innuitian system. In sections where the folds are less prominent the coastline is more regular (Taylor, 1973), and the east coast of Bathurst Island follows a major fault line (Bird, 1967). As this is primarily a lowland environment there are few cliffed sections, except in southwest Melville Island where steep cliffs up to 300 m in height occur. Elsewhere the indented ria coast has many sand or pebble-cobble beaches or deltas, with raised beaches in the backshore and with nearshore shoal areas. In particular, McLaren (1974) and Taylor (1976) note that the east coast of Melville Island is predominantly one of deltas, sand beaches and mud flats.

4.9 SOUTHERN ARCHIPELAGO-MAINLAND

Although this environment is diverse geologically, relief is generally low (<500 m) and many areas have a surface cover of unconsolidated sands and gravels that were deposited by the retreating ice sheets. The mainland coast is predominantly the margin of the Canadian Shield, except to the west of Coronation Gulf. The resistant crystalline Shield rocks protrude into the southern archipelago in three areas; west-central Victoria Island, the Boothia Peninsula and the Melville Peninsula (Fig. 7, page 27). The remaining sections have less resistant rocks, predominantly limestones, that were deposited in structural depressions on the ancient Shield surface. Elevations are generally less than 500 m, with local upland areas where the Shield protrudes into the islands. This is an environment of undulating uplands, plateaux and lowlands, with only local dissected sections. For example, in the Bathurst Inlet and Coronation Gulf areas, folded rocks have been eroded along north-south and east-west structural trends respectively to give a series of inlets, peninsulas and islands. The entire area has an almost continuous, often thick cover of unconsolidated sediments that were primarily deposited by the retreating ice sheets.

Tides are less than 1 m in all areas except for Foxe Basin. In the latter the mean range decreases from 5 m in the southeast to less than 0.6 m at Hall Beach in the northeast. Currents are generally weak everywhere, but in Fury and Hecla

Straits the west to east currents can reach velocities of 1 m/s. This is a very sheltered wave environment and the ice-free season is usually two months or less. Breakup begins in late July or August and most areas are ice-free during August (Fig. 6: Hall Beach, Cambridge Bay and Sachs Harbour, page 26), with freeze-up commencing in October. Local ice conditions vary considerably in response to wind directions. Ice can become trapped along the coasts in large bays or inlets, for example, Committee Bay, and will only be removed with a period of offshore winds, so that some areas may not be ice-free during certain years (Fig. 5, page 25).

The coastal geomorphology of this environment is predominantly that of rocky shorelines or low beaches with sand, pebble-cobble or boulder sediments, and raised beaches in the backshore. These lowland sections are interrupted by sections of cliffs up to 10 m in height, but high cliff coasts are rare (Bird, 1967). The exceptions are in Coronation Gulf, Bathurst Inlet, parts of north Victoria Island (these 3 sections are indicated as "cuesta coasts" in Fig. 21) as well as southeast and west Boothia Peninsula, parts of north and south Banks Island and the north and east coasts of Prince of Wales Island, where cliffs may reach 200 or 300 m. These cliffs are usually fronted by a narrow beach of coarse sediments at their base. The west coast of Boothia Peninsula is indented by some fjords. These high cliff coasts, however, probably account for less than 10% of the

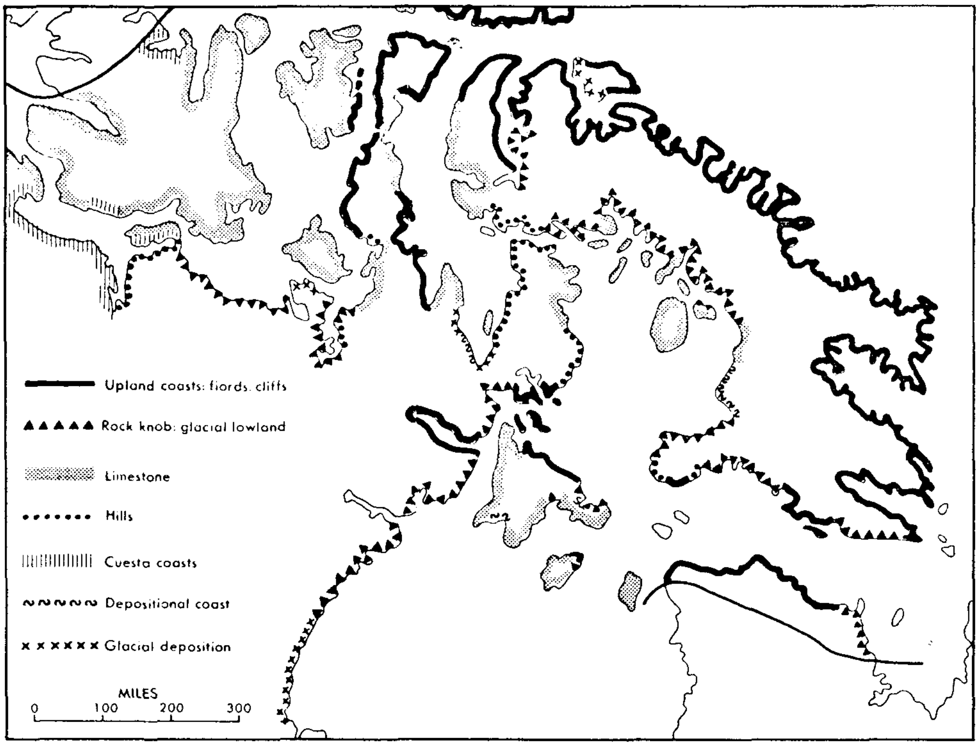


Figure 21. Classification of the coasts of the southeast Arctic (from Bird, 1967).

coastline of this region. The lowland coasts frequently have very shallow nearshore areas that are dotted with reefs and islands (Photo 28), for example, in Queen Maud Gulf. In southeast Foxe Basin the Great Plain of Koukdjuak has extensive boulder-strewn mud flats in an area where the tidal range is in the order of 5 m.

4.10 TUKTOYAKTUK PENINSULA-LIVERPOOL BAY

This section of the Arctic Ocean coastal plain (Figs. 7 and 18, pages 27 and 75) is an area of rapid shoreline retreat. The unconsolidated surficial sediments have very low relief and the

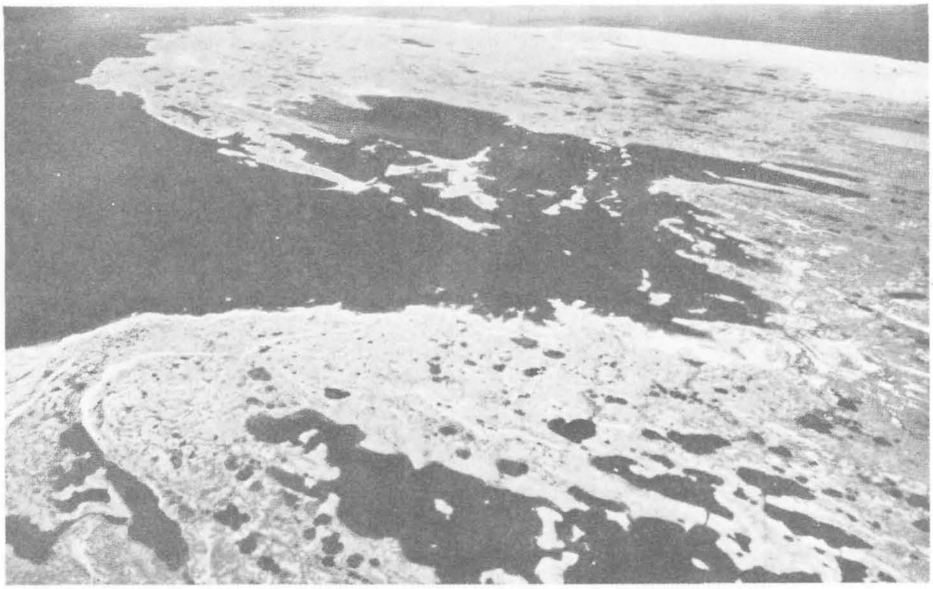


Photo 28. Shepherd Bay, southeast Queen Maud Gulf in early August. An irregular, complex coastline in a very low wave-energy environment (from Dunbar and Greenaway, 1956).

backshore areas are characterized by numerous shallow lakes. The Tuktoyaktuk Peninsula is possibly a large moraine deposited at the terminus of the Pleistocene ice sheet (Prest, in Douglas, 1970) and a rise of sea level following the retreat of the ice has led to inundation of the lowlying area now occupied by Liverpool Bay and the Eskimo Lakes.

Tides in this environment are less than 1 m, though occasional storm-generated surges can raise the water level to greater than 2 m above the normal high-water mark. This is a sheltered wave environment and the open-water fetches vary from less than 50 km to over 200 km, depending on the location of the polar pack ice (Fig. 5, page 25). The inner areas of Liverpool Bay are an extremely low-energy wave environment. The exposed coast is usually ice-free from July to the end of September (Fig. 6: Tuktoyaktuk, page 26), but in a heavy ice year may be open only during September.

The coastal geomorphology of the exposed shorelines of the Tuktoyaktuk Peninsula is primarily characterized by a very irregular shoreline that results from erosion of the lowlying lake topography. In some areas these breached lakes are enclosed by barrier beaches and spits. Occasional low unconsolidated cliffs (up to 10 m high), and beach deposits are undergoing rapid coastal retreat, a maximum of 15 m per year (Rampton and Bouchard, 1975). Rates of retreat are very variable, as low as 1 m per year in some areas, but near Flagpole Point at Tuktoyaktuk, which has an average retreat of 3.8 m per year, as much as 14.6 m of erosion was reported following a major storm in September 1970 (Rampton and Bouchard, 1975). To the west of Tuktoyaktuk the beaches are composed of sand and pebble-size materials. To the east they become primarily sand and the beaches are backed by extensive dune deposits (Lewis and Forbes, 1974). The sand transport direction of littoral sediments on this coast is from southwest to northeast. In the northern part of the peninsula, which has an extremely intricate shoreline, the supply of littoral sediments is less and fewer barriers have developed across the breached lakes. This section has mud flats exposed at low tide and the offshore areas are shoal up to 15 km from the coast. The coasts of Liverpool Bay are predominantly low cliffs, 5 to 20 m in height, fronted by narrow beaches, with deltas, estuaries and embayments on the eastern shore (Logan et al., 1976). In the southwest of Liverpool Bay, the Eskimo Lakes are a brackish environment with a very complex coast, little wave activity and higher backshore relief.

4.11 MACKENZIE DELTA

This delta system is the largest in Canada and covers an area of approximately 13,000 sq. km (Photo 29) (Mackay, 1963).

Photo 29. The western channels at the mouth of the Mackenzie delta (in mid-August) (from Dunbar and Greenaway, 1956).

The river exits through a series of channels into the Beaufort Sea on the western margins of the delta. The period of maximum runoff is early summer, but the river discharges throughout the year. Elevations are extremely low in all of the coastal areas of the modern delta and the main channels are leveed to a height of 3 m in some areas. Although tides are less than 0.5 m on the coast, storm surges can raise the water level up to 3 m and under these conditions the extensive marshes of the lower delta become inundated by sea water. The eastern, or old, delta area includes Richards Island and is an area of generally low relief but offshore, Garry and Hooper Islands attain altitudes of up to 40 m (Logan et al., 1976). The coastal margin of the delta is undergoing erosion at the present time.

4.12 YUKON COAST

This coastal environment is a lowland area of unconsolidated sediments. Relief is generally less than 50 m and the coastal cliffs that characterize this region are rapidly retreating. Tides are less than 1 m, but storm surges up to 3 m have been reported, for example, in 1970 (Forbes, 1975). The coast is ice-free for between 1 and 3 months each year, depending primarily on wind direction during July, August and September. The polar pack ice rarely moves more than 200 km offshore (Fig. 5, page 25), so that fetch distances are limited. Freeze-up is usually completed by early October.

The shoreline is predominantly low, eroding cliffs, but relatively large deltas occur at the mouths of the Malcolm, Firth, Babbage and Blow Rivers. Longshore sediment transport of the eroded sediments has led to the growth of large spits at Nunoluk Spit, Avadlek Spit (on southwest Herschel Island) and Kay Point. The predominant direction of sediment transport is to the southeast, but local reversals occur near the U.S. border and at Kay Point (MacDonald and Lewis, 1973). The barrier beaches are generally low, with berm crests rarely greater than 2 m above high-water mark and the frost table (q.v.) thaws to maximum depths of approximately 1 m (MacDonald and Lewis, 1973).

West of and including Herschel Island, cliffs are in the order of 5 to 50 m, with erosion rates up to 2.5 m/year. Some cliffs have a 10 to 20-m wide beach at their base. Southeast of Herschel Island cliff heights are generally 5 to 20 m, but increase in some areas to 100 m. In this section erosion rates range between 1.5 and 5 m/year (MacDonald and Lewis, 1973). Despite the low levels of wave activity and the short open-water seasons, the erosion rates are rapid, as the coastal exposures of unconsolidated sediments are bound together by permafrost. The ice content is often high, as much as 90% (Photo 30) and erosion occurs by thermal melting of the exposed ice that leads to slumping of the cliff face. Waves acting at the base of the cliff can cause rapid ice melting and this can lead to under-cutting of a thermal niche, which can cause large blocks of the cliff to collapse (Photo 31).

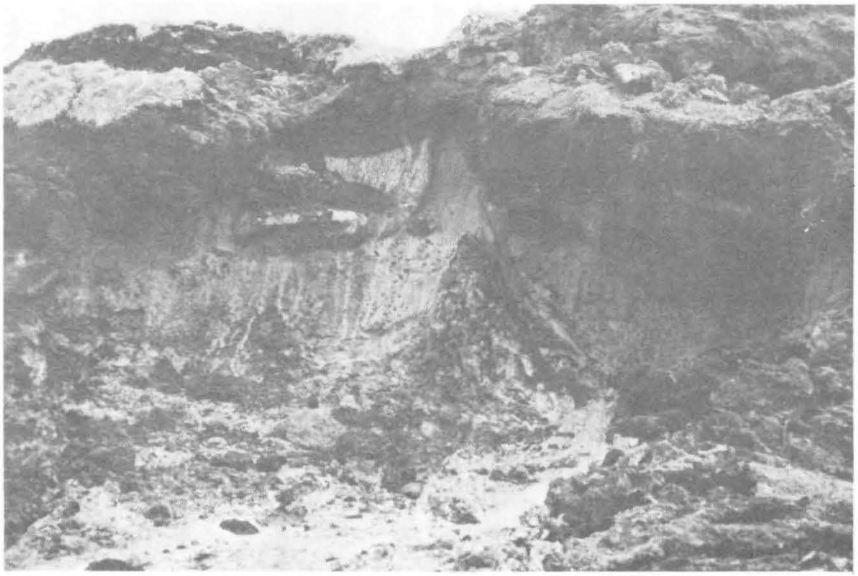


Photo 30. Tundra cliff near Peard Bay, Alaska (August). This cliff is similar to those found on the Yukon Coast. In this example a thick lens of ice has been exposed by a slump. This ice is being melted rapidly and this results in the overlying unconsolidated deposits breaking off and falling onto the beach.

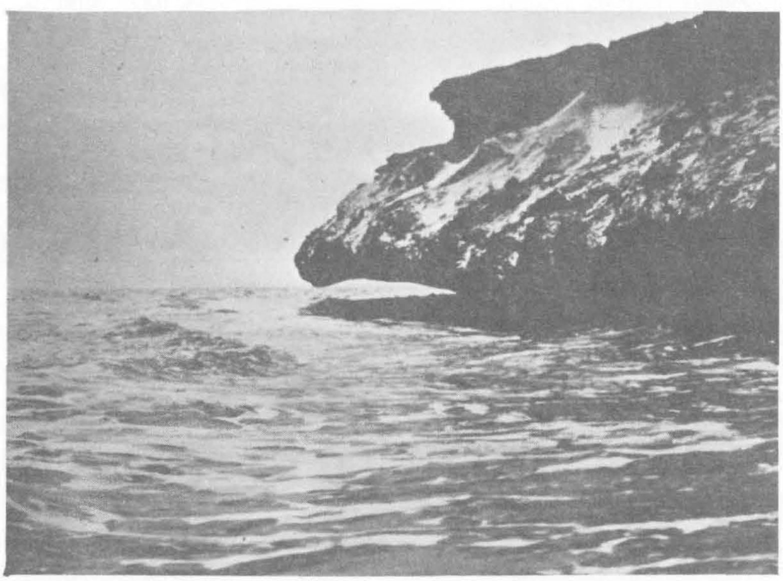


Photo 31. Erosion of a thermal niche in a tundra cliff near Cape Simpson, Alaska. Waves have melted the ice and eroded the cliff at the base during a period of strong onshore winds (photo by J.M. Coleman).

PART 5 - COASTAL ENVIRONMENTS OF THE ATLANTIC COAST

The coasts that border the western North Atlantic have been divided into 7 environments (Fig. 22, Table 9). The exposed outer coasts of Labrador, Newfoundland and Nova Scotia are primarily rocky and contrast with the sections of depositional shorelines in the more sheltered Gulf of St. Lawrence and Bay of Fundy. Ice plays an important role in all but the most southerly areas of this environment.

Primary information sources for this region are Dubois (1973), the Canadian Hydrographic Service Sailing Directions (1973, 1974a, b, c), Owens (1974), and Owens and Bowen (in press).

5.1 LABRADOR AND OUTER NEWFOUNDLAND

The resistant rocks of this coast were eroded by glaciers and subsequently drowned to produce an irregular, barren shoreline. Superimposed on this rugged physical background, the presence of ice for up to 7 months each year, high wave-energy levels in winter and fall, and summer fogs combine to give this coastal environment its character. Geologically this area covers 2 distinct units. The Labrador unit represents the eastern rim of the resistant Canadian Shield, that in northern areas attains an altitude of 1500 m within 15 to 30 km of the coast in the Torngat Mountains. This section was deeply scoured by Pleistocene glaciers to produce an indented, fjord

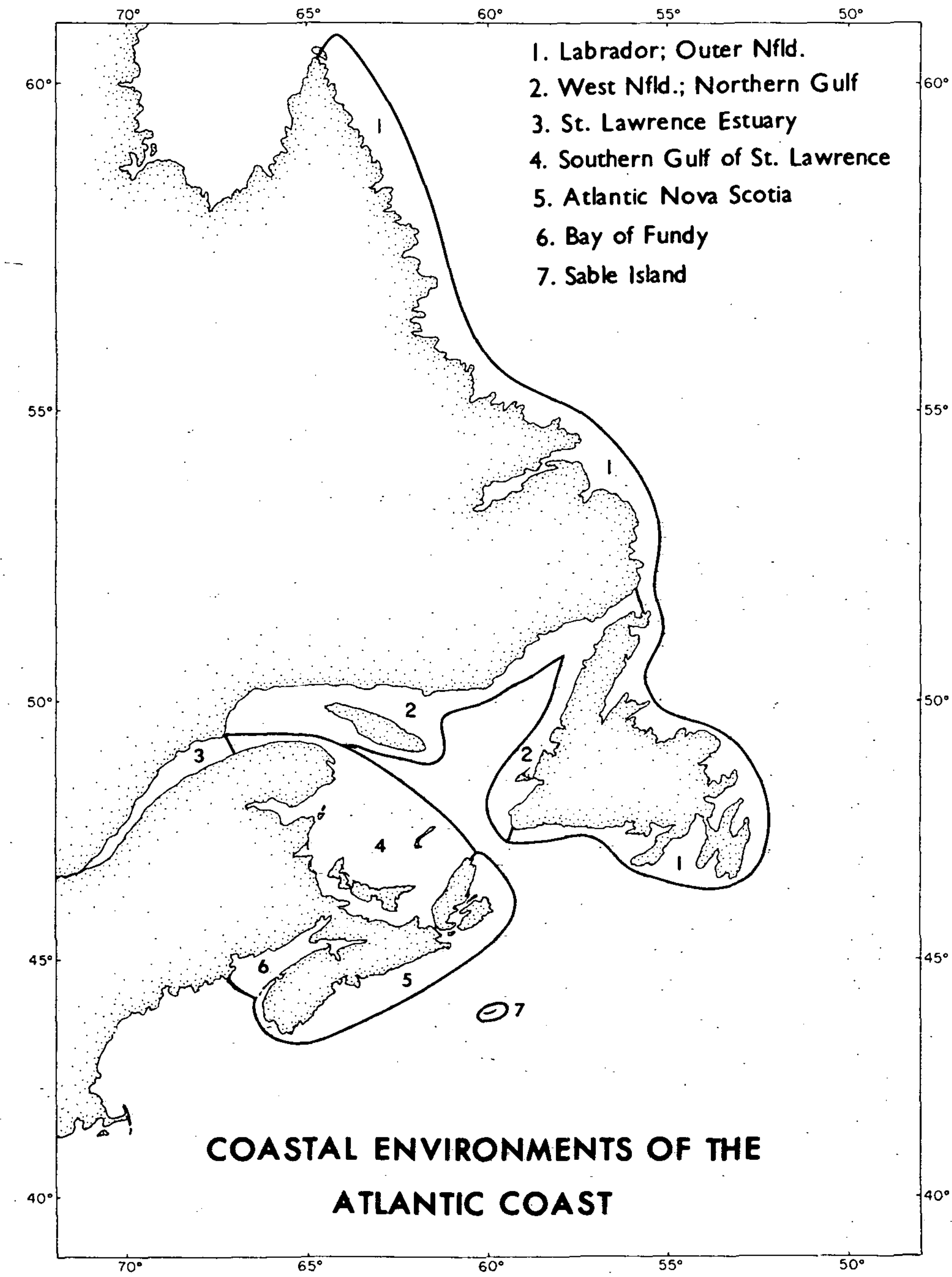


Figure 22. Coastal environments of the Atlantic coast (see Table 9).

TABLE 9. Characteristics of Atlantic Coastal Environments

	GEOLOGICAL CHARACTER	COASTAL ZONE		FETCH AND WAVE EXPOSURE	MEAN TIDAL RANGE	SEDIMENT AVAILABILITY
		BACKSHORE RELIEF	BEACH CHARACTER			
1. Labrador and Outer Newfoundland	Shield rocks in Labrador; volcanic and sedimentary rocks trending southwest-northeast in Newfoundland.	Resistant upland area (200-1500 m near the coast); fjords.	Generally absent; some narrow pebble/cobble beaches in sheltered areas.	Very exposed storm wave environment: bays sheltered. Ice free season is 6 - 10 months.	1 - 8 m	Very scarce.
2. Western Newfoundland and Northern Gulf of St. Lawrence	Shield rocks on mainland; sedimentary rocks on Anticosti and northwestern Newfoundland.	Lowland resistant coast; relief generally <200 m; fjords in central western Newfoundland.	Generally absent; sand beaches on northwestern shore of the Gulf.	Maximum 700 m, enclosed sea, energy levels increase from northwest to southeast. 4 - 5 months of ice.	1 - 2 m	Very scarce except in northwest.
3. St. Lawrence Estuary	Shield and metamorphic rocks in the west; sedimentary rocks in the east.	Resistant uplands in the west (relief up to 1000 m), lowlands (<200 m) in the east.	Generally absent; intertidal sand and mud flats backed by marshes in middle estuary.	Sheltered estuarine environment. Estuary is ice free 7 - 8 months.	3 - 5 m	Very scarce in lower estuary; relatively abundant in middle estuary.
4. Southern Gulf of St. Lawrence	Predominantly sedimentary rocks; metased. and igneous rocks in eastern and western areas: overlain by thin till deposits.	Low, unresistant cliffs (3-10 m) with cliffs up to 100 m in resistant upland areas.	Great variety, ranging from barrier islands to multiple intertidal bars and narrow beaches of reworked talus deposits.	Generally >300 km, enclosed sea. Ice free season is 7 - 8 months.	1 - 2 m	Generally abundant.
5. Atlantic Nova Scotia	Predominantly metamorphic and igneous outcrops overlain by till or drumlins.	Low, resistant rocky shore zone or cliffs (up to 10 m).	Generally absent or pocket beaches; occasional barrier beaches.	Open ocean coast, very exposed. Ice only in sheltered bays during winter months.	1 - 4 m	Scarce or very scarce.
6. Bay of Fundy	Resistant igneous or unresistant sedimentary rocks overlain by till or outwash.	Generally rock cliffs (5 - 200 m).	Pebble-cobble: wide sand or mud tidal flats in the upper bay.	Generally <50 km, sheltered. Ice only in sheltered areas in winter.	5 - 15 m	Abundant in upper bay; elsewhere very scarce.
7. Sable Island	Unconsolidated sand.	Sand dunes.	Wide, sandy beaches.	Open ocean coast, very exposed.	1 m	Abundant.

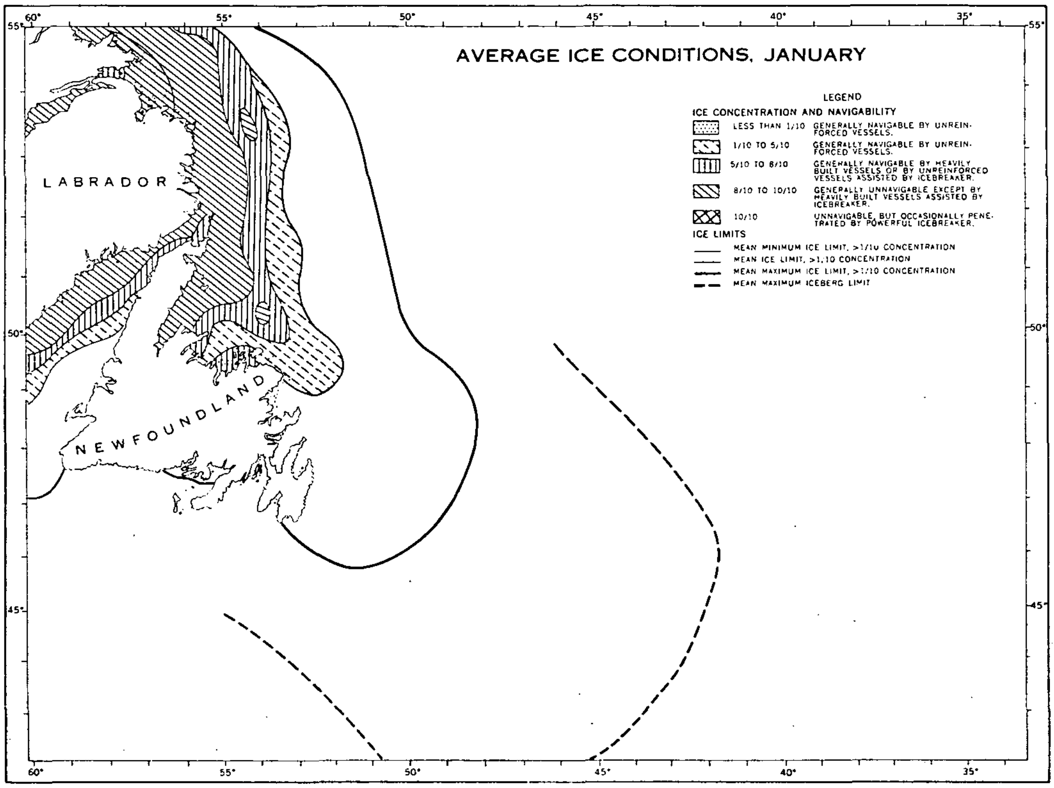
coast. Relief decreases towards the southeast with elevations in the order of 200 to 500 m near the coast. Glacial erosion of the Shield rocks again produced many fjord-valleys, though these are less common than in the northern half of Labrador. The second geologic unit, the west and south coasts of Newfoundland, is a series of resistant volcanic and deformed sedimentary rocks. These are the most northerly part of the Appalachian mountain system and have been folded along southwest-northeast trending axes (Geol. Survey Canada, 1967). Elevations are generally less than 200 m in this section. The island was glaciated by a local icecap that enlarged the preglacial river valleys which followed the structural trends. The resistant rocks of Labrador and Newfoundland provided little material for erosion by the Pleistocene glaciers, and surficial deposits are therefore thin and very scattered.

The mean range of the semi-diurnal tides decreases from a maximum of 8.0 m at Williams Harbour, in the extreme north of Labrador, to 3.0 m at Battle Harbour on the southeast coast of Labrador (C.H.S., 1977). In channels where the tide is constricted this large range produces strong tidal currents, with maximum velocities of 3.6 m/s reported in some locations (C.H.S., 1974a). Mean tidal range around the Newfoundland coast varies between 1 and 2 m.

The prevailing winds in this environment are out of the western quadrant, with a predominance of southwest winds in the summer. Gale-force winds (>50 km/hr) out of the west-southwest are most frequent in the period between October to April, reaching a maximum average of 15 days per month in January with a minimum frequency of 2 to 5 days per month in June and July (C.H.S., 1974a). In Labrador there is considerable modification and channelling of the winds in coastal areas due to local topography. This is a storm-wave environment, and as these waves are generated locally, wave-energy levels are highest in winter months. Wave heights greater than 3 m can be expected for 30% to 40% of the time in fall and winter, as compared to 15% in spring and 10% in summer months (U.S. Naval Oceanographic Office, 1958). Due to the irregular nature of this coastline, many of the fjords and bays are in relatively sheltered wave environments.

Ice plays a major role in limiting the effects of waves in winter and spring. Ice begins to form in bays along the Labrador coast in early November and by the end of December the coastal waters have an 8/10 to 10/10 ice cover (Fig. 20b, page 82). On this coast the ice begins to break up in the south in April and clears northward (Fig. 6: Cape Harrison, page 26), but in heavy ice years a 5/10 cover is common even in July and this section is not ice-free until late August (Fig. 20a). On the east coast of Newfoundland the ice front moves towards the southeast during January and an 8/10 to 10/10 cover persists through February and March (Fig. 23).

a



b

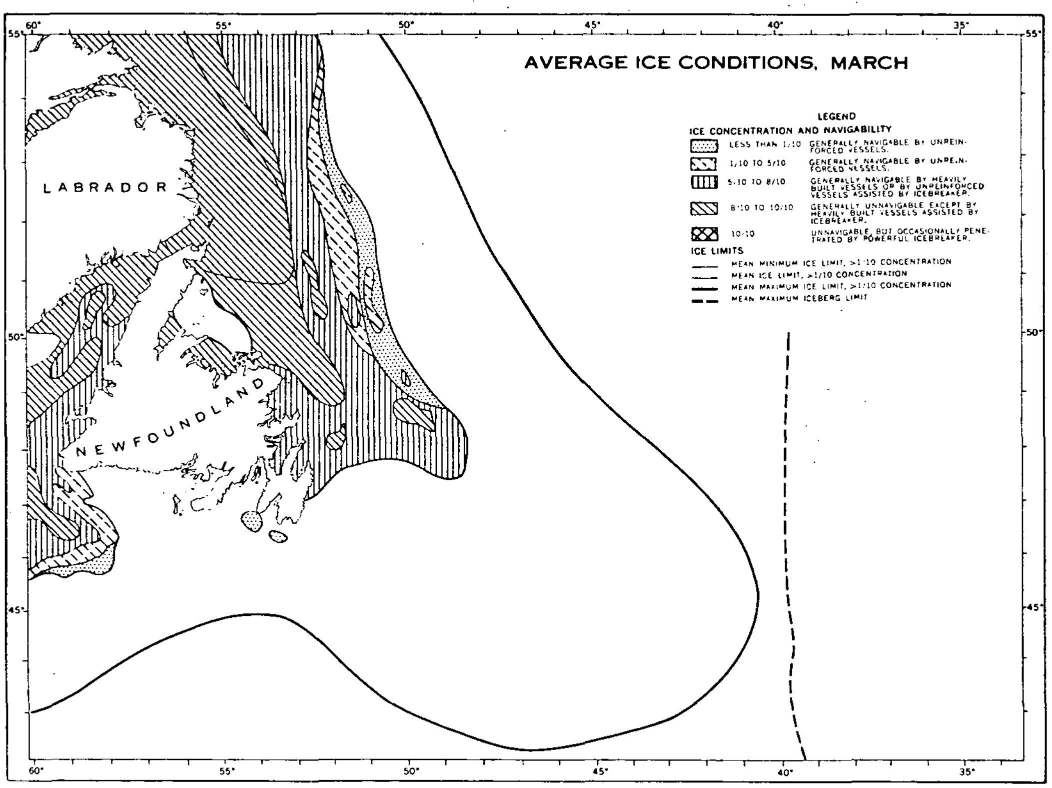


Figure 23. Newfoundland: average distribution of ice (a) January, and (b) March (from U.S. Naval Oceanographic Office, 1958).

This coast is usually ice-free by the end of May (U.S. Naval Oceanographic Office, 1958). The south coast of Newfoundland is usually open all winter (Fig. 8, page 34), but ice often forms in sheltered bays and inlets between January and April.

The coastal geomorphology of this environment is one of fjords, rocky coasts and few beaches. High relief in northern Labrador gives a coastline of deep fjords that cut into the coastal mountains. The southern half of Labrador has a fjord coastline with slightly lower relief, and with more islands and channels along the shore (Photos 6 and 7, pages 37 and 38). Beaches, usually of pebble-cobble sediments, are generally restricted to sheltered environments. The coast of outer Newfoundland has lower relief but can, nevertheless, be broadly described as a lowland fjord coast (Dolan et al., 1972). This part of Newfoundland has a rugged coastline with many islands and bays and has few beaches due to the scarcity of littoral sediment. This is a high-energy coastal environment, dominated by storm waves, in which ice is present on the shorelines and nearshore areas for between 4 and 7 months each year. The south coast of Newfoundland is more sheltered than the east-facing coasts and is usually ice-free during most winter months.

5.2 WESTERN NEWFOUNDLAND-NORTHERN GULF OF ST. LAWRENCE

This environment has the same geologic characteristics as outer Labrador and Newfoundland, but borders on a large marginal sea and is sheltered from the high wave-energy environment of the western North Atlantic. The north shore of the Gulf of St. Lawrence, from the Strait of Belle Isle to the St. Lawrence River at Pointe des Monts, is the southern edge of the Laurentian Plateau region of the Canadian Shield. Relief in the coastal zone is less than 100 m and the coastline is relatively straight but with many small inlets and embayments. Offshore, in the northern Gulf, the Mingan Islands and Anticosti Island are outcrops of resistant limestones that dip towards the south. This results in high relief on the north coast of these islands and low relief on the south coasts. The western coast of Newfoundland is relatively straight and follows the regional southwest to northeast structural trends. The rocks along the northern half of this part of the Newfoundland coast, and in the Port-Au-Port Peninsula, are unresistant sedimentary rocks that have been eroded to a lowland area. The southwest coast of Newfoundland is an upland section of old, resistant volcanic and intrusive rocks, with relief up to 800 m adjacent to the coast.

The tides in this environment are mixed semi-diurnal and have mean range values between 0.8 and 1.7 m (C.H.S., 1977). In the northwest sections of this unit, towards the St. Lawrence estuary, the range increases to values of 2.3 m at Sept Iles and 2.5 m at Pointe des Monts. Some constriction of the tides occurs in the Strait of Belle Isle and currents of 1.8 m/s on flood and 1.4 m/s on ebb tides have been recorded (C.H.S., 1973).

Winds are primarily out of the western quadrant throughout the year, with a shift from southwest in summer to the northwest in winter. Velocities are higher during winter months as the low-pressure systems that cross this region along the Polar Front are both more frequent and more intense. The west coast of Newfoundland has a maximum fetch of 800 km to the southwest, and is the most exposed section of this unit. The north shore of the Gulf is a sheltered environment during periods when waves are generated by winds out of the northwest, as is common in winter months. Wave heights increase in the offshore area from west to east (Table 10) as would be expected in this environment where virtually all waves are generated in the Gulf and where winds are predominantly out of the west.

Ice forms in sheltered environments during November and December. Usually by mid-December a belt of land-fast ice protects the entire north shore (Fig. 6: Sept Iles, page 26) and the northwest coast of Newfoundland (C.H.S., 1973). All of the coasts of this unit are protected by ice during most of February and March (Fig. 24). With offshore (northwest) winds on the north shore, the ice is cleared towards the south in early spring (March). This section is usually ice-free by the end of May (Fig. 24), but in the Strait of Belle Isle ice can persist into late July. The Gulf does not freeze over completely

TABLE 10. Wave Height Data, Gulf of St. Lawrence, 1967 (in metres)

	Median Significant Wave Height			Expected Significant Wave Height Once/Year
A. Northern Gulf	Summer	Winter	Average June-Dec.	
Sept Iles	0.6	0.8	0.7	4.9
Off West Anticosti Island	0.8	1.2	0.9	7.9
Off East Anticosti Island	0.9	1.6	1.1	6.1
Cape North (South Cabot Strait)	1.2	3.2	1.4	7.6
Cape Whittle (North Strait of Belle Isle)	1.1	1.4	1.1	5.8
B. Southern Gulf				
Northwest Prince Edward Island	0.6	1.1	0.9	5.5
East Prince Edward Island	0.8	1.3	0.9	5.8
North Magdalen Islands	1.1	1.9	1.4	7.6

Source: from Ploeg, 1971

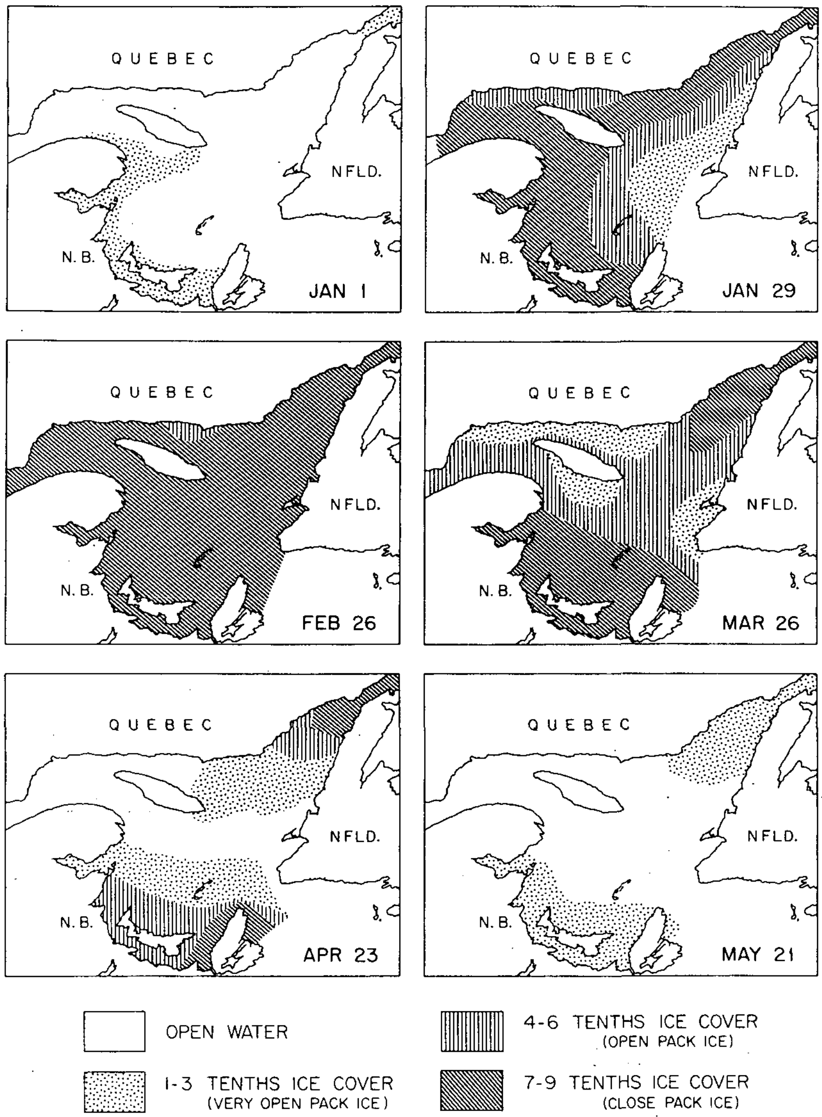


Figure 24. Five-year mean ice distribution, Gulf of St. Lawrence, on selected dates (after Matheson, 1967).

and the nature of the ice cover varies considerably from year to year, depending on wind patterns and temperatures.

The coastal geomorphology throughout the west and north shores of the Gulf is characterized by a relatively straight coast and low rocky shorelines. In the eastern half of the north shore there are large numbers of bays and inlets with low, rocky islands and reefs in the offshore zone. This eastern section is largely devoid of sediment and the intertidal zone is predominantly rock with the few beaches that occur being limited in size. The west section of the north shore, west of Pointe de Natashquan, is rocky but has some extensive sediment accumulations, for example at Pointe de Natashquan itself and at the mouths of the rivers Sainte-Marguerita, Moise, Mingan and Romaine (Dubois, 1973). The supply of sediments by these rivers has led to the development of local sand beaches. In addition, some local erosion of exposed glacial deposits provides sediment directly to the littoral zone. In the Mingan Islands and Anticosti Island the southerly dipping limestones give steep cliffs (up to 100 m on Anticosti) on the north coasts and low, shelving shorelines with many reefs on the south coasts (C.H.S., 1973).

The northern half of the west coast of Newfoundland is a low, irregular rocky shoreline (Photo 32) that gives way southward to an upland coast, with some fjords in the vicinity of Bonne Bay and the Bay of Islands. Local beach accumulations are found where coastal erosion of unconsolidated glacial deposits provides sediment to the littoral zone. The coastal geomorphology of this environment as a whole is characterized by low, rocky coasts in a relatively sheltered wave-energy environment.

Photo 32. West coast of Newfoundland, Port-Au-Port Peninsula, a section of resistant rocky shorelines.

5.3 ST. LAWRENCE ESTUARY

This is a tidal river estuary and has features of fluvial, estuarine and coastal environments. Geologically the eastern half of the estuary is an upland of resistant Shield rocks on the north shore, with relief up to 500 m, and resistant and deformed sedimentary and metamorphic rocks on the south shore, with relief up to 1000 m. On the north shore of the estuary the Saguenay River is a large fjord that was eroded by the Pleistocene ice sheet and is now a subsidiary part of the estuarine environment. The section to the west of Québec City is a lowland region of less resistant sedimentary rocks. In lowland sections the bedrock is mantled by thick deposits of unconsolidated sediments that provide material to the shore zone.

The estuary has a long funnel-shape and mean tidal range increases west from 3.0 m at Pointe-au-Père, to 4.1 m at Québec City, and to a maximum of 4.97 m at Saint-Joachim (which has a spring range of 6.37 m) (C.H.S., 1977). Thereafter, the range decreases to 1.9 m at Grondines but small water-elevation changes (less than 0.2 m) due to the tides are detectable as far as Montréal. One characteristic of the tides in this estuary is that the water level rises faster than it falls. For example, at Grondines the ebb usually lasts for 8 hours whereas the flood tide runs for as little as 4 hours (Dohler, 1969).

This is a low wave-energy environment due to the very small fetches within the estuary. In addition, wave energy is dissipated over a large, vertical area in sections where the tidal range is high. The dominant shoreline processes in the upper estuary are fluvial, and in the middle and lower estuary are related to the tides. Ice forms in the intertidal zone during December and usually persists into late April (Fig. 6: Québec, page 26). The river usually has a 10/10 ice cover but the ice is mobile rather than forming a solid cover due to the relatively strong currents.

The coastal geomorphology of this predominantly estuarine environment ranges from rocky shorelines to wide intertidal mud flats backed by marshes. The rocky coasts are predominantly cut into resistant Shield or metamorphic outcrops so that rates of erosion and sediment supply are low. In the middle and upper estuary, particularly on the south shore, the intertidal platforms are up to 2 km wide in some locations and are mantled by muds and sands. There are also accumulations of coarse material (cobbles and boulders) that were deposited by glacial and drift ice (Dionne, 1968). These intertidal flats are backed by extensive marsh deposits. One of the major processes acting on the flats and marshes is related to the effects of ice erosion and deposition during winter and spring months. The ice causes erosional scars and the rafting of intertidal sediments and marsh blocks (Dionne, 1972).

5.4 SOUTHERN GULF OF ST. LAWRENCE

The broad lowland area of the southern Gulf of St. Lawrence is bordered to the northwest and to the east by the upland areas of the Gaspé Peninsula and the Cape Breton Highlands respectively. This is a sheltered wave environment with low tidal ranges and a relative abundance of littoral sediments. Shoreline processes are affected by ice for up to 4 months each year.

The resistant metamorphic and sedimentary rocks of the Gaspé Peninsula trend approximately east-west and are separated from the sedimentary lowlands to the south by the large estuary of the Baie des Chaleurs. In the east, the southern Gulf is bounded by the igneous and volcanic rocks of the Cape Breton Highlands that follow the southwest-northeast regional structural trends of the Appalachian system (Fig. 9, page 36). The broad lowlands of sedimentary rocks between these two upland sections have a semi-circular shape with very shallow depths in the offshore zone. The Magdalen Islands, located in the central part of the shallow shelf, are small outcrops of these lowland rocks. Prince Edward Island was separated from the mainland as the result of the drowning of a pre-glacial river valley system that was enlarged by glacial erosion. Over most of this lowland section, extensive deposits of glacial sediments were deposited by the ice sheets.

This is a micro-tidal environment with mean ranges between 0.5 and 2.0 m. The tides are mixed semi-diurnal, except in the vicinity of Northumberland Strait where they are predominantly diurnal (Fig. 25: Shediac). Winds are predominantly out of the westerly quadrant with high velocities during winter months. The wave environment is dominated by the effects of locally-generated storm waves associated with the cyclonic depressions that cross this region. West and north-facing coasts are exposed to higher wave-energy levels than east-facing shorelines, as wave heights increase from west to east in the southern Gulf (Table 10, page 122). The beaches and

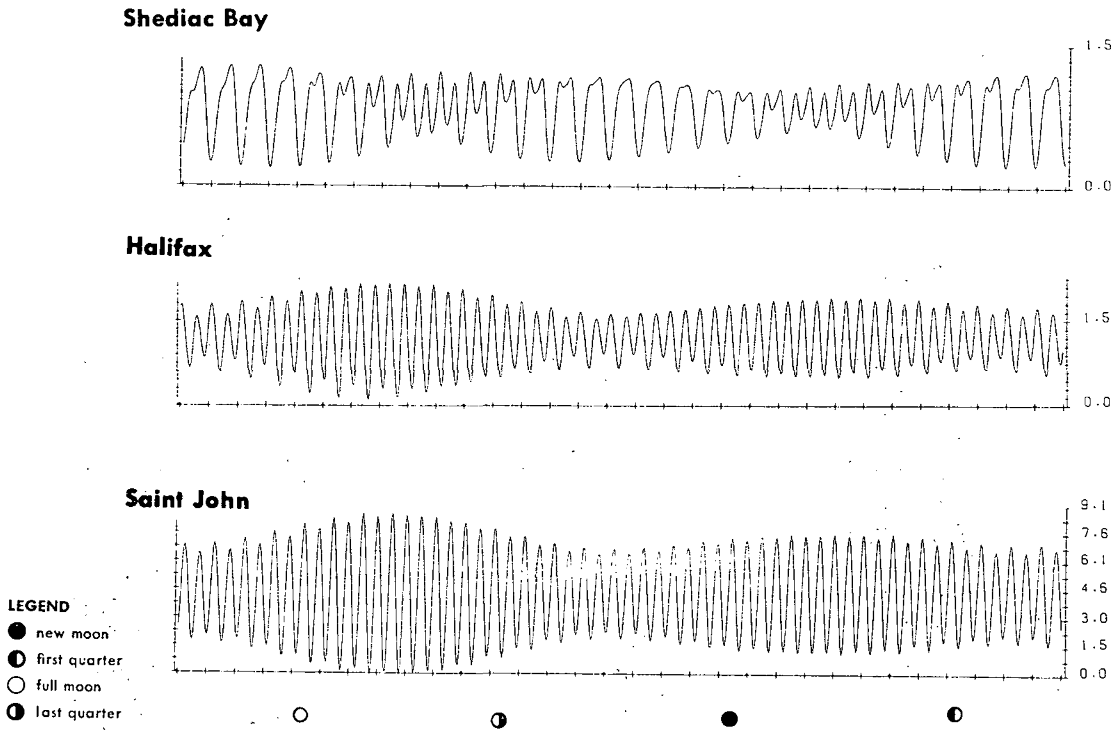


Figure 25. Typical tidal curves from Shediac Bay, N.B., Halifax, N.S. and Saint John, N.B. for a one-month period (in metres) (from C.H.S., 1977). See also Table 4 (page 17) and Figure 4 (page 14) for further data and locations for Halifax and Saint John. Shediac Bay is adjacent to Charlottetown, P.E.I. (station 3, Fig. 4) on the mainland coast of New Brunswick.

nearshore zones are affected by ice from mid-December to April or May each year (Fig. 6: Cambellton and Summerside, page 26, and Fig. 24) and this limits the effectiveness of wave activity at the time when wave-energy levels would otherwise be at a maximum (Owens, 1976).

The coastal geomorphology of this environment (Fig. 26) is primarily one of rock cliffs and barrier islands. The upland

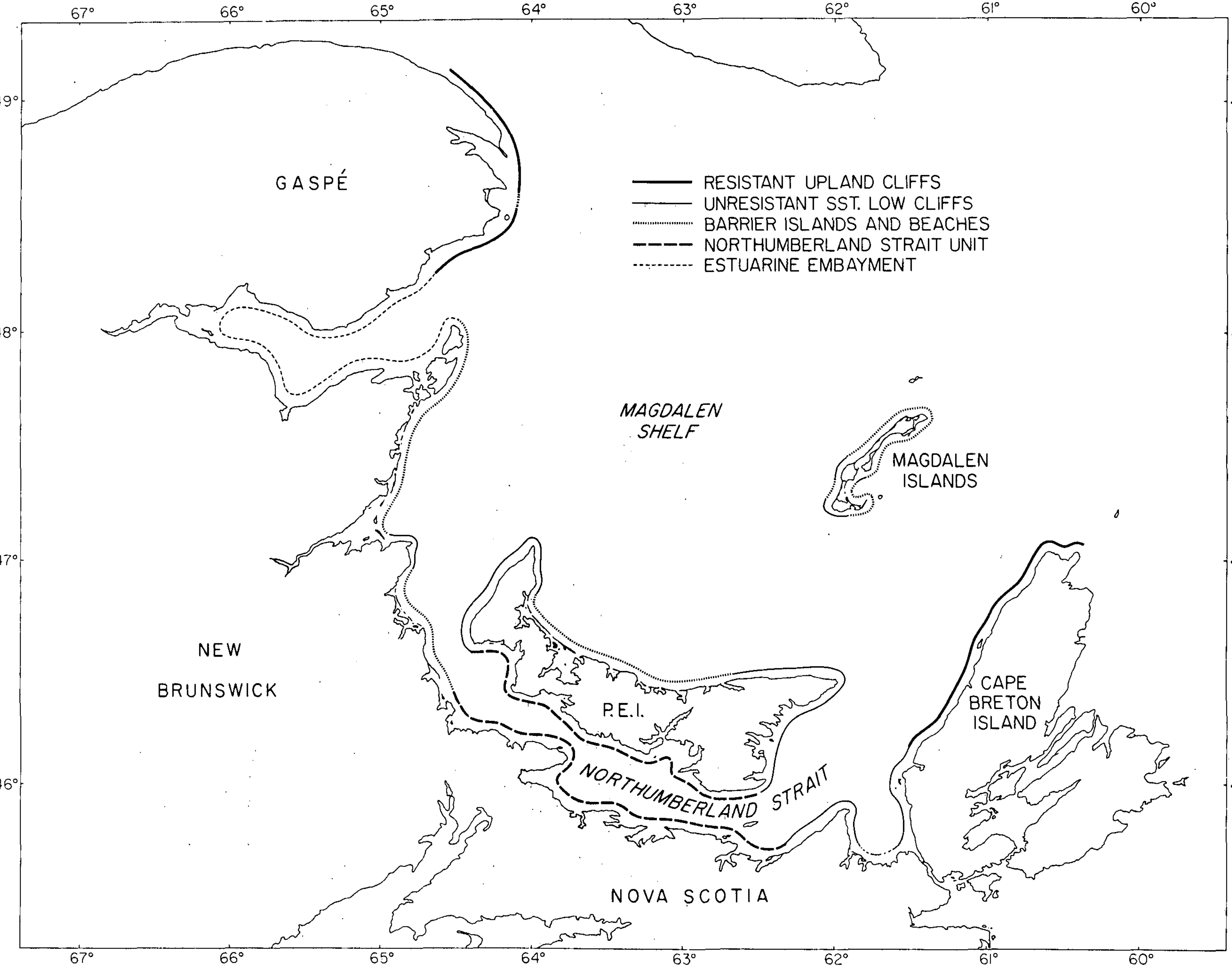


Figure 26. Coastal geomorphology of the southern Gulf of St. Lawrence (from Owens, 1974).

coasts of the Gaspé and Cape Breton Island have resistant cliff shorelines (with local relief up to 800 m) (Photo 33) and only occasional pocket beaches of pebble-cobble sediments. The low-

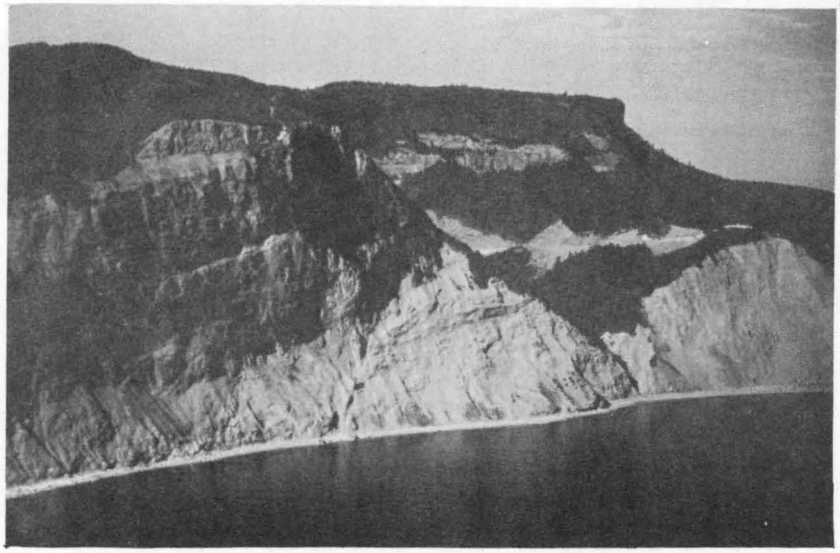


Photo 33. Cliffs west of Percé, Gaspé Peninsula, P.Q. The cliffs are approximately 120 m high and the sediments of the narrow beach at their base are derived from reworked talus deposits (August 1972).

land coastline has been drowned to produce many shallow estuaries and embayments. Erosion of the unresistant sedimentary rocks (Photo 34) and the unconsolidated glacial deposits has provided material for the development of an extensive system of sand barrier islands and barrier beaches that now partially or completely enclose many of these shoreline indentations (Owens, 1975). The barrier system is particularly well-developed along the north coast of eastern New Brunswick

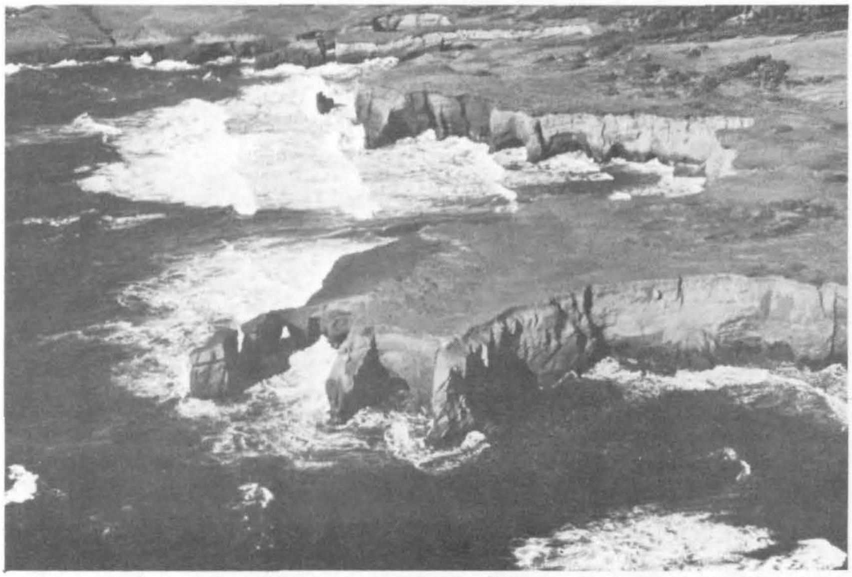


Photo 34. Unresistant, low sandstone cliffs (15-20 m), west coast of Magdalen Islands, P.Q. These cliffs are typical of the lowlands of the southern Gulf of St. Lawrence (photo by P. Hague, August 1972).

(Bryant, 1972; Owens, 1974, 1975; Greenwood and Davidson-Arnott, 1975; Davidson-Arnott and Greenwood, 1976; and Munroe, 1977), northern Prince Edward Island (Photo 35)(McCann, 1972 and Armon, 1975) and on the Magdalen Islands (Owens, 1977a). The coast of Northumberland Strait is a sheltered environment and has a variety of shoreline types that include low sandstone cliffs, intertidal platforms with sand and mud deposits (Photo 36), and small, sandy barrier beaches (Owens and Bowen, in press). This barrier system is the most extensive found in Canada and represents the major characteristic of this coastal environment.

Photo 35. Cavendish Beach, north shore of Prince Edward Island. The wide sand beaches are backed by extensive dunes and a tidal lagoon (August 1972).

Photo 36. Intertidal sand bars on a low, rocky section of coast in Hillsborough Bay, south Prince Edward Island. The sediments are derived from local erosion and the multiple linear bars have developed on the wide, gently-sloping intertidal rock platforms (mean tidal range is 1.9 m).

5.5 ATLANTIC NOVA SCOTIA

This environment has a resistant rocky coast that follows the regional southwest-northeast trends of the Appalachian system (Fig. 9, page 36). The coast is exposed to high wave-energy levels from the western North Atlantic, although it is somewhat sheltered from waves generated by winds out of the western quadrant. This is a lowland environment with relief less than 100 m, except for the northeast coast of Cape Breton Island which has an upland cliff shoreline. The rocks are predominantly resistant metamorphic and igneous outcrops that have been eroded by the glaciers and subsequently drowned to produce many local irregularities with large embayments and offshore islands. These resistant rocks provide very little sediment to the shore zone. In southeast Cape Breton Island and northern Chedabucto Bay less resistant sedimentary rocks outcrop and these have been eroded to form a deep embayment along a major fault (Fig. 9) (Owens, 1971). This section also has the only sizeable deposits of unconsolidated material and is a section of extensive local beach accumulations.

The tides along this coast range from 0.9 m at Sydney to 3.7 m at Yarmouth, but are generally less than 2 m (Fig. 25: Halifax, page 129). Winds are predominantly offshore and out of the west (Fig. 3, page 12), but this is nevertheless a high-energy coast. Wave generation is related primarily to winds associated with low-pressure systems and there is a marked increase in wave-energy levels in winter months. Occasional extra-tropical storms affect this coast, and these are most prevalent between July and October. Wave heights are slightly lower than off Newfoundland, but a maximum wave height of 11 to 14 m can be expected once each year (Neu, 1972), and wave heights greater than 4 m are common throughout winter months (Neu, 1971) (see also Cape North in Table 10, page 122). In sheltered bays and in the Gulf of Maine wave-energy levels are much lower than on the outer coast. Ice plays a relatively minor role in limiting wave activity. Shore ice forms in sheltered bays and persists for up to 4 months, but the exposed coasts remain generally ice-free. Some dampening of waves may occur in the offshore during heavy ice years when pack ice intrudes along the coast as it is moved south by the Labrador current.

The coastal geomorphology of this environment is primarily irregular, low rocky shorelines (Photo 37). Littoral sediments are scarce, except in east and southeast Cape Breton Island with only scattered pocket beaches in sheltered bays and coves in other areas. A few extensive beaches have developed where there are local sources of unconsolidated sediments (e.g., Martinique Beach). There are many lagoons and extensive marshes in sheltered sections due to the very irregular nature of the shoreline (Photo 38).

Photo 37. Low, resistant rocky coast, Chebucto Head, Halifax Harbour, N.S. This shoreline type is typical of much of the Atlantic coast of Nova Scotia.

Photo 38. River estuary and marshes in a sheltered section of the outer Nova Scotia coast: Musquodoboit Harbour.

5.6 BAY OF FUNDY

This is a large reentrant in the northeast Gulf of Maine. The characteristics of this environment are the large tidal ranges that are everywhere greater than 5 m. The funnel-shape of the Bay of Fundy results from fluvial and glacial erosion along southwest-northeast structural trends. The straight south coast is a resistant volcanic intrusion. In the upper bay erosion of relatively unresistant sedimentary rocks (Fig. 9, page 36) has led to the development of 2 large embayments (Minas Basin and Chignecto Bay) that are separated by a resistant upland area. The relatively straight north shore is an upland coast of resistant crystalline rocks.

Tides and tide-generated processes dominate the littoral and nearshore zones of this environment. The mean tidal range increases from 5 m at the entrance of the Bay to greater than 10 m in Chignecto Bay and Minas Basin (Fig. 27, Photo 39). The tides are semi-diurnal (Fig. 25: Saint John, page 129) and due to the large volumes of water entering and leaving the bay, currents up to 1.9 m/s are common in constricted areas, with maximum velocities of greater than 5 m/s in Minas Passage. Due to the large tidal range, wave energy is dissipated over a considerable vertical height. The importance of waves generated in the Atlantic Ocean and Gulf of Maine decreases from west to east within the Bay. As winds are predominantly out of the

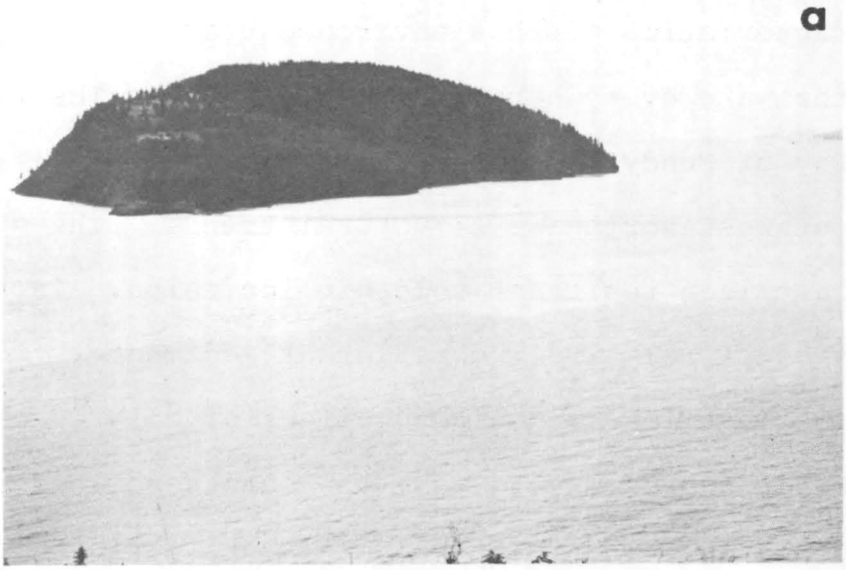


Photo 39. Five Islands, Nova Scotia at (a) high, and (b) low tides. The mean tidal range is 11.6 m and extensive mud flats are exposed at low tide.

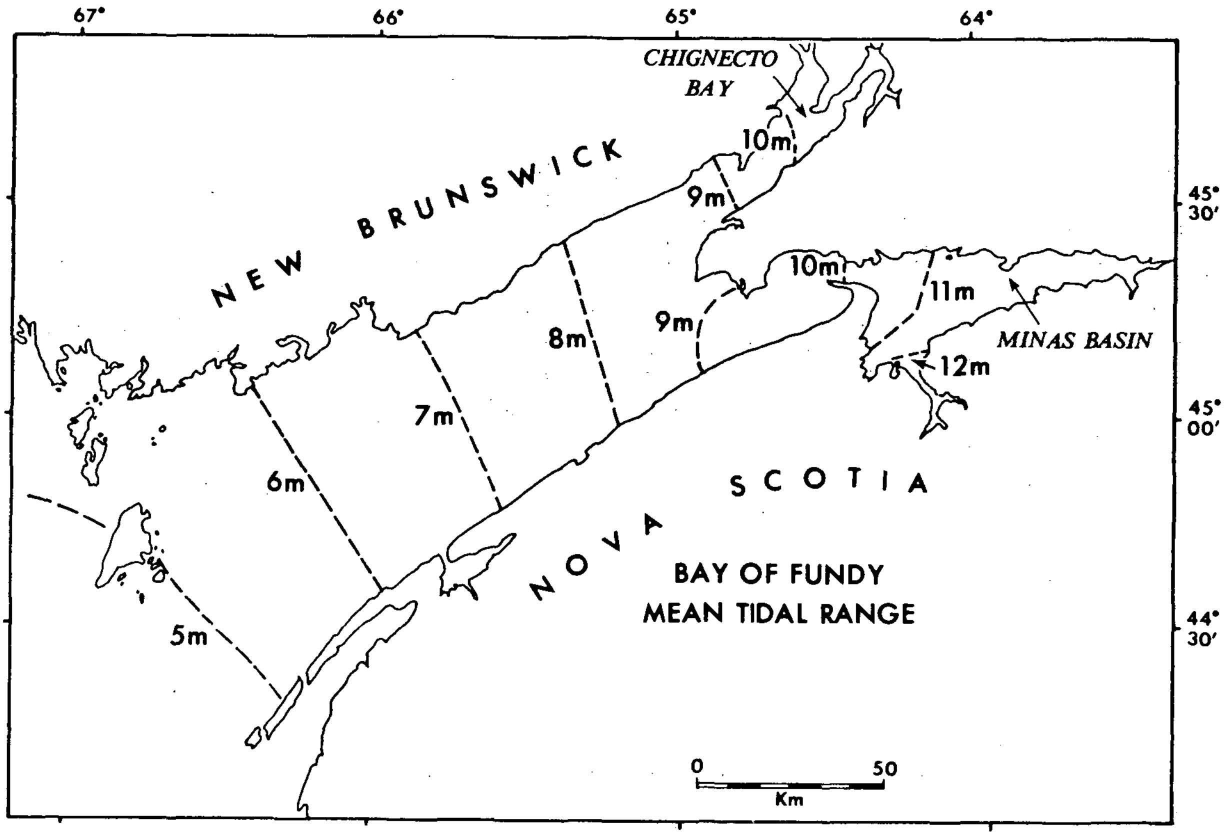


Figure 27. Tidal range in the Bay of Fundy.

west, local waves are generated along the axis of the Bay. Wave heights are greater than 3.6 m during summer months and are greater than 4.0 m during winter months for 10% of the time (Swift et al, 1973). Ice is present on the shoreline in most areas from January to April, particularly in sheltered sections, but the sea ice is constantly in motion due to the strong tidal currents. Shorefast ice develops and is particularly important in Chignecto Bay and Minas Basin from late December until mid-April (Knight and Dalrymple, 1976).

The coastal geomorphology is primarily rocky coasts, with cliffs up to 200 m in some areas (Owens, 1977b). The south shore has wide intertidal platforms that in eastern areas are covered with coarse sediments. This platform is backed by cliffs up to 30 m in height (Photo 40). Large beaches with

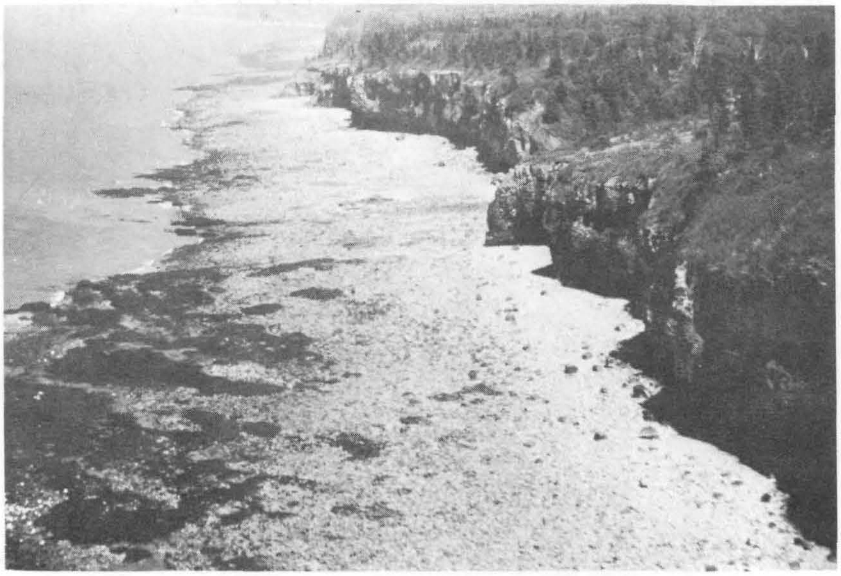


Photo 40. Southeast coast of the Bay of Fundy, east of Digby Gut, at low tide. The wide (c. 150 m) intertidal rock platform is mantled by pebble-cobble sediments and at the high-water level gives way to resistant cliffs (May 1976).

mud flats in the lower intertidal zone occur in large embayments at the head of the Bay, where sediment is trapped as it is transported alongshore (Owens, 1977b). In Minas Basin and Chignecto Bay the intertidal platforms are up to 5 km wide and are mantled by extensive mud or sand deposits (Photos 39 and 41) (Klein, 1970; Dalrymple *et al.*, 1975). The north shore has predominantly rocky coasts with few accumulations of littoral sediments.

Photo 41. Sand waves exposed at low tide on the wide intertidal flats east of the Avon River estuary on the south shore of Minas Basin. These sand waves are up to 1 m high, are spaced approximately 5 m apart and are migrating from left to right in the lower part of this photograph.

5.7 SABLE ISLAND

Sable Island is a small sand deposit that lies approximately 200 km southeast of the mainland of Nova Scotia. This depositional remnant on the outer margin of the continental shelf is composed entirely of unconsolidated sands. The island, which is orientated west-east, is arcuate in shape (Photo 9, page 39) and is 37 km long with a maximum width of 1.5 km. The winds in this micro-tidal environment (tidal range 1.1 to 1.6 m) have a distinct seasonal variability with strong northeast winds in winter and lower velocity southwest winds in summer (Owens and Bowen, in press). The seasonal change in wind direction and velocity is reflected in the characteristics of the surface waves of this region. Offshore wave heights are greater than 2.5 m for 10% during summer months and 40% during winter months (James and Stanley, 1967).

The island is characterized by 2 dune ridges that parallel the north and south coasts. The dunes have been destroyed in the southwest section during historical times (since the 1850's) and the adjacent flat inland areas are regularly inundated during storms. James and Stanley (1968) suggest that there is a cyclical movement of sediment in the littoral and nearshore zones around the island and that the beaches undergo erosion in winter months and subsequent shoreward transport of material during the summer. Cameron (1965) determined that the west end of the island has eroded 14.5 km in the last 200 years, while the east end has accreted 17.7 km. It appears, therefore, that the island is not being reduced in size at the present, but rather is migrating slowly eastward on the shallow shelf (James and Stanley, 1967). The higher overall levels of wave energy on the north shore give that coast a beach that is both narrower and steeper than that on the south-facing coast (Photo 42).

Photo 42. View to the south across an eastern section of Sable Island. A large overwash channel has cut through the dunes on the north shore (indicated by the arrow).

PART 6 - COASTAL ENVIRONMENTS OF THE GREAT LAKES

The Canadian shorelines of this series of large lakes have been subdivided into 9 coastal environments (Fig. 28, Table 11) on the basis of geology and shoreline types. The coastal processes are relatively uniform throughout the lakes system, which is a sheltered, non-tidal environment.

Coastal studies by Rukavina, St. Jacques and Coakley (see references), provided a great deal of the information used for the discussion of the lower Great Lakes. Little work has been carried out in the remainder of the region. The Great Lakes Sailing Directions (C.H.S., 1976) and B.A.M. Phillips (Lakehead University, pers. comm.) were primary information sources for the upper Great Lakes.

6.1 SOUTHERN ONTARIO

This large section of coast, which includes all of Lake Erie and most of the Lake Ontario shoreline, is considered a single environment as the coastal geomorphology is relatively constant between the two systems. The bedrock of this flat lowland area is mantled by extensive glacial deposits of sand and clay. The major relief feature is the Niagara Escarpment that extends west-east between the two lakes (Fig. 13, page 45). The relatively resistant limestones associated with this escarpment form a narrow upland belt that dams the waters of Lake Erie and parallels the south shore of Lake Ontario.

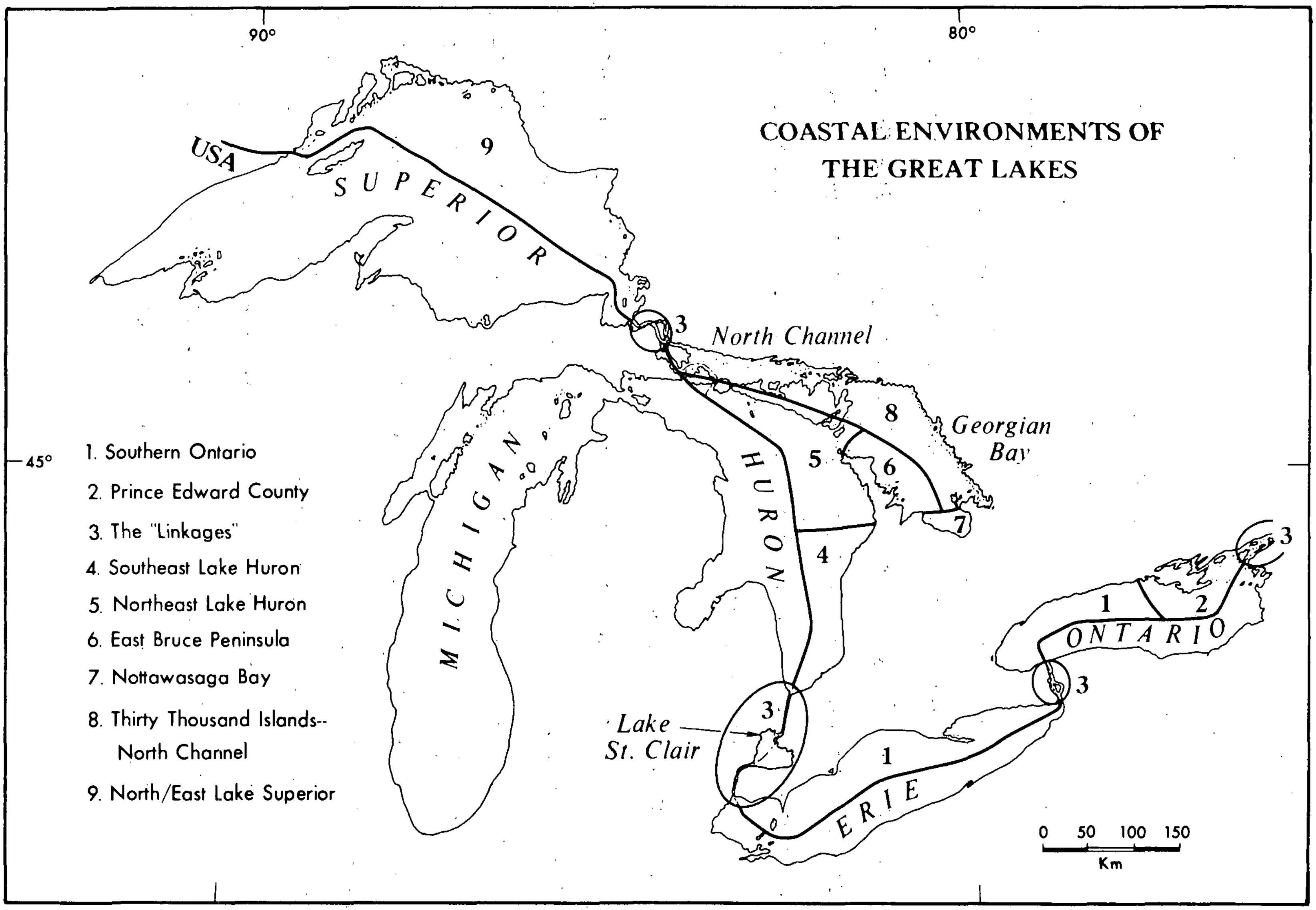


Figure 28. Coastal environments of the Great Lakes (see Table 11).

TABLE 11. Characteristics of Great Lakes Coastal Environments

	GEOLOGICAL CHARACTER	COASTAL ZONE BACKSHORE RELIEF	COASTAL ZONE BEACH CHARACTER	FETCH AND WAVE EXPOSURE	SEDIMENT AVAILABILITY
1. Southern Ontario	Sedimentary rocks overlain by extensive unconsolidated sand and/or clay deposits.	Eroding cliffs 5-20 m in general: maximum 110 m.	Mixed sand/pebble at base of the cliffs: 5 large sandy depositional features.	Maximum 400 km east-exposed, west-sheltered. Lake ice for 3 - 4 months.	Abundant
2. Prince Edward County	Relatively resistant limestones - thin cover of glacial deposits, topography trends SW/NE.	Cliffs generally 5-10 m: maximum 30 m.	5 sandy bayhead barriers in west, with dunes: elsewhere narrow or sand/pebble.	South and west exposed up to 400 km, east very sheltered. Lake ice for 3 - 4 months.	Abundant in west; elsewhere very scarce.
3. The "Linkages"	Predominantly resistant rocks.	Usually low.	Absent or pebble-cobble riverine beaches.	<50 km, very sheltered, dominantly a fluvial environment.	Very scarce (except for St. Clair delta).
4. Southeast Lake Huron	Sedimentary rocks overlain by unconsolidated sand and/or clay deposits.	Eroding cliffs, usually low: 5-30 m.	Beaches of sand to boulder range near cliffs; predominantly sand in the south.	Maximum 300 km (to northwest). Moderate wave energy levels. Ice 3-4 months.	Abundant.
5. Northeast Lake Huron	Resistant dolomite: dips below lake at a low angle.	Low relief, many islands and reefs.	Absent or pocket beaches of pebble/cobble.	Exposed to south and west, moderate wave energy levels.	Very scarce.
6. East Bruce Peninsula	Resistant dolomite escarpment.	High relief: cliffs up to 100 m.	Absent or pocket beaches.	Sheltered.	Scarce
7. Nottawasaga Bay	Sedimentary rocks overlain by unconsolidated sand and/or clay deposits.	Usually low relief.	Sandy bay-head barrier.	Exposed to northwest: otherwise sheltered.	Locally abundant.
8. 30,000 Islands - North Channel	Resistant Shield rocks on mainland, resistant dolomite and limestones on Manitoulin Island.	Low or upland coast - cliffs up to 50 m.	Absent or narrow, pocket beaches.	<150 km, very sheltered. Lake ice 3-5 months.	Very scarce.
9. North Shore Lake Superior	Resistant Shield rocks.	High relief, cliffs up to 300 m.	Absent or narrow, pocket beaches.	Up to 500 km, exposed. Lake ice 3-4 months.	Very scarce.

Elsewhere relief is low and the shoreline trends result from the formation of two large northeast-southwest orientated, elongate basins that were scoured by the Pleistocene ice sheets. Lake Erie is very shallow, average depth 20 m, with maximum depths of 64 m in the northeastern section of the lake (Fig. 10, page 41). Lake Ontario is more trough-shaped, with the deepest portion (maximum 244 m) lying on an axis parallel to the south shore (Hough, 1968), and has a narrower nearshore zone than Lake Erie (Rukavina, 1976, Fig. 1).

Winds are primarily out of the west, along the axis of the lakes, so that maximum fetch distances (up to 400 km) coincide with the prevailing and dominant winds. Wave-energy levels increase from west to east in both lakes. Significant wave heights are greater in winter months and throughout the ice-free period wave heights greater than 1 m can be expected for 50% of the time (Table 12). The maximum significant wave heights are in the order of 9 m for Lake Ontario in March (0.04% probability; once in 7 years), and 8 m for Lake Erie in November (0.15% probability; once in 2 years) (Richards and Phillips, 1970). Maximum wave periods are in the order of 6 to 7 seconds for Lake Ontario (Brebner and LeMéhauté, 1961). Wave heights are greatest during the period November to April and at a minimum from June to August. Ice plays an important limiting role on wave action from mid-December to mid-April (Fig. 6: Cornwall, Hamilton and Windsor, page 26). Lake Erie freezes over most winters, but Lake Ontario

TABLE 12. Selected Significant Wave Height Probability

	Lake Ontario		Lake Erie		Lake Huron		Lake Superior	
	>1m	>2m	>1m	>2m	>1m	>2m	>1m	>2m
January	63%	15%	72%	11%	77%	10%	48%	4%
April	50%	4%	62%	7%	52%	4%	44%	4%
July	3%	-	3%	-	4%	-	4%	-
October	47%	3%	58%	2%	68%	5%	45%	4%

Note: These values are computed for a fetch length of 170 km, (from Richards and Phillips, 1970).

which is deeper and has a larger volume of water, and therefore more stored heat, has frozen over only twice in 100 years. Usually Lake Ontario has a maximum ice cover in the order of 15% of the surface area.

Lake levels for Lake Erie varied over a range of 1.5 m between 1900 and 1975, with seasonal fluctuations in the order of 0.5 m (Fig. 11, page 43) (Clemens, 1976). Lake Ontario levels varied over a range of 1.95 m with similar seasonal fluctuations.

For both lakes, low lake levels occur in January-February and the seasonal high is in June (Laidly, in Pincus, 1962). Wind set-up and set-down are important in both lakes, but particularly so in Lake Erie where water-level variations up to 2 m can occur at either end of the lake (Clemens, 1976) (Fig. 12, page 44). In lowlying sections high lake levels frequently result in flooding of backshore areas (Boulden, 1975).

The coastlines of this environment are predominantly low, eroding cliffs of unconsolidated sands and clays. Maximum cliff heights of 110 m occur in the Scarborough Bluffs, just east of Toronto Harbour in Lake Ontario, and in places the rates of erosion reach 3 m/year, although the average is less than 0.3 m/year for this section (Matyas et al., 1974). In general, cliff heights range from 5 to 50 m, and erosion rates vary spatially and temporally depending on exposure to waves, lake levels, cliff height, and the nature of the cliff material (Environment Canada and Ontario Min. of Nat. Resources, 1975). Beaches at the base of the cliffs are absent or are of sand-pebble material. On the extreme northeast coast of Lake Erie bedrock outcrops in the shore zone to give a series of headlands, separated by sand beaches, that interrupt the general straight trend of this coast (Rukavina and St. Jacques, 1971).

Cliff erosion and littoral sediment transport have led to the development of several large accretional features. Along the northeast coasts, sediments are transported towards the east (Rukavina, 1976). In Lake Ontario (Fig. 29) this has produced the bay-head beaches of the Prince Edward County area

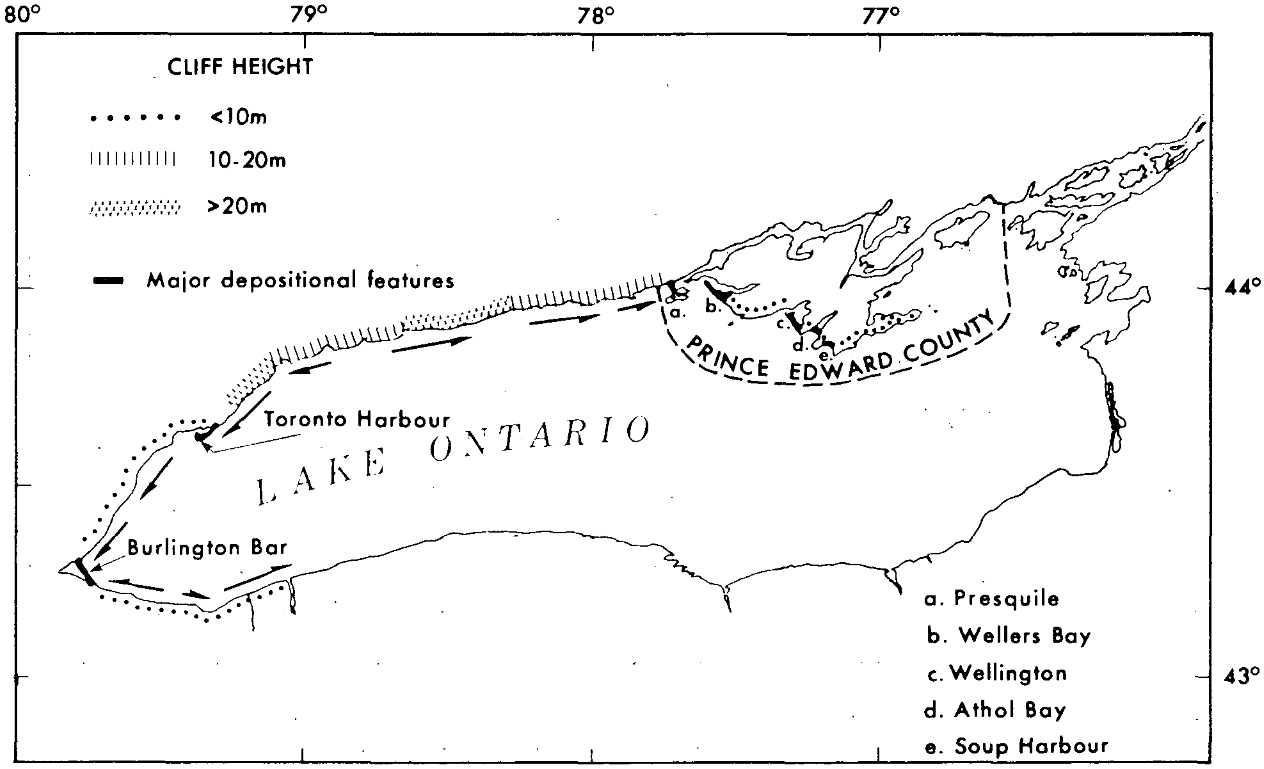


Figure 29. Lake Ontario: cliffs, sediment transport directions, and depositional features (compiled from various sources).

(see below) and in Lake Erie the 40-km long spit of Long Point (Fig. 30) is prograding at a rate of 7 m/year and has dunes up to 10 m in height (Wood, 1960; St. Jacques and Rukavina, 1973). In western Lake Ontario sediment is moved to the southwest from Scarborough Bluffs, towards the spit that encloses Toronto Harbour. Little material passes the end of this spit system (Coakley, 1970), but at the southwest end of the lake sufficient

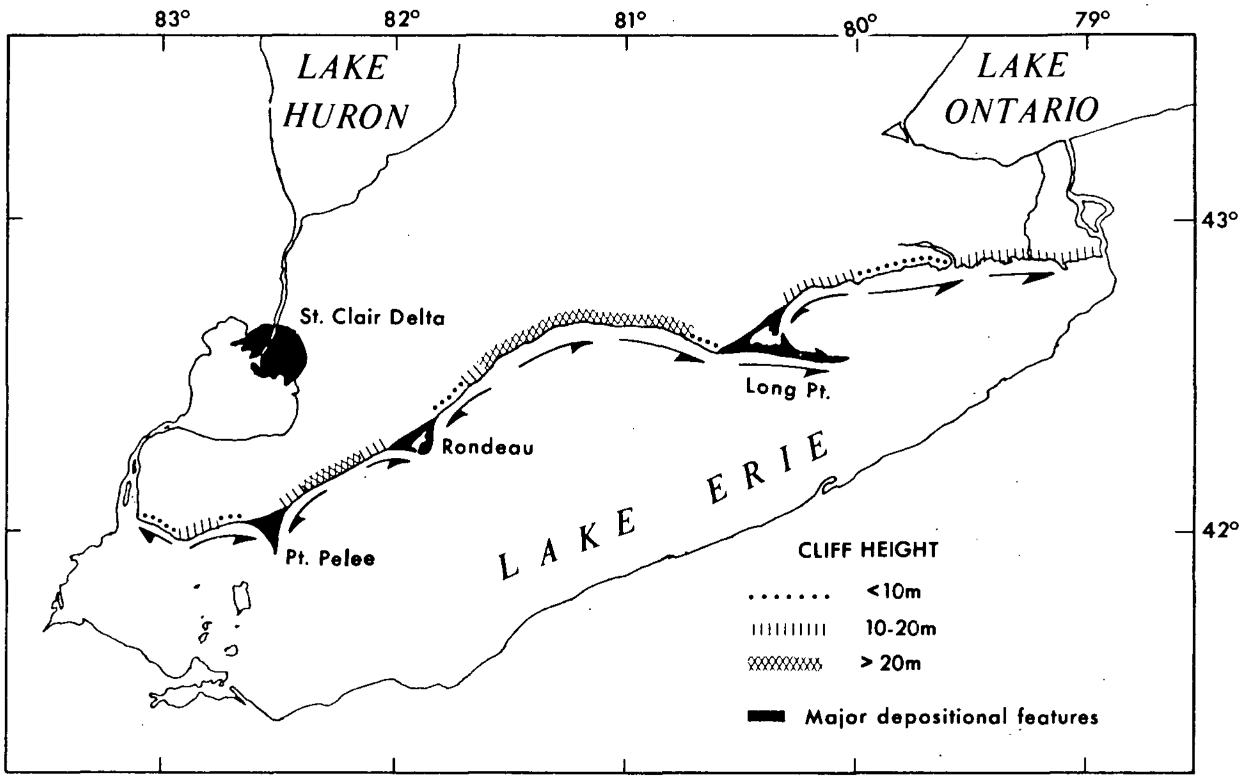


Figure 30. Lake Erie: cliffs, sediment transport directions, and depositional features (compiled from various sources).

material has accumulated by longshore transport along the north and south shores for a large barrier to form across Hamilton Harbour and enclose an extensive bay area (Fig. 29) (Rukavina, 1969). In the sheltered southwest shore of Lake Ontario, material fed into the littoral zone from cliff erosion often accumulates locally due to the inability of wave-generated currents to transport the sediments alongshore (Rukavina, 1969). In western Lake Erie sediment is similarly moved towards the southwest along the north shore and two large forelands have developed

(Rondeau Point and Point Pelee) (Fig. 30). No information is available for Rondeau but Point Pelee is migrating slowly to the west and is presently being eroded (Coakley, 1976). The three large depositional features on the north shore of Lake Erie have developed on submerged moraines (q.v.) (Rukavina, 1976). In western Lake Ontario there is a seasonal variation in the nearshore morphology with elevation changes up to 1 m. This variation is related to changing lake levels and to storm frequency. Erosion in early spring and mid-summer is followed by recovery in late summer and fall and by a relatively stable situation in winter months (Rukavina, 1974).

The primary characteristics of the coastal geomorphology of this unit are a straight shoreline of eroding, unresistant cliffs, with areas of sediment accumulation that are fed by the longshore transport of material eroded from the cliffs.

6.2 PRINCE EDWARD COUNTY

This environment in northeast Lake Ontario is an area of local high relief (76 m above lake level) formed by an outcrop of relatively resistant limestones. Glacial deposits occur in this environment, but they are less extensive and generally thinner than in other parts of southern Ontario. The limestones were eroded along southwest-northeast trending axes by the ice sheets to produce a series of depressions that parallel these trends.

The prevailing winds are out of the southwest, parallel to the long axis of Lake Ontario, so that the southwest-facing beaches are exposed to maximum wave-energy levels in the lake (Table 12, page 149). The northeast section is a sheltered wave environment and in many parts of this indented coast wave-energy levels are very low. Ice limits wave activity on the shoreline from mid-December to mid-April (Fig. 6: Cornwall, page 26).

Seasonal variations in lake levels are in the order of 0.5 m and short-term variations due to wind set-up are particularly important when strong winds parallel the axis of the lake (c.f., Fig. 12, page 44).

The coastal geomorphology of Prince Edward County is characterized by exposed rock headlands and cliffs, bay-head barrier beaches and sheltered environments with marshes. Along the south coast the resistant limestones form cliffs with accumulations of pebble-cobble material in sheltered sites that is derived from local erosion. In western sections erosion on this exposed section of shoreline has produced wide, flat rock platforms that extend offshore up to 1 km (Photo 43). Five large bay-head barriers have developed across the southwest-northeast orientated depressions at Presqu'ile, Wellers Bay, Wellington Bay (West Bay Bar), Athol Bay (East Bay Bar), and Soup Harbour (Fig. 29, page 151). The sheltered sections created by these barriers have extensive marshes. The southerly protruding outcrop that forms

Photo 43. Exposed rock platform near Wellington Bay, Prince Edward County, Ontario.

the Prince Edward County area interrupts the west to east longshore transport of sediments that are eroded from the bluffs on the north shore of Lake Ontario. These littoral sediments have been trapped in reentrants that were formed by glacial erosion to produce the large sandy barriers (Rukavina, 1970). Dunes have developed up to 3 m in height on West Lake Bar (St. Jacques and Rukavina, 1972) and are up to 6 m on the Wellers Bay barrier. Each of the five barriers is a separate feature and is bounded by rocky headlands. In contrast to the sandy barriers in the northwest of this environment (Photo 44), pebble-cobble beaches predominate to the east of Athol Bay (St. Jacques and Ruakvina, 1972). The north and east coasts of Prince Edward

Photo 44. Low, sand barrier beach, West Bay Bar, near Wellington, Prince Edward County, Ontario (May 1969).

County are a series of large bays and channels that include the long, narrow, winding Bay of Quinte. This is a very sheltered, low wave-energy environment that has many rocky shores with marshes in the bays and coves.

6.3 THE "LINKAGES"

This environment is composed of the St. Lawrence River, the Niagara River and Welland Canal, the St. Clair River-Lake St. Clair-Detroit River section, and the Sault St. Marie area. Each of these components is a link within the Great Lakes system, but as these are fluvial environments (with the exception of Lake St. Clair) or narrow channels, and not strictly coastal environments, this unit is discussed only briefly.

The St. Lawrence River, including Lake St. Francis, Lac St. Louis and Lac St. Pierre, extends 500 km from the northeast corner of Lake Ontario to Ile d'Orléans at the head of the St. Lawrence Estuary. In the southwest, an extension of the resistant granite Shield rocks (the Frontenac Axis) (Fig. 13, page 45) dams the waters of Lake Ontario and is a section of many islands and bays (the Thousand Island region) that has many gradient changes. Between Lake Ontario and Montréal the river level drops 69 m and has been modified by the construction of the St. Lawrence Seaway, a 290-km section of locks and canals for navigation. East of Montréal, the river has been deepened by dredging, but otherwise remains unmodified. Between Lac St. Pierre and Ile d'Orléans, the water is fresh but is subject to tidal reversals, with a mean tidal range of 1.9 m at Grondines that increases to 4.1 m at Québec City (C.H.S., 1976 and 1977). East of Ile d'Orléans, the channel widens and the water becomes brackish as the river merges with the estuary of the St. Lawrence.

Although low amplitude, choppy waves can develop in the narrow lakes and in the wider parts of the channel, this is a very low wave-energy environment, dominated by fluvial processes. Ice is present from mid-December to mid-April (Fig. 6: Montréal, page 26). The ice on the river moves as a pack, rather than as a solid cover, and forms on the shorelines as a type of ice foot (q.v.). The shorelines are predominantly narrow, rocky outcrops or pebble-cobble riverine beaches. In extreme Eastern sections, where tides become a factor, intertidal mud flats are common.

The 56-km long Niagara River drains the upper lakes into Lake Ontario and cuts across the resistant dolomites of the Niagara Escarpment, that acts as a dam to the waters of Lake Erie. The river drops a total of 99 m between the two lakes (Fig. 10, page 41), including a 51 m drop as it crosses the northern edge of the escarpment (the Niagara Falls). This section of the linkage system is a fluvial environment. To the west of the river, the locks of the 44.4 km Welland Canal provide shipping access between the two lakes.

Lakes Huron and Erie are joined by the St. Clair River (63 km, with a 1.7 m fall), Lake St. Clair, and the Detroit River (51 km). A large delta has formed in the northeast part of Lake St. Clair where the river enters the lake. This delta has numerous large distributary channels and contains many islands and low marshes (Pezzetta, 1973). The maximum fetch distance in the lake is 42 km, so that this is a very low wave-energy environment. The east coast of Lake St. Clair, north of the Thames estuary, is a low, dyked marsh section that is very susceptible to flooding during periods of high lake levels. South and west of the Thames, very narrow beaches and low (5 m), eroding bluffs predominate. The remaining sections of this linkage are fluvial environments.

The rapids of the Sault St. Marie between Lake Superior and Lake Huron have formed where resistant Shield rocks form a barrier to the waters of Lake Superior (Fig. 13, page 45). Canals and locks have been constructed to allow navigation between the two lakes, which have an elevation difference of 7 m. This is a river-dominated environment with predominantly rocky shores.

6.4 SOUTHEAST LAKE HURON

Between Sauble in the north and Sarnia in the south, the southeast coast of Lake Huron is characterized by cliffs of unconsolidated glacial deposits and sand or sand-pebble beaches. The cliffs are composed predominantly of sand or clay materials and rise to maximum heights of 50 m, although in general heights are between 5 to 30 m. Erosion of these unresistant cliffs provides material directly to the littoral zone for reworking by wave action.

Wave generation by the prevailing westerly winds is limited by a short fetch (120 km) (note: the wave data shown in Table 12 (page 149) is for a fetch of 170 km). As the coast is open to longer fetches from the northwest (up to 300 km), waves generated from this quadrant can attain greater heights, particularly during ice-free winter months. This causes a net movement of sediments to the south in the littoral zone of this coastal unit (Quigley et al., 1974). Maximum wave heights occur in winter months and waves in the order of 9.5 m could be expected approximately once in 4 years (Richards and Phillips, 1970). Ice is present on the lake or on the beaches for up to 4 months each year (January to early April). Superimposed on long-term variations in lake levels (that are in the order of 2 m, Fig. 11, page 43) are seasonal variations and storm surges of approximately 1 m or less. These variations can have a marked effect on erosion rates, particularly if high lake levels coincide with high-energy storm waves.

The coastline of this low-lying environment is relatively straight, as littoral processes have eroded the unresistant cliffs and have deposited the products of this erosion across river exits and bays. In low-lying sections sandy barriers with backshore dunes enclose sheltered bays where marshes have developed. Adjacent to the eroding cliffs, beaches are narrow and are frequently composed of a mixture of sand and coarse sediments (pebbles-cobbles-boulders). Northeast of Clark Point and southwest of Grand Bend, sand beaches predominate.

6.5 NORTHEAST LAKE HURON

The morphology of the western Bruce Peninsula and southern Manitoulin Island is primarily controlled by the outcrop of a band of resistant Niagara dolomite. This outcrop trends north through the Bruce Peninsula, then curves towards the west through Manitoulin Island and then south to form the western shore of Lake Michigan (Fig. 13, page 45). This resistant limestone escarpment effectively separates North Channel and Georgian Bay from Lake Huron. The outcrop dips south and west, towards the centre of a basin located between Lakes Michigan and Huron (Fig. 14, page 46). The rocks of this part of the Lake Huron coast, therefore, dip towards the central part of the lake at low angles. Glacial deposits are discontinuous and often thin, and this region has a rugged appearance, with local elevations up to 150 m above lake level.

This coast has fetch distances of 300 km to the south and 200 km to the southwest and is exposed to the highest wave-energy levels that can be generated on the lake. Wave heights of 5.7 m can be expected to occur on the average once each year (Cole, 1971). In general, wave heights do not exceed 3 m, except for brief periods during winter months (Richards and Phillips, 1970). Ice limits wave activity during the period from late December to early April. Lake-level variations up to 0.5 m occur annually. However, unlike coasts of unconsolidated cliffs, water-level changes are of less importance on rocky coasts except in sections where there are local beach deposits.

The coasts of northeast Lake Huron are characterized by a low rocky shore zone, that has many reefs and islands offshore. This type of shoreline results from the low slope of the shales, limestones and dolomites that dip below the lake (Lewis, 1970). The general curved nature of the coast results from the saucer-shape of the Michigan Basin (Fig. 13, page 45). Although this is predominantly a rocky coast, pocket beaches of sand or sand-cobble sediments are common. These beaches are derived from the products of local cliff erosion and are more extensive where there are deposits of glacial sediments on the coast.

6.6 EAST BRUCE PENINSULA

By contrast to the west coast of the peninsula, where the rocks dip into the lake at a low angle, the east coast is the resistant edge of the dolomite Niagara escarpment (Fig. 13, page 45). This rugged, indented rocky coast has cliff heights between 30 and 70 m, with a maximum of 110 m. South of Cape Croker the cliffs are eroded into unconsolidated sediments, predominantly clays. Although this cliff coast is composed of relatively resistant dolomites and unconsolidated sediments, rates of erosion are low throughout this environment because of the sheltered nature of this part of Georgian Bay. Many of the cliff faces are buried in their lower sections by accumulations of talus. Prevailing winds blow offshore and the maximum fetch lengths are only 75 km (to the northeast) and 115 km (to the north). Wave-energy levels are considerably lower than on the west coast of the Peninsula. A few small pebble-cobble beaches have developed in embayments; these are predominantly of pebble-cobble size material.

6.7 NOTTAWASAGA BAY

This small bay at the southern end of Georgian Bay was eroded between the Niagara escarpment to the west and the Shield rocks to the east (Figs. 13 and 14, pages 45 and 46). The head of the bay is similar to a very large pocket beach and it acts as a sediment trap for material eroded from the two adjacent shores of the bay. In one section of this predominantly sand beach coast, at Wasaga Beach, sediments have accumulated to form a large (9.5-km long) barrier that is backed by a wide dune system (Martini, 1975). The beaches at the head of this bay face the north-northwest and are exposed to a maximum fetch of 200 km along the axis of Georgian Bay. This is, however, a sheltered wave-energy environment.

6.8 THIRTY THOUSAND ISLANDS - NORTH CHANNEL

The mainland coast is the edge of the exposed, resistant Shield (Fig. 13, page 45) and the rocks are predominantly pink or gray granites. The south coast of North Channel (Manitoulin Island) is a resistant outcrop of limestones and dolomites that are part of the Niagara escarpment system (Fig. 13) but lower than on the west Bruce Peninsula. Coastal relief is generally low and in all sections the shoreline is very irregular, with many inlets, islands and reefs. As the resistant rock outcrops are only occasionally covered by thin patches of unconsolidated sediments little material is available for shoreline erosion and the beaches are narrow and of pebble-size (B.A.M. Phillips, pers. comm.) sediments.

Georgian Bay is largely sheltered from waves generated in Lake Huron. This coastal environment is one of low or moderate wave-energy levels. With the irregular nature of the coast, many sections of the shoreline are in very sheltered environments. Georgian Bay and North Channel freeze over during winter months and ice can be expected on the beach and in sheltered nearshore environments from mid-December to late April.

The coastal geomorphology of this environment is predominantly low, rocky, irregular shorelines. This rugged character is interrupted by small beaches, usually of pebble-cobble sediments, and by sections of upland, rock cliffs that are generally between 5 and 20 m in height, occasionally reaching 50 m. Where beaches enclose lagoons, or in sheltered inlets, marshes have developed (B.A.M. Phillips, pers. comm.). Beaches are limited in size and extent by the scarcity of littoral sediments.

6.9 NORTH SHORE LAKE SUPERIOR

The Canadian coast of Lake Superior lies entirely within the zone of resistant Shield rocks (Fig. 13, page 45). Except for the section near Sault St. Marie, local relief is high, particularly in northwestern sections, and coastal cliffs of 50 to 100 m are common. At Thunder Cape, cliff heights are in the order of 300 m. The resistant Shield rocks have little surficial material.

Fetch lengths vary between 250 and 500 km and most of the coast is exposed to relatively high wave-energy conditions. Maximum wave heights occur in November (Table 12, page 149) (Ploeg, 1971), with waves of 9.1 m occurring on the average once each year (Cole, 1971) and waves of 11.3 m can be expected once in four years (Richards and Phillips, 1970). Ice is present for at least four months each year, beginning to form on the shoreline and in bays and harbours between late December and mid-January (Fig. 6: Port Arthur, page 26). The lake may freeze over briefly some years but usually the central part remains open (Marshall, 1967). The ice decays during April and the beaches are usually ice-free by May. Annual fluctuations in lake levels are in the order of 0.6 m, but storm surges up to 2 m can occur. The lake has the lowest long-term variation in water levels, approximately 1.13 m (Fig. 11, page 43).

The character of the coast of northern Lake Superior is predominantly one of a bold, rocky shoreline, often with high cliffs and deep bays. The northwest coast has high cliffs, up to 300 m, that have very large talus slopes. From Nipigon to Wawa, relief is high inland but cliffs are not common and the coast is predominantly low, resistant rocky shorelines (c.f., Photo 37, page 136). This rocky coast is interrupted by beaches that are supplied with sediment from small deltas. These deltas have accumulated at the mouths of rivers that erode material from former lake deposits in backshore areas (B.A.M. Phillips, pers. comm.). The eastern shore, south of Wawa, is a section of low relief, irregular shoreline, large embayments and shallow water. Sediments are relatively abundant and numerous barriers or spits have developed, predominantly of sand-sized sediments (B.A.M. Phillips, pers. comm.).

PART 7 -

LITTORAL PROCESSES, COASTAL GEOMORPHOLOGY AND OIL SPILLS

7.1 INTRODUCTION

The preceding chapters illustrate the great variety of climatologic, oceanographic and geologic environments that are found in the coastal zones of Canada. One result of this high degree of variability is that the impact, distribution and persistence of oil differs considerably from one coastal environment to another. The application of a geographic or a thematic approach (Owens, 1977a, page 77) for all of Canada's coasts would involve innumerable permutations and combinations of littoral processes and shoreline types; these approaches would be both repetitive and inordinately lengthy.

A more basic approach that is developed in this report involves discussion of the fundamental relationships between oil spills and littoral processes, as well as consideration of the behaviour of oil on different shoreline types. This fundamental approach requires a knowledge of the characteristics of the major types of oil and of the mechanics of weathering. These are discussed briefly in the first section (7.2). The approach also requires an understanding of some of the basic process and form interactions that control the character of the shoreline. The second section (7.3, page 174) achieves this by an examination of the effects of littoral processes on oil followed in section

7.4 (page 232) by a discussion of the impact and persistence of oil in relation to coastal geomorphology. Within each section the major points are summarized at the end of each part of the text discussion in italics.

7.2 GENERAL CONSIDERATIONS

The Chemical and physical characteristics of the oil that is deposited on the shoreline are the primary factors in assessing the impact and expected persistence of the contaminant. Oil types vary widely from light, volatile, refined oils (such as gasoline) to tarry lumps that are almost solid. In addition, the impact and persistence of oil is related to the processes by which the oil degrades. Weathering and aging are discussed here briefly in terms of the basic processes only: other important factors, such as climate and temperature, are considered in the regional aspects of a spill (Part 8, page 313).

Types of Oil

Crude oils vary considerably in their chemical and physical properties. Louisiana crude is very light, whereas Arabian or Venezuelan crudes are generally heavy and sometimes almost asphaltic. Oil is composed of a wide range of compounds, from light gases to heavy solids (see Appendix, page), and the various refined oils result from a distillation process that uses increasing temperatures to separate groups of compounds. Crude or refined oils can be categorized into 3 broad groups:

(1) Liquid or free-flowing oils (such as unweathered light crudes, aviation gasoline, diesel fuels, kerosenes, and most other refined oils). These are generally very volatile and have high rates of evaporation. The oils of this group have a low viscosity and float on water but rarely form emulsions.

(2) Very viscous oils (such as heavy crudes, weathered light crudes, and Bunker fuels). These are less volatile due to the lower amounts of light fractions that result from either refining processes or from natural evaporation. The oils of this group float on water and readily form emulsions (for example, "chocolate mousse" - a water-in-oil emulsion).

(3) Semi-solid or tarry oils (such as asphalt or weathered crudes). These are non-volatile and are very viscous at normal (<38°C) temperatures. They may float on water or sink, and do not emulsify.

One of the most important physical properties of oil, in terms of impact on the shoreline, is the pour point. This is the temperature below which the oil will not flow. If the ambient temperature is below the pour point the oil behaves like a solid mass (Otto, 1973). For the many different petroleum types these temperatures range between -57°C and +32°C but the majority of oils have a pour point below 0°C and are, therefore, fluid on water surfaces. The Bunker C oil spilled by the tanker "Arrow" in February 1970 had a pour point of -1.1°C. As the waters of Chedabucto Bay were below this temperature at the time of the spill, the oil on the water had a semi-solid consistency by the time it reached the coasts (Task Force, Operation Oil, 1970). Once on the shoreline, surface temperatures of the oil were raised above the pour point, as air temperature and sunlight (solar radiation) increased in spring and early summer, so that the oil began to flow and to penetrate deeper into the beach sediments. Similarly the oil spilled by the "Irving Whale" had a pour point of 11.1°C and congealed upon contact with seawater (Ages, 1971).

Gasoline and other free-flowing oils are always at temperatures above their pour point whereas semi-solid or tarry oils are usually below their pour point and will only flow when exposed to relatively high ambient temperatures (>15°-25°C). As a result of this difference, the free-flowing oils rapidly penetrate most beach sediments whereas the semi-solids tend to be deposited on the surface and will only penetrate if the sediments are coarse (for example, pebbles or cobbles that have large voids between particles) or if ambient temperatures are high.

Persistence of Oil

The rates at which oil degrades (i.e., its physical properties and/or chemical composition change) is a function of weathering and aging. The processes by which this takes place are bio-degradation (particularly microbial oxydation), evaporation, dissolution and photo-oxydation. The primary factors that control rates of degradation are the initial composition and the physical nature of the oil, in particular volatility, fluidity and density (Otto, 1973). As oil is a compound mixture of many different hydrocarbons, each of which has its own boiling point, the ambient temperature is usually above the boiling point of some of these compounds (methane, for example, has a boiling point of -164°C). Because of their low boiling points the light (volatile) fractions evaporate when exposed to the atmosphere.

Another major factor in degradation is the amount of available energy; this energy can be either thermal or mechanical, or can be the result of biochemical processes. Thermal energy is related to air or water temperatures and as these increase so do rates of most weathering processes. Inputs of thermal energy result in both physical and chemical changes. Temperatures vary considerably both in space (geographically) and in time (daily and seasonally), so that when an oil spill occurs the local climate and the time of year are critical elements in estimating the persistence of the oil. For example, oil spilled in an arctic environment during winter months will degrade at considerably lower rates than the same oil on a Lake Ontario beach in August. Sittig (1974) notes that microbial action is reduced in arctic environments as bacterial metabolism is low and because oil is more viscous at lower temperatures.

Mechanical energy is related to the action of waves, tides and winds that cause changes in the physical character of the oil. As a result of the mechanical dispersion and breakdown of oil by the hydraulic action of waves, greater surface areas are exposed to degradational processes because of an increased surface to volume ratio. For example, during periods of storm-wave activity the amounts of energy dissipated in the littoral zone increase, so that mixing and erosion are high and the oil is physically broken down into smaller particles. Newly exposed oil then undergoes rapid chemical changes, particularly the loss of light fractions.

The burial of oil decreases rates of degradation by reducing the input of mechanical energy and by insulating oil from surface radiation. Once oil is buried it can persist over long periods of time without physical or chemical change.

As oil weathers and changes chemically its physical properties also change. The process of emulsification, for example, leads to a lower viscosity so that oil flows more readily. On the other hand, as weathering progresses the lighter fractions are lost, leaving a more asphaltene residue, and the viscosity increases and the oil becomes less mobile (Rashid, 1974).

The salinity of the water is an important factor in rates of dissolution. With lower salinity the oil becomes more soluable. Therefore, in areas of low salinity or freshwater (such as the Great Lakes) the oil is more readily diluted and thinned.

Once oil reaches a quasi-equilibrium with local environmental conditions the rates of weathering decrease rapidly, until such time as these environmental conditions change. The latter can occur as temperatures increase during spring and summer months or as inputs of mechanical energy expose new surface areas of the oil. The important points are that the properties of spilled oil are in a constant state of change, and that the rate of degradation is particularly high immediately following exposure of oil to the atmosphere.

SUMMARY

(1) The physical and chemical characteristics of crude and refined oil vary considerably.

(2) "Light" oils have volatile components that readily evaporate on exposure.

(3) "Heavy" oils have a high viscosity and degrade more slowly.

(4) Rates of degradation depend on (a) the physical and chemical composition of the oil, and on (b) the available energy (thermal or mechanical).

(5) Buried oil degrades very slowly.

(6) *The physical and chemical characteristics of spilled oil change constantly.*

(7) *Rates of degradation are usually high immediately following a spill.*

7.3 LITTORAL PROCESSES AND OIL ON THE SHORELINE

Littoral processes can be broadly defined as those forces that act to form or change a shoreline. The primary interact-tions are related to waves and tides, but consideration must also be given to winds and to the effects of ice. The relationships between each of these 4 parameters are discussed in terms of the role that each parameter plays in shoreline development and dynamics. Consideration is also given to sediment transport systems (or the sediment budget), which involve the pathways of sediment movement and which determine whether there is a net loss or gain of sediments at a particular location. In addition, some of the ways in which oil on the shoreline modifies littoral processes are discussed.

7.3.1 Waves

Wave Energy and Oil

Wave generation results from the interaction between winds and gravity. Waves transmit energy through the water and the dimensions of a wave and the energy levels are determined partly by wind velocity and duration, and partly by fetch. When waves reach shallow water they are deformed, due to bottom friction effects, and on reaching the shoreline breakers form as orbital motions within the wave become unstable. The rush of water towards the shore that follows breaking of the wave is referred to as the bore and the uprush of water on a beach is termed the swash. Once the swash reaches its maximum level on the beach, water either infiltrates the beach sediments or withdraws down the surface of the beach (backwash). Within the nearshore zone the most important subdivisions, in terms of wave processes, are (1) the breaker zone, (2) the surf zone, and (3) the swash zone (Fig. 31). The single most important aspect of waves or wave-generated processes is that they dissipate energy in the littoral zone.

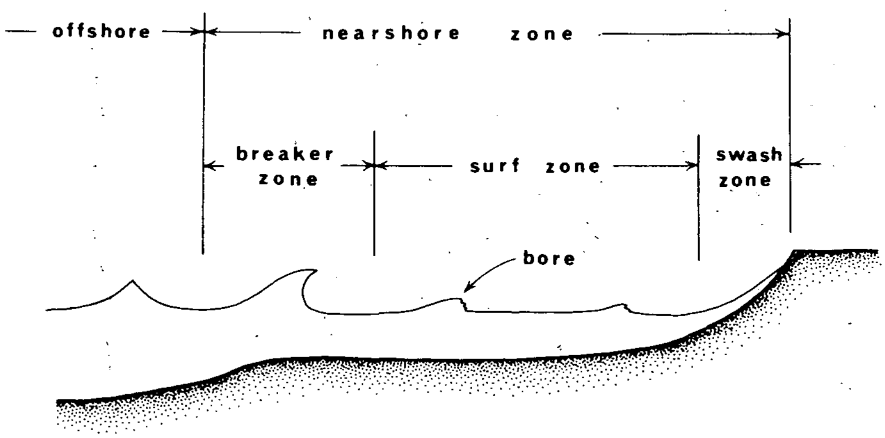


Figure 31. Subdivisions of the nearshore zone into breaker, surf and swash zones (from Komar, 1976).

Two fundamental types of waves occur: sea and swell. Sea waves are those that are found within the generating area (Fig. 32) and are directly related to local wind conditions, for example, storms. As waves leave the generating area they are no longer influenced by local winds and they travel as long-period swell waves. Many of the waves that approach the Pacific coast are generated in distant parts of the ocean to the west and travel more than 15,000 km in some cases before expending their energy on the British Columbia coast. By comparison, the Gulf of St. Lawrence is not affected by swell waves and is a storm-wave environment dominated by the effects of locally-generated

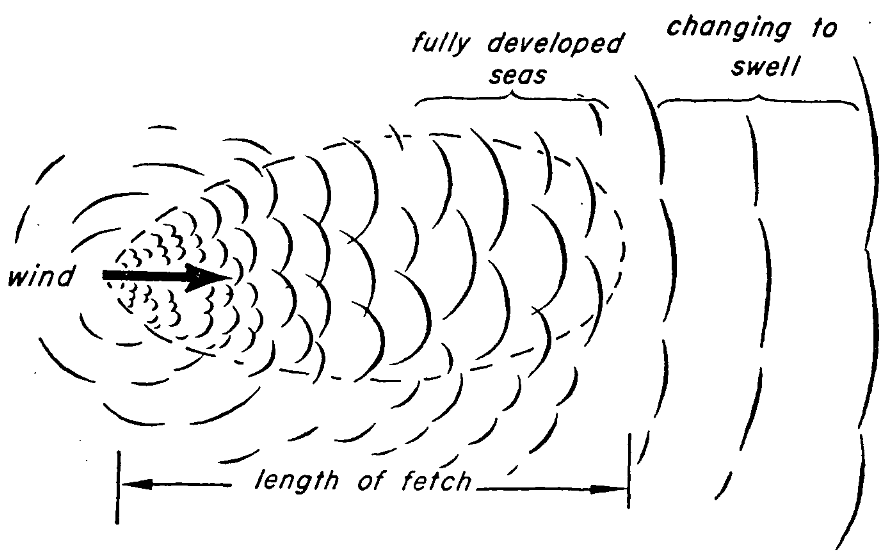


Figure 32. The development of sea and swell waves. The fetch, defined by the dashed line, is the area of water over which the wind generates waves. Upon leaving the generating area, the sea waves become swell waves (from Bascom, 1964).

waves. This latter type of wave has a shorter period, usually less than 8 seconds as compared to greater than 10 seconds for swell waves.

The levels of wave energy on a beach depend on the exposure. Coasts open to swell and/or storm waves are high-energy environments. Those environments that are sheltered or that have limited fetches have lower energy levels (for example, the Arctic Archipelago). A high-energy environment is one in which physical processes transmit moderate or high amounts of energy to the littoral zone daily throughout the year. In a low-energy environment, levels of energy are low throughout the year, but the coast may be subject to occasional intense storm-wave activity. Between these two extremes are a range of environments where orientation of the coast, frequency of storm winds, and fetch distances determine local shoreline energy levels. An example referred to earlier (page 33) is the Magdalen Islands in the central Gulf of St. Lawrence, where the winds, and therefore the locally-generated waves, are predominantly out of the west. This results in higher energy levels on the west-facing shorelines than on the relatively sheltered east-facing beaches.

At the local level on a shoreline, wave energy is transmitted by bottom friction, breaking processes and swash action. The areas of maximum energy dissipation are the breaker zone and the swash zone. The actual mechanics of energy transfer vary depending on the character of the incoming waves and on nearshore topography. Three distinct types of breakers have been defined (Galvin, 1968). Spilling breakers are characterized by a cascading line of foam at the wave crest and usually occur on low-gradient beaches (Fig. 33). These breakers have

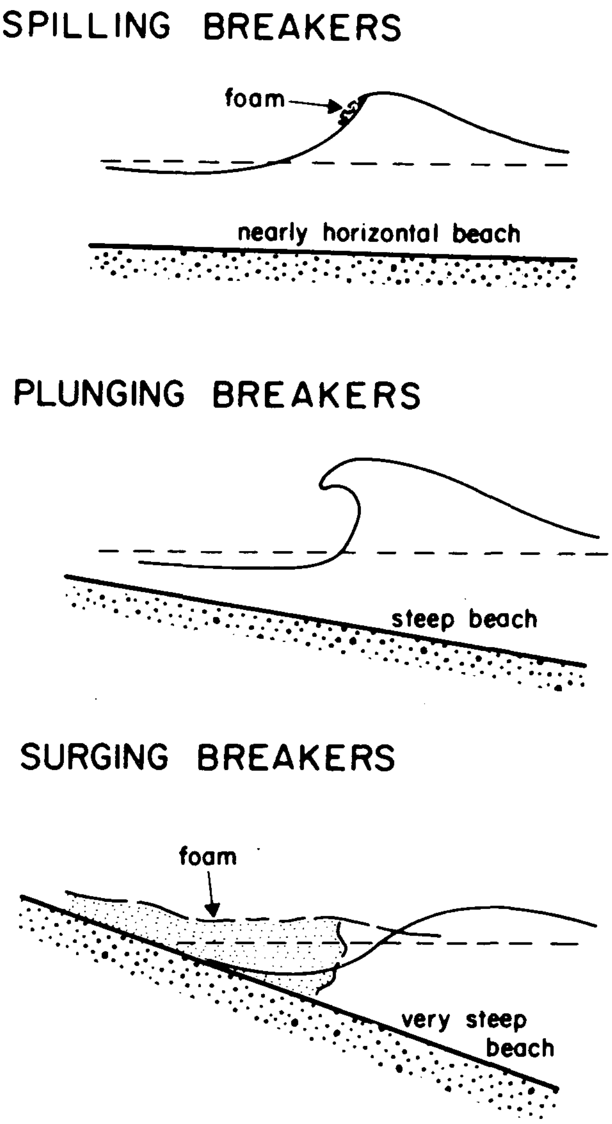


Figure 33. The three major types of breaking waves (from Komar, 1976). The dashed line indicates the mean water level.

a large swash component as wave energy is dissipated horizontally towards the beach. Plunging breakers are common on steep beaches and as the crest collapses, energy is transmitted vertically downwards and a strong backwash is generated. In addition, the crest of the waves curls over so that air is trapped and compressed as the breaker collapses. Surging breakers are typified by the collapse of the wave crest near the point of maximum swash uprush on very steep beaches (Fig. 33).

Breaker type and the width of the surf zone depend partially on the nearshore topography and on tidal water-level changes (Fig. 34). Due to deeper water at high tides the waves break on the beach face and, because the beach gradient is high, tend to form plunging breakers (Fig. 34c). At low tide waves break on the shallow nearshore terrace, the surf zone is much wider due to the lower gradient, and spilling breakers predominate (Fig. 34d).

The transfer of energy to the littoral zone has a direct effect on oil. Mechanical energy from breaking waves or swash causes the physical dispersion and breakdown of oil on the water and on the shoreline.

Oil on the surface of water is subject to dispersion in the breaker, surf and swash zones. In addition to the breaking up of an oil slick into smaller slicks or individual oil

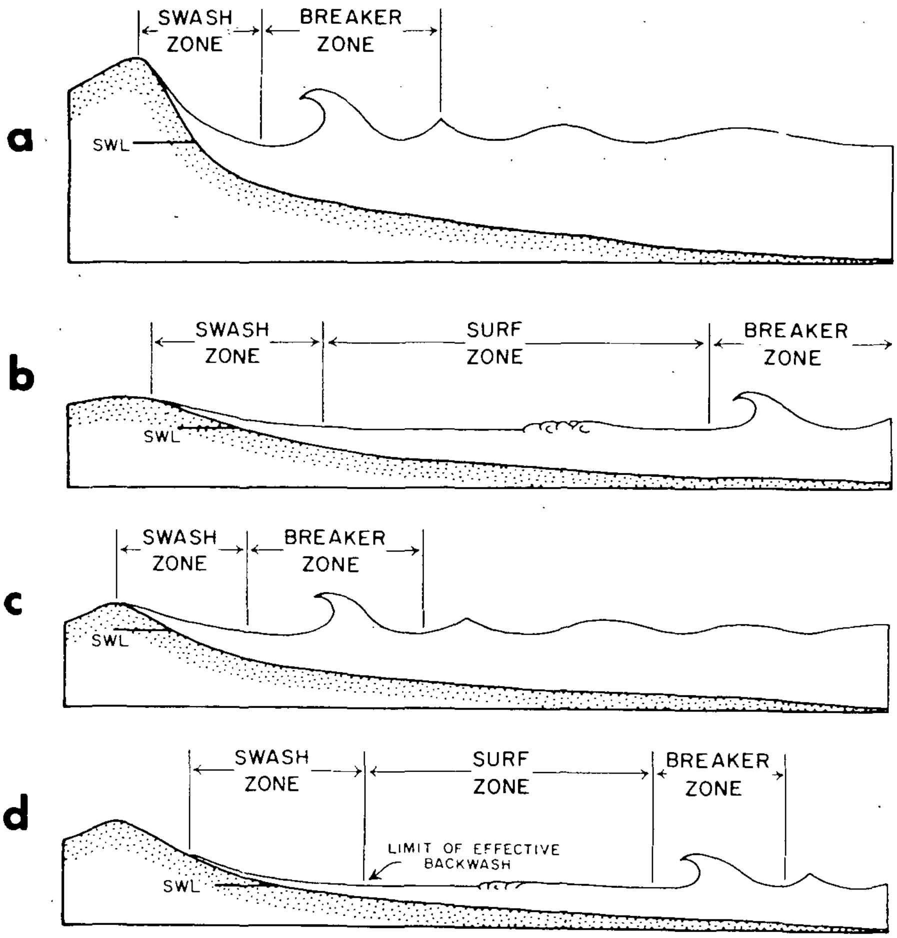


Figure 34. Changes in the surf zone width and breaker type. (a) A steep beach with deep water nearshore; plunging breakers are close to the shoreline and the surf zone is absent or narrow. (b) A low-gradient beach has a wide surf zone at all times. (c) Moderate-gradient beach at high tide; plunging breakers, no surf zone. (d) Moderate-gradient beach at low tide; spilling breakers, wide surf zone (from Ingle, 1966).

particles, mixing of oil and water can lead to the formation of emulsions, such as "chocolate-mousse". Oil on the shoreline itself is similarly affected and can be abraded and dispersed as individual particles (Photo 45) are removed from

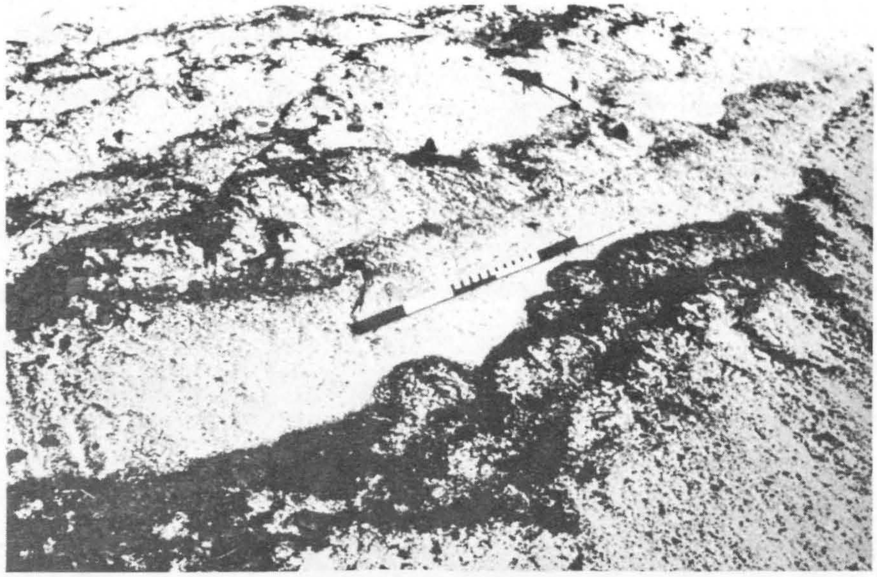


Photo 45. Individual particles of weathered Bunker C oil washed ashore on a sand beach, Black Duck Cove, Nova Scotia, April 1970. The scale is 60 cm in length.

the littoral zone by backwash. This essentially transports oil from the beach into the water column.

As waves break on a shoreline, oil can be splashed above the normal level of wave activity, in the same manner as wave spray splashes beyond the normal swash line. When this occurs the oil is deposited beyond the zone of wave erosion and abrasion, and is not subject to further physical breakdown except during storms.

The rate at which wave-induced degradation processes occur is directly related to levels of incoming wave energy. On exposed shorelines the physical breakdown occurs at a higher rate than in more sheltered, lower energy environments. Photograph 46 shows a low-energy beach in Chedabucto Bay in May 1970 with oil stranded across the entire intertidal zone. Photograph 47a is from an adjacent area with a high-energy outer beach and a low-energy lagoonal environment. This photograph, taken approximately 3 months after the oil was stranded, can be compared with Photograph 47b taken within the lagoon 3 years later. These photographs show that even in adjacent locations energy levels can vary considerably. The exposed beach was cleaned by the mechanical wave activity within 3 months, whereas the sheltered backshore lagoon remained heavily contaminated by oil after 3 years (see also Photos 90 to 92, page 297).

Photo 46. Very sheltered environment, north shore Chedabucto Bay, May 1970. Thick Bunker C completely covers the entire intertidal zone 3 months after the spill. The oil was still evident as a 50% to 100% cover after 3 years.

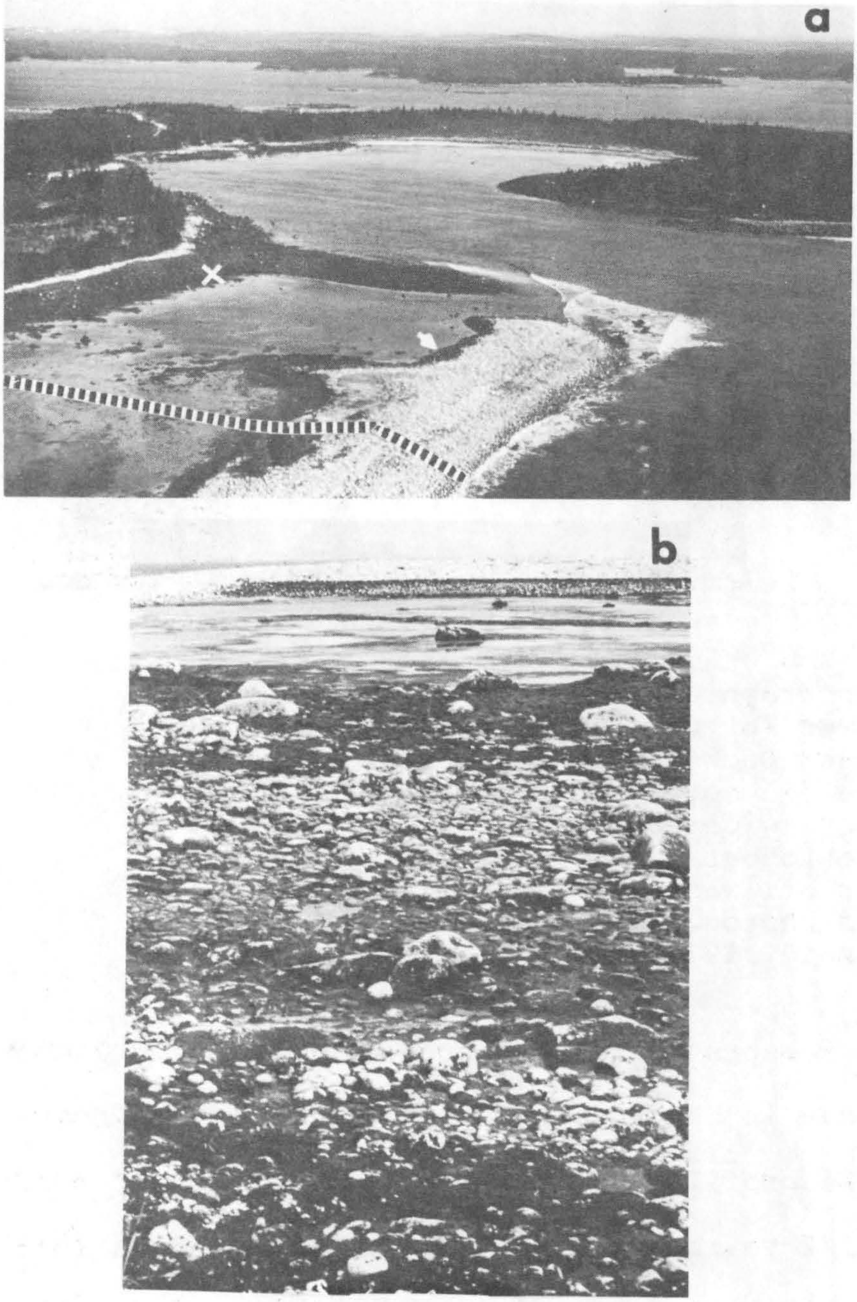


Figure 47. Black Duck Cove, Nova Scotia. (a) June 1970. The outer, exposed cobble-boulder intertidal beach was cleaned within 3 months of oil being stranded there. Oil within the lagoon degraded more slowly, and (b) shows the site marked by the white cross 3 years after the spill, May 1973. The dashed line is the line of the profile in Figure 35 and the arrow locates Photo 90 (page 297).

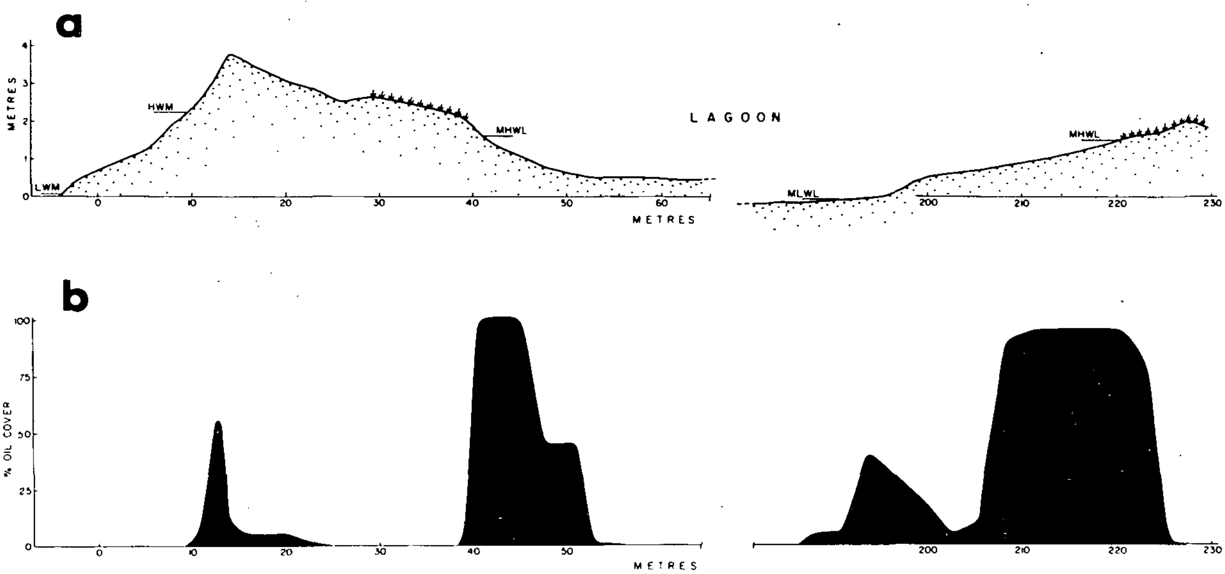


Figure 35. Topographic profile (a) and surface oil cover (b) across the spit and lagoon at Black Duck Cove, Nova Scotia, June 1973. The oil cover was measured on a one-metre wide transect along the line of the topographic profile 3 1/2 years after oil was stranded at this location. See Photograph 47a (from Owens and Rashid, 1976).

Figure 35 presents a profile across the spit and lagoon at Black Duck Cove in Chedabucto Bay, illustrated in Photograph 47. On the profile the measured distribution of surface oil is shown 3 1/2 years after the oil was stranded on this section of shoreline. In this figure it can be noted that the high-water mark (HWM) was higher on the outer beach than in the lagoon (MHWL) due to the effects of breaking waves and to swash run-up on the more exposed section of the spit. In much of the low-energy lagoon environment, the oil still covered

100% of the surface, but on the exposed shore it remained only above the mean high-water mark (above the limit of normal wave activity).

The relationship between wave-energy levels and rates of degradation has been discussed by Rashid (1974). He noted that analysis of oil samples, collected in Chedabucto Bay three years after the oil was stranded, showed that rates of weathering were low in low wave-energy environments and that the oil remained mobile (low viscosity), but that samples from a high-energy environment were more degraded and had a higher viscosity.

In areas where large volumes of oil are washed ashore and/or in a low-energy environment (e.g., Photo 46), the oil coats the entire intertidal zone. A feature of oil deposition on the shorelines of Chedabucto Bay was that in areas of high or moderate wave activity (even though large volumes of oil were washed ashore), the oil tended to be stranded only in the upper parts of the intertidal zone. The lower half of the intertidal zone often dries out slowly or may be wet due to water seeping out of the beach face. As oil does not readily adhere to a wet surface, oil in the lower intertidal zone could be refloated by a flooding tide and carried to the upper parts of a beach. In addition, if the oil were trapped against the shoreline by the action of bores in the surf zone, then the majority of the oil would be moved up a beach on a rising tide and deposited on the upper intertidal zone at the turn of the tide and in the early stages of the ebb.

Oil deposited in the upper intertidal zone is usually eroded rapidly if wave action is present. During high tides the upper intertidal-zone beach is characterized by plunging breakers that transmit energy vertically down to break up oil particles or oil layers. Plunging breakers also have a strong backwash that transfers oil particles seaward.

A secondary effect of waves on oil-contaminated shorelines is related to the water temperature. If the seawater is colder than the ambient temperature this can reduce the temperature of the oil and therefore reduce the degradation rates of oil that becomes covered by breaking waves or swash. The converse is also true but less common as ambient air temperature is usually higher than water temperature.

Waves, Beaches and Oil

The most important effect of the energy transfer associated with the hydraulic action of waves, in terms of shoreline dynamics, is the dispersal and redistribution of sediments. On coasts of unconsolidated sediments (i.e., beaches) the material is reworked by waves and this results in specific patterns of offshore-onshore and alongshore morphology. The amounts of sediment that are redistributed are related both to the size of the material and to the available wave energy. As the sediment size increases (e.g., from sand to cobbles to boulders) so the force required to initiate and maintain transportation increases. Sands are readily moved by all waves, but cobble-sized materials require a much higher force in order to be redistributed.

Oil deposited on a beach will tend to be moved by wave action provided that a complete cover of oil is not formed and provided that the oil particles are sufficiently small in size to be moved by the available wave energy (Photo 45). If the oil is a thick continuous deposit in a low wave-energy environment, the processes of redistribution and mechanical breakdown will be very slow (Photo 46). With higher wave-energy conditions an oil cover can be dispersed, abraded and broken up into individual particles. These particles are then subject to transportation, further abrasion and to weathering. The mechanical breakdown of oil is not achieved by the force of the waves alone. As waves break or as swash runs up the beach the sediment that is being redistributed acts as an abrasive tool on stranded oil.

(i) Changes Perpendicular to the Beach. During periods of high-energy wave activity beaches are usually eroded. On sand beaches this results in the transfer of material from the beach to the adjacent low-tide terrace (see definitions and diagram, Appendix, page 401). As levels of wave energy decrease, the sediment is returned to the beach by constructive wave activity. The time period over which these cycles of erosion and deposition occur varies from one coastal environment to another.

On a shoreline that has a large seasonal difference in wave-energy levels, erosion predominates in one season and construction (or accretion) in another. This is common on the west coast of North America (a swell environment) and is usually referred to as a "summer-winter" beach cycle, with erosion predominating in winter months (Fig. 36). As a result of winter erosion there are major changes in beach morphology, in particular, the berm is lower or absent in winter months, but is replaced during the summer.

In other areas a storm/post-storm cycle predominates, for example, on the northeast coast of North America (a storm-wave

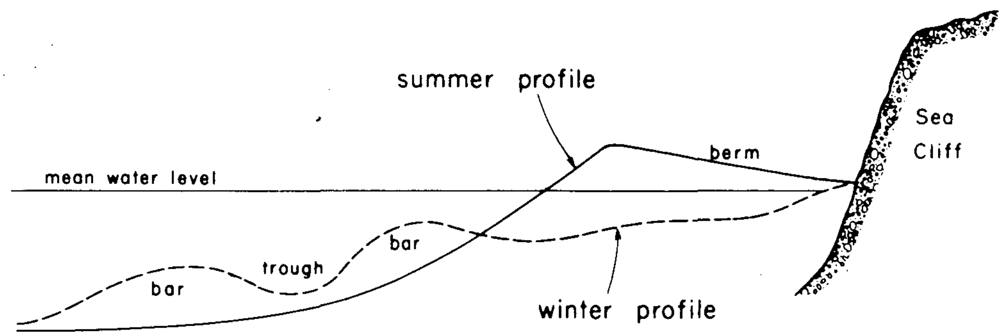


Figure 36. Idealized summer-winter beach profiles (after Komar, 1976).

environment) (Hayes and Boothroyd, 1969; Galvin and Hayes, 1969). In this situation the seasonal variation is overshadowed by higher-frequency cycles of erosion during the passage of storms and construction in the post-storm recovery period. The eroded berm is reconstructed following the storm, as wave-energy levels decrease, by the landward migration of a ridge and runnel system (Photo 48) that welds onto the beach (Photo 49) within a few weeks or less, if not interrupted by further storm-wave activity (Fig. 37).

Photo 48. Ridge welding on the upper beach near the high-water level, Magdalen Islands, P.Q., November 1974 (from Owens and Frobel, 1977).

Photo 49. Aerial view of ridge (marked by the arrow) welded on the beach, Magdalen Islands, P.Q., November 1974 (Photo by J.R. Belanger, Bedford Institute).

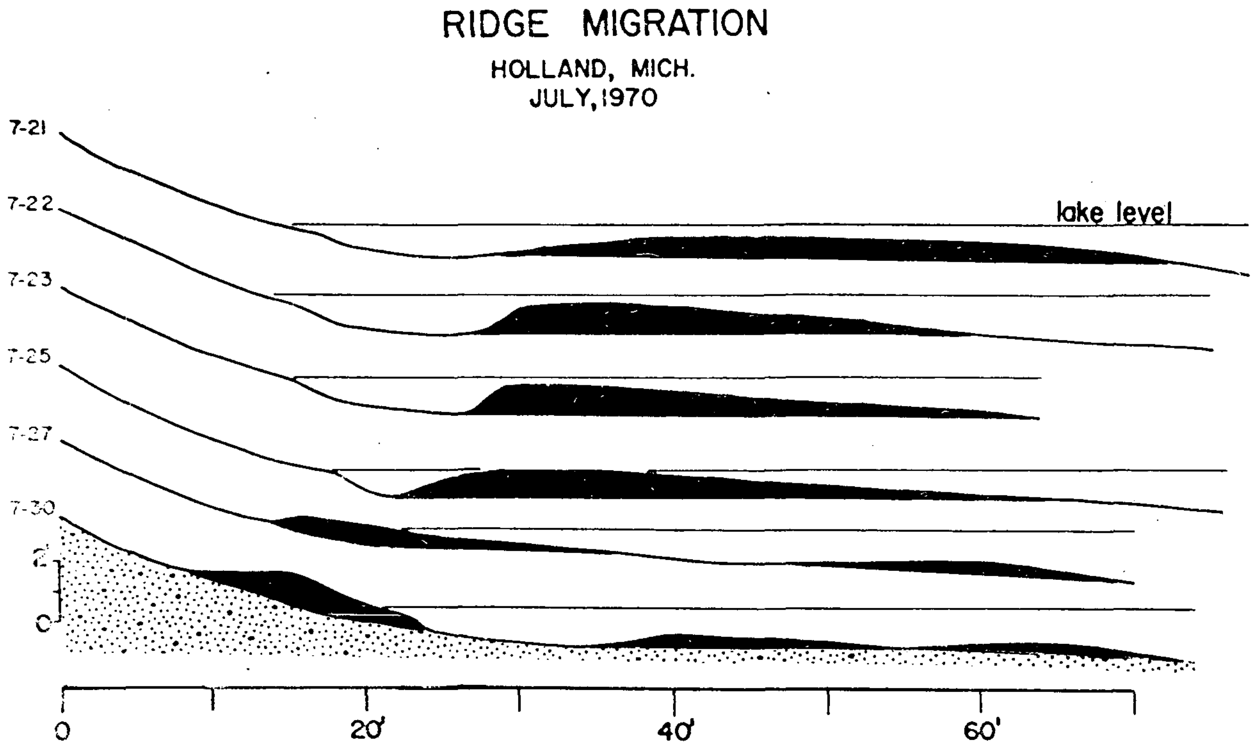


Figure 37. Sequence of onshore ridge migration over a 10-day period, Lake Michigan (from Davis and Fox, 1971).

These two different cycles occur not only in different environments but can also be found at the local level. Owens and Frobel (1977) found that on the exposed west coast of the Magdalen Islands, in the Gulf of St. Lawrence, a "summer-winter" cycle predominated, but that a "storm/post-storm" cycle prevailed on the more sheltered east-facing beaches of these islands. In addition, the study found that in both types of cycles a small ridge migrated landward within 2 to 4 days following a storm (Photo 50). This very small ridge welded onto the

Photo 50. Initial migration of ridge onto beach within 24-hours following a storm. Photo taken at low tide, Magdalen Islands, P.Q., November 1974 (from Owens and Frobel, 1977).

beach face and reestablished a small berm on the eroded beach. Subsequently a larger ridge migrated landward to complete the recovery cycle.

These two cycles of erosion and deposition are basically similar but occur on different time scales due to differences in the character of the wave-energy environment.

During an erosion phase on a beach, sediments and oil would be removed and transported into the nearshore area. This would lead to a rapid breakdown of the oil particles as the particles are rolled around by wave action. If oil is deposited on a beach immediately following the erosion phase, but before recovery has commenced, the oil on the beach would be buried as constructive waves return sediment by the landward migration of ridge systems. Figure 38 shows this type of situation where

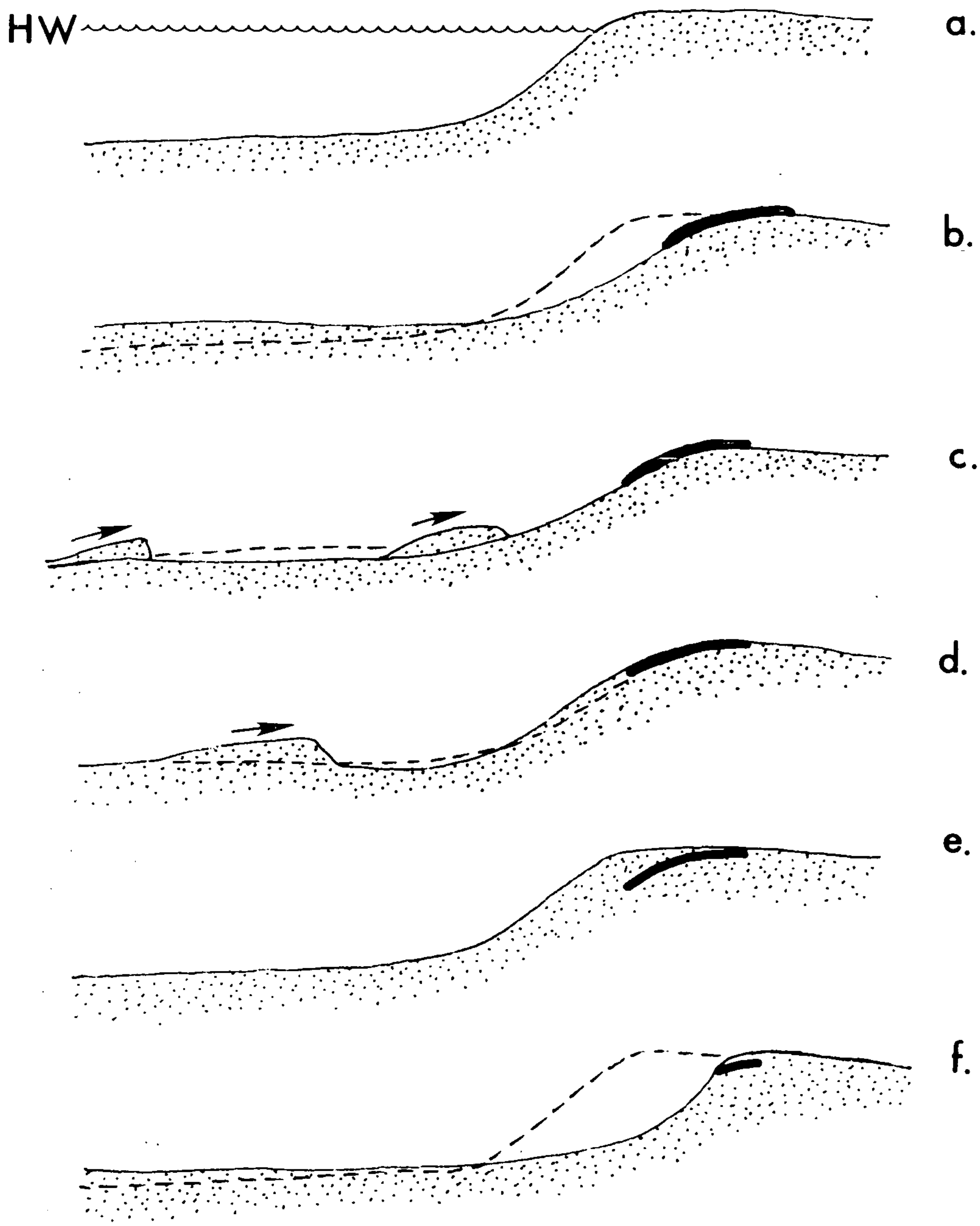


Figure 38. Sequence of storm erosion and oil deposition (b), burial (d)(e), and exposure following a second storm (f) on a sand beach (from Owens, 1977b).

a beach (a) is eroded and the oil is then deposited on the remnant berm during or after the storm (b). As the beach recovers a small ridge (c) migrates up the beach within a few days (d) and eventually the large ridge system will restore the eroded berm (e). The buried oil would then only be exposed during a period of further beach erosion (f) (Photo 51). If the cycle

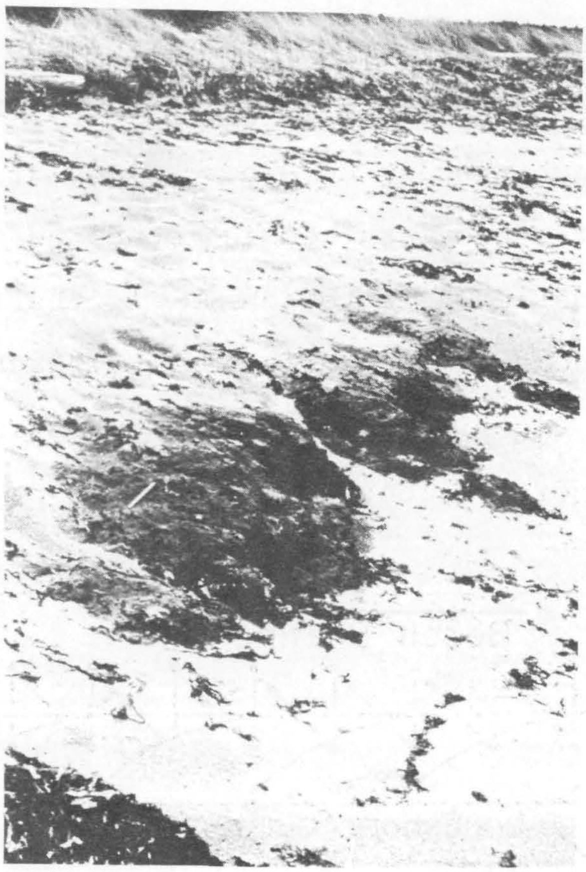


Photo 51. Oil exposed in the upper intertidal zone on a sand beach following storm-wave activity, Point Michaud, Nova Scotia, May 1970. This photograph corresponds to stage "f" in Figure 38.

is one of storm erosion and post-storm recovery this would be a fairly rapid process. If the oil were deposited in a "summer-winter" beach cycle during the spring or early summer phase, the oil would be buried and remain so until the erosion phase in the following fall and early winter.

(ii) Changes Alongshore. Waves that approach a beach at an angle cause the longshore movement of sediment by a process that is referred to as longshore or beach drift (Fig. 39). This results from the swash running up a beach face at an oblique angle, followed by the backwash combing down the sediments. The backwash runs straight down the beach due to the influence of gravity. By this mechanism, material on the beach surface, that can be moved by the incoming waves, is in a continuous state of motion and is transported alongshore.

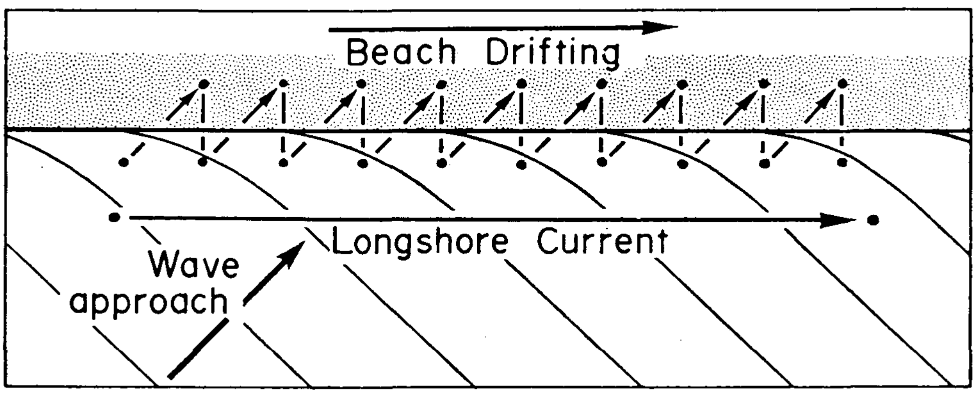


Figure 39. Waves approaching a beach obliquely produce a longshore current and a longshore drift of sediments by swash and backwash action (from Bird, 1968).

A common feature on sand beaches is a type of rhythmic topography called beach cusps (Photo 52). These are generally small in size and reflect differential erosion and accretion by swash action. The process by which beach cusps are formed can change the beach from a flat surface to a rhythmic pattern of small embayments and protuberances. Similar rhythmic topography that is on a larger scale up to 500 m between protuberances results from nearshore circulation patterns generated by incoming waves. These large features can migrate alongshore under certain conditions and this migration causes alternating periods of erosion and deposition on a given section of beach (Bruun, 1955; Bakker, 1968; Dolan, 1971).

If a beach that has migrating rhythmic topography becomes oiled, the alongshore movement of the rhythmic features would slowly lead to a breakdown of the oil cover (Fig. 40). This

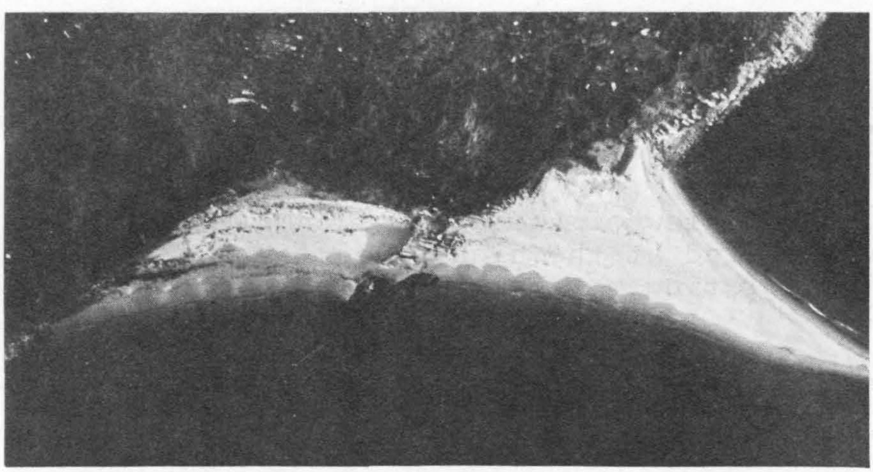


Photo 52. Aerial view of beach cusps, Musquodoboit Harbour, Nova Scotia, May 1975.

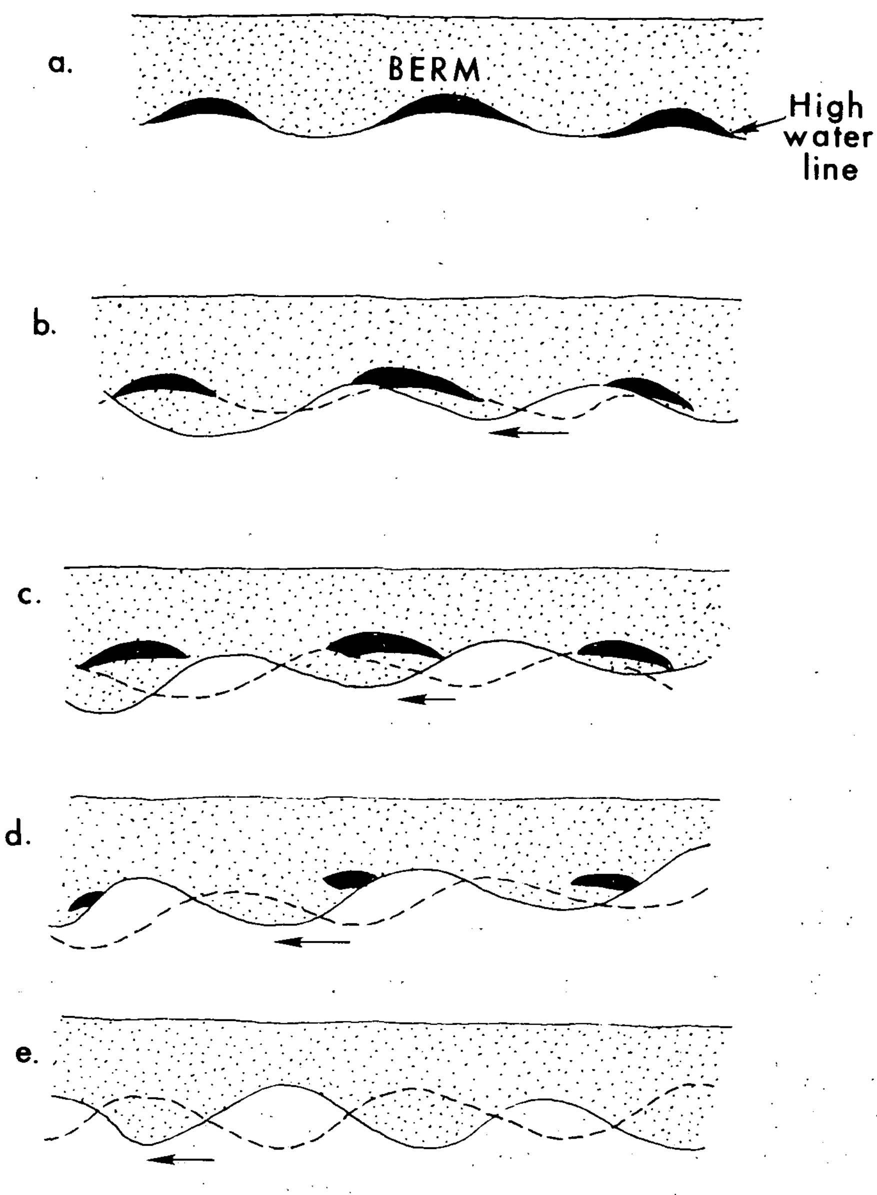


Figure 40. Plan view of the effects on oil deposited at the high-water level by migrating rhythmic topography.

migration pattern is in fact a sequence of continuous erosion and deposition that would cause the oil to be broken down into smaller particles which would then be either buried or transported seaward.

(iii) Changes Above Mean High-Water Mark. The alongshore and across-the-beach changes described above occur primarily in the intertidal zone. In the event of very high levels of wave energy or a rise in water level caused by a storm surge (for example, Fig. 12, page 44), wave activity can extend to the highest parts of the beach system.

On sand beaches backed by dunes this can cause erosion of the dune face or even breaching of the dune system (Photo 53). If a dune is breached, sediment is then moved landward through the dune systems and sometimes even into the backshore lagoon, as in Photograph 53. This process is referred to as overwash. Dykes built across the entrance to overwash channels, if conditions permit, can prevent oil reaching backshore areas.

Photo 53. Aerial view of overwash channels on a sandy barrier beach, Magdalen Islands, P.Q. (Photo by P.R. Hague, August 1972).

If the beach is composed of pebble-cobble sediments, this overwash process is common during periods of high wave-activity levels, as these large sediment particles tend to be thrown landward by waves that break on the beach. On this type of beach the berm is backed by a storm ridge (Fig. 41, Photo 54) that is only affected by wave action during periods of storm waves. These coarse sediments are not moved down the beach by backwash as the swash rapidly infiltrates the many large voids between the sediments, and therefore backwash is non-existent or backwash velocities are very low.

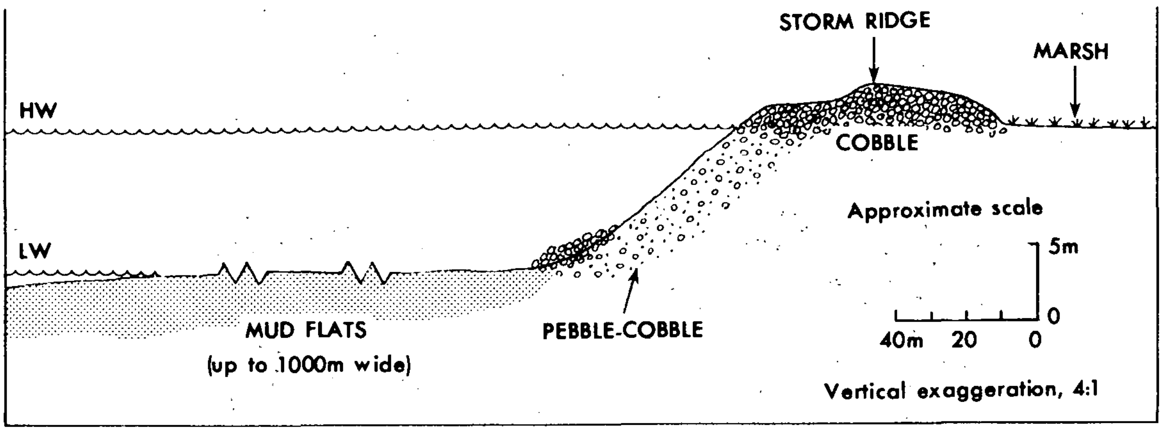


Figure 41. Cross section across a pebble-cobble beach in the Bay of Fundy (from Owens, 1977b).

When oil is washed ashore during periods of storm surges, or very high wave-energy levels, it can be deposited on the beach or can be thrown up by splashing waves above the mean high-water mark (Photo 55). If overwash is taking place oil may even be washed over the beach into the dune system or onto

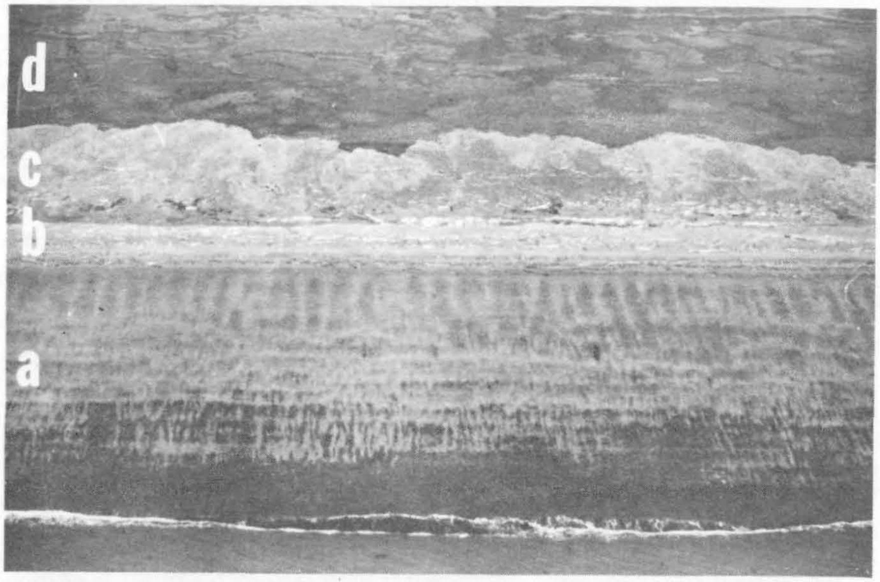


Photo 54. Aerial view landward of pebble-cobble beach, Advocate Harbour, Bay of Fundy, N.S. (a) intertidal zone, (b) berm and storm ridge, (c) overwash, and (d) marsh. This photograph covers a 150 m section of beach (see also Photo 74, page 259, for ground view of a similar beach).

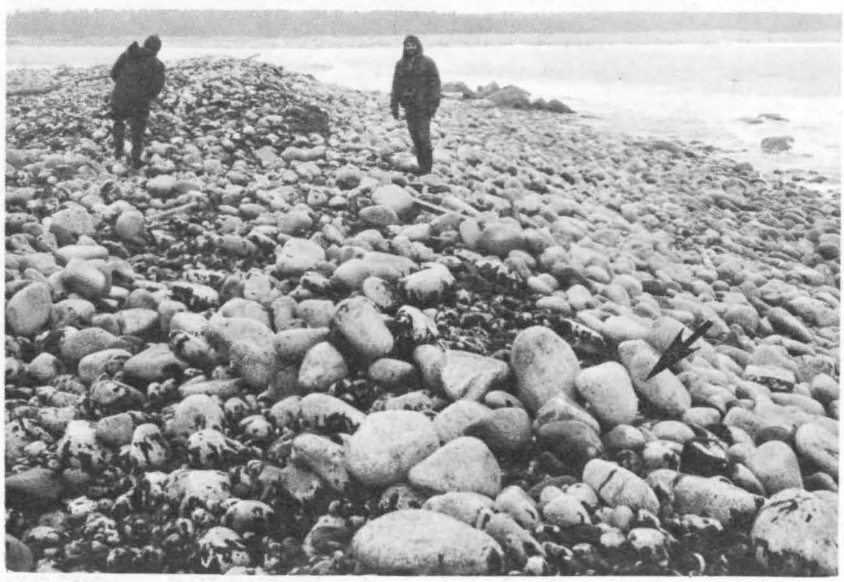


Photo 55. Oil stranded above the high-water mark (indicated by the arrow), Black Duck Cove, N.S., May 1973, 3 years after the spill (photo at low tide by J.R. Belanger, Bedford Institute).

the backshore lagoon. Oil above the mean high-water mark would only be subject to mechanical wave action during wave-energy conditions similar to that under which it was deposited. On sand beaches subsequent high wave-energy levels would probably result in erosion of the oil. On cobble beaches, however, sediments would be transported towards the storm ridge and the oil would become buried (Photo 56, Fig. 42). As the cobble

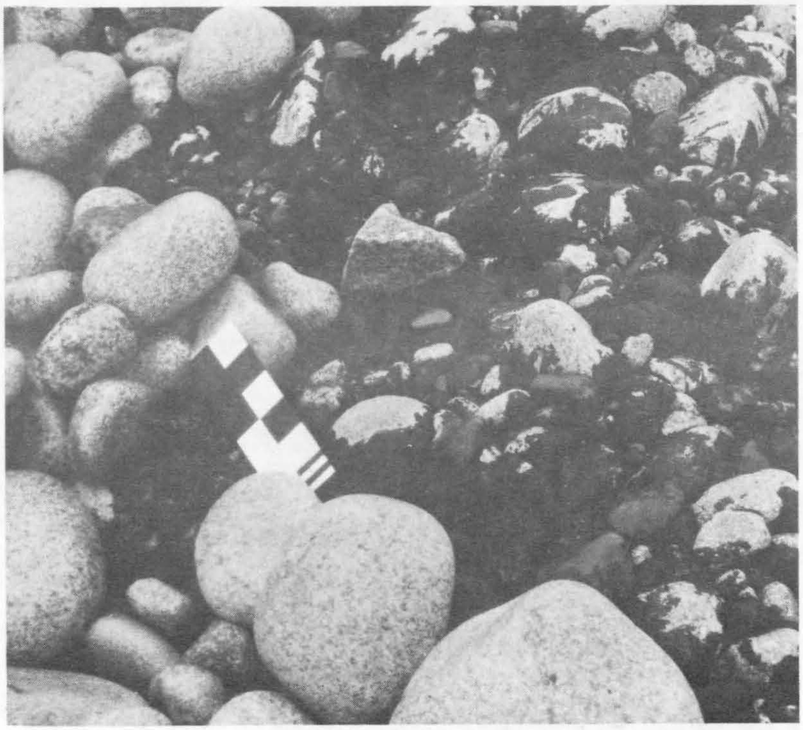


Photo 56. The landward movement of cobbles on the berm and storm ridge results in burial of stranded oil. In this photograph, clean sediments are being moved over the oil from left to right. The scale is 30 cm in length. (Photo by J.R. Belanger, Bedford Institute).

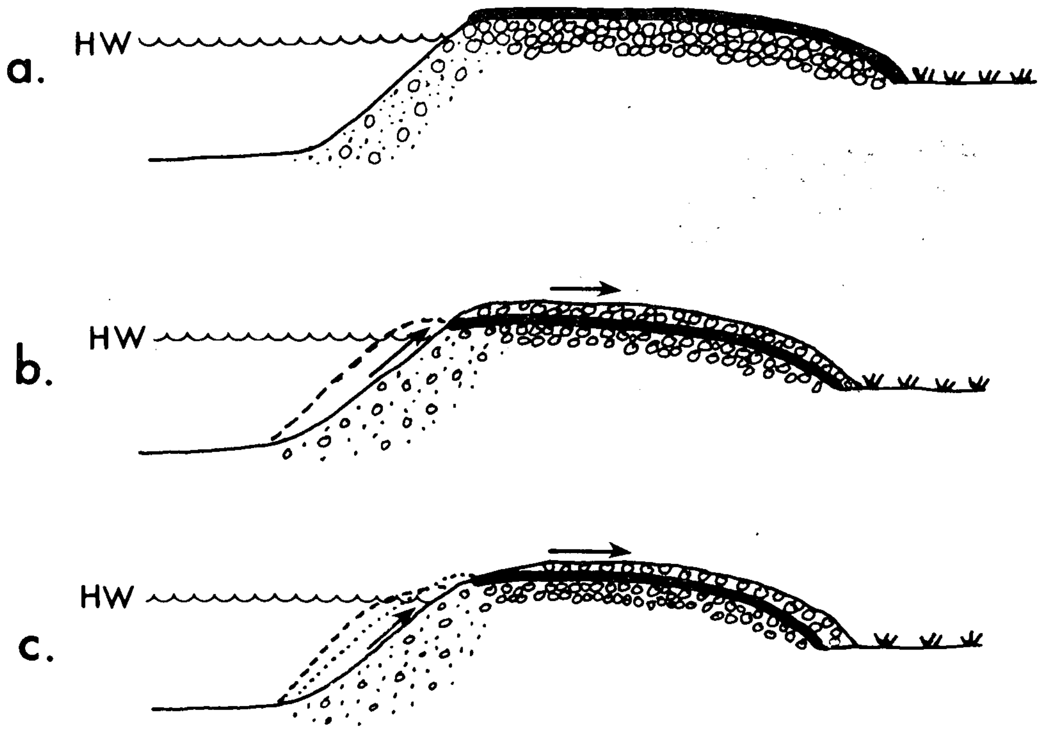


Figure 42. Effects of storm-wave activity on oil stranded on a cobble beach: (a) oil is deposited above the high-water level (HW) during storm conditions, a second storm erodes the beach and waves push material onto the upper beach to cover the oil (b); a subsequent storm continues the process, gradually exposing more of the buried oil layer (c) (from Owens, 1977b).

beach is eroded, the layer of buried oil is exposed in the beach face (Photo 57a). If oil is stranded on a cobble beach over a long time period, several erosion-deposition cycles can lead to exposure of more than one layer of oil in the beach face (Photo 57b).

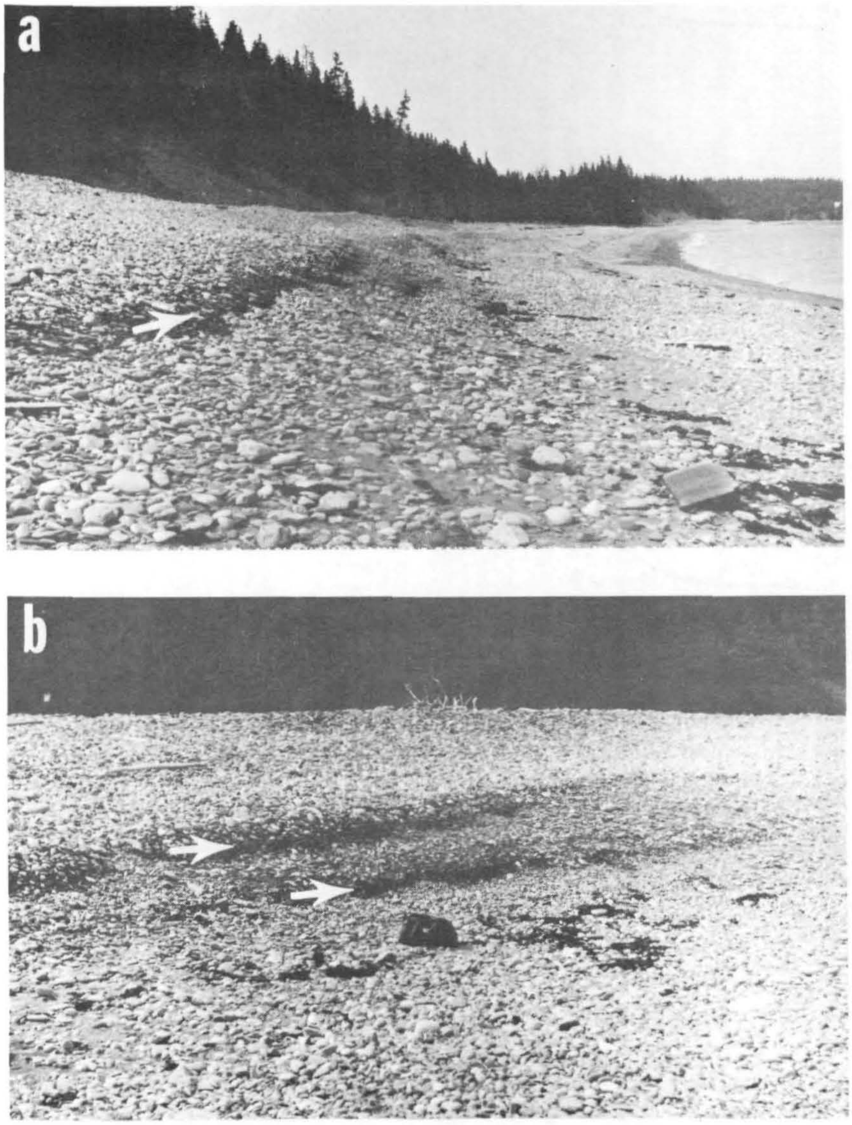


Photo 57. (a) Buried layer, and (b) double layer of oil exposed in a beach face, Hadleyville, Nova Scotia, August 1970. In (b) the beach was contaminated on at least two occasions, between which the first layer was buried by storm-wave activity.

Waves, Rocky Coasts and Oil

On shorelines where there is no beach, wave energy is directed against a cliff or rocky coast. The amounts of available energy that reach the shoreline depend again upon nearshore topography. If the nearshore is shallow (i.e., there is a shore platform) energy is lost by bottom friction and by the waves breaking on the platform (Photo 15, page 63). If the shore platform is absent, as on many upland or mountain coasts, and the nearshore zone is deep, waves will break directly on the rocks or cliffs (Photo 58). Where waves break near or directly against cliffed or rocky shorelines part of the wave energy is frequently transmitted seawards as the wave is reflected. This is often clearly visible on breakwaters or jetties that are built into deep water and that have vertical

Photo 58. Steep rocky coast, near Passamaquoddy Bay, New Brunswick.

walls, and can even be observed on steep cobble beaches. This reflection can lead to collision between incoming waves and reflected waves, causing turbulent conditions near the shoreline.

Oil that is deposited on rocky or cliffed shorelines is subjected to mechanical energy as the waves reach the shoreline. This type of coast has small amounts of sediment so that stranded oil is subject primarily to the hydraulic action of waves. Oil particles would be abraded, however, as they are rolled against the rock surfaces by wave action. The rate of oil dispersion depends once again on the levels of incoming wave energy. For example, if the nearshore zone is deep, less energy is lost by bottom friction and oil is more rapidly eroded.

Oil slicks that approach a shoreline may not be stranded if incoming waves are reflected. This frequently occurs where waves enter a cove or small embayment. Reflection from the sides of the cove can prevent the oil being stranded on those shorelines and the oil would then tend to collect at the head of the cove (particularly if there is a beach there) or may be removed seaward. In addition, the oil would likely be thoroughly mixed and broken down in the zone of collision between the incoming and reflected waves.

SUMMARY

(1) Waves physically break down oil on the shoreline as mechanical energy is dissipated in the littoral zone.

(2) Oil is mixed with water or broken into individual particles in the breaker, surf and swash zones.

(3) Breaking waves can splash oil on the upper parts of the shoreline beyond the normal limit of wave action.

(4) As levels of wave energy increase, rates of physical breakdown increase; this results in higher rates of degradation because more surface area of the oil is exposed to weathering.

(5) Energy levels vary locally (exposed or sheltered shorelines) and regionally (high or low wave-energy environments).

(6) The timing of oil deposition on a shoreline is important in determining the persistence and rates of natural cleaning.

(7) Oil can be buried or eroded depending on beach dynamics and on whether the beach is in an erosional, constructional or equilibrium phase.

(8) Summer-winter beach cycles predominate on coasts where there is a marked seasonal variation in energy levels; shorter erosion-recovery beach cycles are characteristic of storm-wave environments.

(9) Oil on a beach can be buried or eroded as rhythmic features migrate alongshore.

(10) *Oil deposited above the mean high-water mark will only be eroded or buried by subsequent wave activity on that part of the shoreline.*

(11) *Wave reflection from steep shorelines can prevent deposition of oil on those shorelines.*

7.3.2 Tides

Gravitational effects of the sun and moon on the earth's water bodies result in regular, periodic changes in the water level. These effects vary geographically so that the magnitude of the water-level changes (the tidal range) varies from one area to another. The relative effects of the sun and the moon also change regularly and this results in a monthly and seasonal variation in the tidal range. High, or spring, tides occur twice a month (e.g., Fig. 19: Frobisher, page 79) and are highest twice a year at the spring and autumn equinoxes. Tidal water-level changes are usually semi-diurnal but may in some areas have a diurnal cycle, with one high and one low tide each day. Frequently there is a mixed effect and this can cause irregularities in successive high- and low-tide levels (e.g., Fig. 25: Shediac Bay, page 129). Whatever the local character of the type of tide or of the tidal range, these vertical water-level changes result in currents (a transfer of energy) and can have an important effect on sediment transport. Tidal water-level changes also influence wave-energy levels at the shoreline.

Tidal Energy and Oil

Tidal energy is related to horizontal currents that are generated by the rise and fall of the water level. These currents are important in areas of high tidal range (>3 m), or where the horizontal water movement is constricted by channels or inlets. Current velocities of 5 m/s are reported in the Minas Passage at the Head of the Bay of Fundy (Owens and Bowen, in press) and 7 m/s in the Seymour Narrows of British Columbia (C.H.S., 1977). Such currents can cause the mixing and breakup of oil on the water surface.

In areas of low relief a large tidal range can expose wide areas of the nearshore zone at low tides. Large intertidal flats (as wide as 10 km) are particularly characteristic of the Bay of Fundy (Photo 39, page 138), southern Hudson Bay and Ungava Bay. Apart from these examples that result from very low nearshore gradients and/or high tidal ranges, most coasts that have a tidal range greater than 3 m have a wide intertidal zone that is exposed at low tide. If sediment is present in these intertidal zones and tidal currents are sufficiently strong to move the material then the tides can greatly influence the sediment transport pattern of that area. On the south shore of the Minas Basin the sediments are in a constant state of motion and sand waves migrate across the intertidal zone due to the effects of ebb- and flood-tidal currents (Dalrymple et al., 1975) (Photo 41, page 141). Oil stranded on the intertidal zone can, therefore, be subject to burial, erosion and abrasion as sediments are redistributed by tidal action.

Tidal Range and Oil

The variations in water level due to tides are one of the most important controls on the distribution of wave energy on a shoreline. In non-tidal environments, wave energy is transmitted to the shoreline at a single elevation. The effectiveness of wave action decreases as tidal range increases because wave energy is dissipated over an increasingly larger vertical range (Hayes, 1975). It should be noted that water-level changes can be caused by other factors such as storm surges or seiches, and these are discussed elsewhere particularly with reference to the Great Lakes (page 42), to overwash (page 197), and to winds (page 216).

The effect of tidal range on wave energy is demonstrated in Figure 43 which shows semi-diurnal tides for a micro-tidal environment (<2 m range) (Davis, 1964) and for a macro-tidal environment (>4 m range). In the micro-tidal environment (e.g., Fig. 19: Tuktoyaktuk, page 79) during a 24-hour period the entire incoming wave energy is concentrated in a vertical band that, in this case, is only 1 m wide. When the tidal range is increased (e.g., Fig. 19: Frobisher) the wave energy is then spread over a much wider vertical band. Also important is the fact that during the ebb and flood of the tide the water

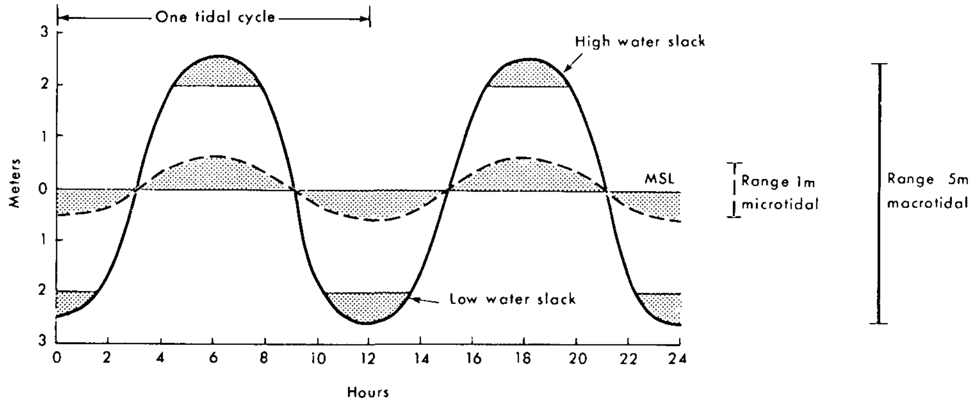


Figure 43. Typical curves for semi-diurnal tides in a micro- and macro-tidal environment. The shaded areas indicate the levels on the shoreline at which wave energy is concentrated.

level is continuously changing so that wave energy is active at one level for only a short period of time. At the turn of the tide (slack water period) wave action is concentrated at one level for periods up to 3 hours. As a result, in tidal environments wave energy tends to be most effective at the high- and low-water levels.

The variability in wave-energy concentrations due to tidal water-level changes has a direct bearing on the rates of physical breakdown of oil on a shoreline. These rates would be higher in a micro-tidal environment when compared to a macro-tidal environment with the same levels of incoming wave energy. The primary effect of an increase in tidal range and, therefore, an increase in tidal energy, is to reduce wave-energy levels by spreading the energy over a wider, vertical section of shoreline. As wave energy is a primary factor in the physical breakdown and dispersion of stranded oil the increase in tidal range reduces the effectiveness of waves to clean an oiled shoreline.

Tidal range varies during monthly and six-monthly cycles. The monthly cycle of spring (high) and neap (low) tidal ranges is well-illustrated in Figure 19 (Frobisher, page 79). During one month the tidal range at Frobisher varies from as little as 2 m at neap tides to a maximum of 10 m at spring tides. As a result of the seasonal variability at this site the highest tidal ranges (up to 11.6 m) occur during October (C.H.S., 1977b). This variability in ranges is particularly noticeable in areas of high tidal range, but is found in all tidal environments and is another factor in controlling concentrations of wave energy at different, vertical locations on the beach. This, therefore, also affects local rates of oil degradation. If oil is stranded on the higher parts of a shoreline at times of spring tides it will not be affected by waves until the next spring tide period, or unless there is an increase in wave height that allows waves to affect that part of the shoreline (Photo 59).

Tidal range has a significant effect on the non-mechanical degradation of oil. As the water level rises and falls with each tidal cycle, oil deposited in the intertidal zone is

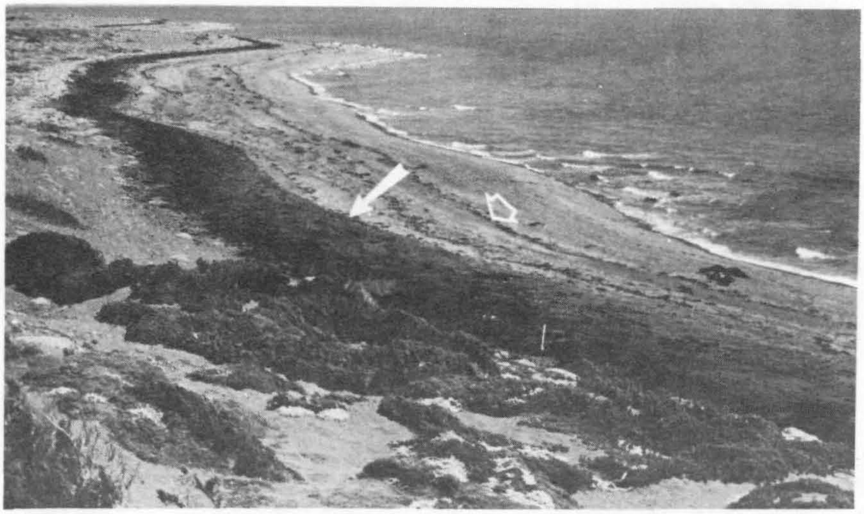


Photo 59. Oil on a sand beach in a sheltered wave environment in the Straits of Magellan. The oil above the limit of high spring tides (solid arrow) remains unaffected by littoral processes after 2 1/2 years. The normal high-water level is indicated by the open arrow.

alternately exposed and submerged. Therefore, there is a considerable variation in the rates at which different degradation processes operate in different parts of the intertidal zone. These processes are related to temperature and sunlight, and to the wetting and drying of water on the oil surface. The actual rates at which the different physical and chemical processes can occur depends on the location of the oil as well as the tidal range. Oil deposited near the low-water level is submerged for approximately 75% of the time during each tidal cycle, whereas oil near the high-water mark is exposed for 75% of the time. As a result of this differential exposure, oil in the upper intertidal zone is subject to higher rates of weathering than the oil that is covered by water during most of the tidal cycle.

Tidal range is a critical element in the distribution of oil on the shoreline. As the range increases so oil can be distributed over a wider intertidal zone. If the range is low, oil is concentrated over a narrower, vertical band and, therefore, the thickness of the stranded oil is greater. Oil thickness is important in relation to wave-energy levels, as low levels of incoming energy may be able to disperse a thin layer of oil but may be insufficient to remove a thick layer of oil in a micro-tidal environment (see below, page 228). If the tidal range is large, oil is spread over a wider surface area and the layer of stranded oil, therefore, tends to be thinner, thus allowing the hydraulic action of waves to be more effective in the breakdown of the oil.

Salt marshes are inundated usually only during spring tides. Oil in marsh areas would, therefore, not be stranded on the marsh surface itself except during periods of storm surges or spring tides.

Tidal Inlets and Oil

Where a lagoon or estuary is partially enclosed by a barrier beach in a tidal environment there is an exchange of water between the lagoon and the open sea during the tidal cycle. As a result, the inlet through which the tide passes is a zone of constriction and this can lead to high current velocities during the ebb and flood period. Oil near an inlet can be transported into the sheltered lagoon during a flood tide (Photo 60). Should this happen it is highly likely that the oil would be stranded there and, in this type of environment wave energy is minimal, therefore, rates of degradation related to littoral processes would be low (Photo 47, page 183).

Photo 60. Oil being carried through a small inlet into a lagoon on a flood tide, Baie des Chaleurs, P.Q., October 1974.

SUMMARY

(1) *Tidal energy can redistribute sediments and can, therefore, abrade oil in intertidal areas.*

(2) *Erosion and deposition of sediments by tidal currents in the intertidal zone can cause burial and erosion of oil deposited there.*

(3) *Tidal currents in inlets or constricted channels lead to the mixing and breakup of oil on the water surface.*

(4) *Tidal range is a major factor in controlling the concentration of wave energy on the shoreline, and, therefore, the rates at which wave action can disperse stranded oil.*

(5) *In macro-tidal environments (range >4 m) wave energy is dissipated over a wide vertical band, but in micro-tidal areas (range <2 m) wave energy is concentrated in a narrow vertical band.*

(6) *Oil deposited during periods of spring tides on the higher parts of the shoreline will remain unaffected by tidal and wave action until the next period of spring tides.*

(7) *Oil deposited in the intertidal zone is alternately exposed and submerged during each tidal cycle. The rates at which the different physical and chemical*

processes operate in aging of the oil vary depending on the location of the oil and the amount of time that it is covered by water.

(8) *Tidal range controls the area of shoreline on which the oil can be deposited. As range increases so does this area, and the thickness of the oil layer tends to decrease. The reverse is true for areas of low tidal range.*

(9) *The exchange of water between lagoons and the open sea through tidal inlets can result in oil being carried into the sheltered backshore areas by flooding tidal currents.*

7.3.3 Winds

Winds are the agent that generates waves but can also have other effects, particularly in the supra-tidal zone, by the transport of fine-grained sediments and by inducing storm surges.

Material that is sand-size or smaller can be transported near the ground by wind. In an area where oil is deposited on the berm, perhaps by spring tides, wind-transported sediment could bury the oil. This would be likely in a situation where the beach is backed by dunes and where the winds are off the land. Sediment would be readily available from the dune area and would then be blown onto the upper parts of the beach. During periods of strong winds, large volumes of sand can be transported and an oil layer could be partially or completely buried within a few hours. The effect of such burial is to reduce rates of weathering and aging.

Strong onshore winds can cause a rise in water levels at the shoreline by the piling up of water against a coast. This can occur on any coast, but is more common in large embayments or in areas that have an irregular shoreline. An example of a wind-generated storm surge is given for Lake Erie in Figure 12 (page 44). As a result of storm surges, waves can act on higher parts of the shoreline that would otherwise be beyond the limit of normal wave activity. This can result in erosion of dunes or overwash (Photo 53, page 197). In areas where the beach has not developed much above the mean high-water mark, as is the case in most sheltered wave environments (e.g., the Great Lakes), storm surges can have a considerable effect on the redistribution of backshore sediments or on backshore erosion. Oil on the water surface can be moved by winds. If these winds are onshore, the oil will be trapped against the shoreline. Deposition of the oil would then occur either during an ebb tide or as the water level falls following a wind-induced storm surge. In the latter case, the oil could be deposited above the normal limit of wave activity. If the effect of the storm surge leads to overwash, oil can be carried onto backshore areas or into sheltered lagoon environments.

Onshore winds can also move oil into lagoons through tidal inlets. Wind-induced storm surges can also lead to the inundation of marsh areas and can carry and strand oil in this sensitive biological environment.

Wind velocity directly affects rates of weathering. The process of evaporation and, therefore, the removal of the light fractions, is dependent in part on wind velocity. In experiments on the aging of oil in an arctic environment, McMinn and Golden (1973) note that during a storm, with wind velocities between 55 and 90 km/hr, rates of aging increased on oil not buried by snow. The high wind velocities resulted in an increase in oil density as the volatiles were evaporated.

SUMMARY

(1) Wind-blown sediments can bury oil deposited on the upper beach.

(2) Onshore winds can trap oil on a shoreline; this oil is then deposited during the ebbing tide or following the lowering of storm-surge water levels.

(3) Oil can be moved through tidal inlets by winds and can be deposited in low wave-energy environments or on salt marshes.

(4) Wind velocity is an important factor in evaporation of volatiles from oil surfaces.

7.3.4 Ice

The formation of ice on the water or on the shoreline modifies littoral processes. Ice can redistribute sediments in the littoral zone but the most important effects are to prevent wave generation or to protect the shoreline from wave action (Owens and McCann, 1970; Taylor and McCann, 1976).

Waves are not generated in areas that have a sea-ice cover. Ice on the water also acts to limit fetch (open-water) areas and to dampen waves that travel into an area of pack ice. The primary result is that in ice-affected regions wave-energy levels are considerably reduced. In northern arctic areas wave generation is limited to only a few months each year (McCann, 1973). High levels of wave activity in these high arctic coastal environments are infrequent due to the requirements that the sea over which the waves are generated be ice-free and that the wind direction coincide with the open-water fetch for a particular shoreline during a long enough period to generate high waves. In the Gulf of St. Lawrence, an area of locally-generated waves, maximum wind velocities occur during the period October to March. Sea ice limits wave generation from December to April and, therefore, considerably reduces levels of wave energy during winter months, at a time when they would otherwise be at a maximum (Owens, 1976).

Rates of natural weathering and aging of oil are reduced in cold environments due to the lower air (and water) temperatures (McMinn and Golden, 1973). The degradation processes that affect oil on the shoreline are further reduced where sea ice is present because of the lower levels of wave energy (due to prevention of wave generation or to dampening of existing waves). This reduction in energy levels, and the consequent reduction of the rate at which oil on the shoreline is physically broken up, is greatest in arctic regions.

Ice also forms on the shorelines and this fast ice acts as a defense against waves reaching the littoral zone. This fast ice, usually referred to as an ice foot (Owens, in press) (Photos 61 and 62) forms before and persists longer than the sea ice, thereby reducing further the period during which the waves can act on a beach.

Waves can be reflected from an ice foot (as would be the case at high tide in Photo 62). This would cause mixing and the physical breakdown of the oil on the water surface as well as preventing the oil reaching the ice foot. Oil that has been deposited on an ice foot can be eroded if the adjacent water areas are ice free, or could be enclosed and buried by further accumulations of ice that would result from snow or from the freezing of wave spray and swash. Upon subsequent exposure the oil would be released either onto the sea or onto the shoreline. Oil on the shoreline prior to the development

Photo 61. Initial stages of ice-foot formation, January 1974, Richibucto Head, New Brunswick. This ice foot is growing as wave spray and swash freeze on the upper intertidal zone.

Photo 62. Ice foot on an arctic beach, Cape Ricketts, Devon Island, N.W.T., following breakup (29 July 1968). This ice foot is approximately 4 m high and the high-tide line is clearly visible above the person's head (photograph taken at low tide).

of an ice foot would simply be frozen over and buried until the ice foot melts.

In latitudes where open water is present for only a few months each year, littoral processes are greatly modified. Rates of longshore sediment transport (beach drift) are low and the beach is rarely subject to changes, such as storm-wave erosion or migrating rhythmic features. As a result, erosion or burial of oil would only occur during the infrequent periods of wave activity. In parts of the Queen Elizabeth Islands periods of storm waves could be as infrequent as every 2 or 3 years.

During periods when the beach is free of ice, individual small or large floes can be pushed into the littoral zone by wind action. If the ice grounds on the beach it can push sediment landward to form a ridge (Photo 63). This would affect

Photo 63. Ice-push ridges formed by the grounding of ice floes, Allen Bay, near Resolute, N.W.T., (August 1968).

the oil on the beach by mixing it with the beach sediments or by burying it beneath the ice-push ridge. An important effect of ice pushing sediments and oil up the beach would be that the oil would be deposited above the maximum limit of wave activity. Rates of degradation would then be lowered as the oil would be buried and would not be subject to reworking and dispersion by littoral processes.

On beaches in arctic and sub-arctic environments, water in the sediments freezes during periods of sub-zero temperatures. This sub-surface ice fills the spaces between sediment particles and acts as a lower limit for oil penetration. In the Arctic Archipelago the depth to the "frost table" (i.e., the depth to which the beach thaws and is ice-free) varies from less than 25 cm in winter and spring to a maximum of approximately 100 cm in summer and autumn (Owens and McCann, 1970; Taylor and McCann, 1974; Owens and Harper, in preparation). Oil on a beach in early summer could penetrate to greater depths as the frost table melts. Oil that penetrates a beach during the arctic summer could become enclosed as the frost table depth decreases in autumn and winter. This enclosed oil could then be released the following summer.

Oil can also have an effect on ice and can change rates of thaw. This is discussed below on page 228.

SUMMARY

(1) Ice on the sea prevents wave generation and dampens existing waves. This reduces wave-energy levels at the shoreline.

(2) Lower energy levels reduce the rate at which oil on the shoreline is dispersed and, therefore, rates of degradation are lowered.

(3) An ice foot on the shoreline absorbs wave energy and prevents that energy from being dissipated on the beach.

(4) If waves are reflected from an ice foot or from fast ice in the nearshore zone, this would prevent oil reaching the shoreline.

(5) Oil on a shoreline prior to freeze-up would be buried by an ice foot as swash and wave spray freeze.

(6) Oil can be incorporated in an ice foot if it is in the formation stage. The oil in an ice foot would be released during the melt season.

(7) On a beach with stranded oil, ice push would bury oil or mix the oil and sediments, and could push it above the maximum limit of wave activity, thereby reducing rates of degradation.

(8) Ice in the beach sediments acts as a lower limit for penetration of oil in the littoral zone.

7.3.5 Sediment Budget

The dynamics of a beach depend to a large extent on the amounts and types of sediment that are available for reworking by littoral processes. Sediment is fed into a system by coastal erosion, by rivers, by onshore transport or by beach erosion (Bowen et al., 1975). The system looses sediment by accretion in dune, beach, inlet and lagoon areas, by offshore transport or by removal (by man) (Photo 64). Major changes in the equilibrium of a beach can result from an alteration in the balance between the input and output rates (this balance is usually referred to as the sediment budget).

On a beach where little sediment is fed into the system, a net loss of material would result in retreat (erosion) of

Photo 64. Sediment removal from a pebble-cobble beach, Salisbury Bay, New Brunswick, June 1976.

the beach. This could occur as the result of a major storm that would transport material offshore beyond the depth in which normal waves can move the sediment.

On exposed coasts, barrier beaches or spits migrate alongshore. In the case of barriers the whole system, including the associated inlets, is in motion and accretion at one end of the barrier is concurrent with erosion at the other end. In addition to this longshore migration, a beach can also move landward (erode) if more sediment is lost from the system than is fed into it, or can grow seaward (accrete) if the balance is the reverse. The overall erosion or accretion of a beach system can occur on relatively short time scales, i.e., measurable yearly.

Whatever the causes or the nature of these changes in the sediment budget, the resulting erosion or deposition directly affects the erosion or burial of oil stranded on the beach. The rates of these changes vary as levels of energy input to the beach system vary, so that changes are generally slow in a low wave-energy environment such as the arctic.

Beaches are in a state of dynamic equilibrium with the forces that act upon them, so that most changes are part of a normal sequence or cycle. The dynamic equilibrium can be upset by man's activities, such as by sediment removal or by the construction of coastal engineering structures. Where sediment is removed from a beach and there is no adequate sediment input to naturally replace that which is lost, the beach will undergo erosion. Oil deposited on such a beach would, therefore, be removed naturally as the beach retreats. The construction of jetties or groynes can alter the pre-existing sediment budget and the new patterns of sediment dispersal would lead to local erosion and deposition (Fig. 44). If oil is on the shoreline at the time of these changes it would be either buried or eroded.

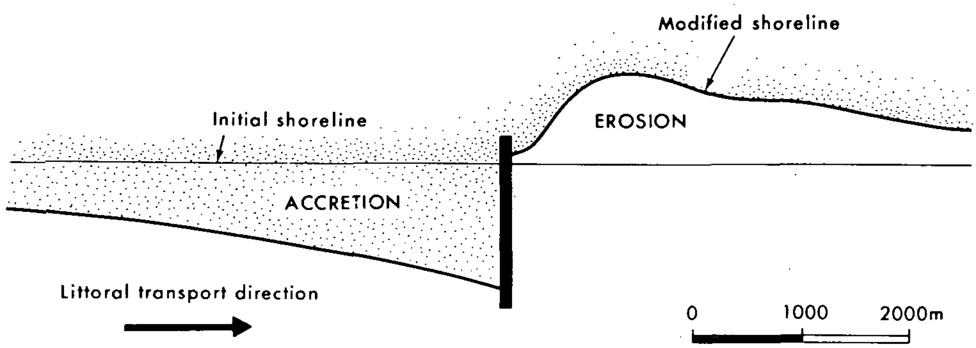


Figure 44. Initial shoreline and changes that result from construction of a groyne across the beach (after Komar, 1976).

<u>*SUMMARY*</u>

(1) Beaches are a dynamic feature and changes occur on large and small scales, and over long and short time periods.

(2) Rates of change are controlled by the amounts of energy available to redistribute the sediments, and by the availability of sediments.

(3) *The net loss or gain of sediment in a beach system results in erosion or burial of oil stranded on that beach.*

7.3.6 Effects of Oil on Littoral Processes

The relationship between littoral processes and shoreline changes is a series of complex, feed-back interactions. For example, the way in which a wave breaks depends on the near-shore topography and on the character of the wave itself. Also tidal current velocities depend on the magnitude of the water-level changes and on the cross-sectional area of the channel through which the water must pass. Similarly there are dependent interrelationships between the various processes, for example, tidal range and the concentration of wave energy on a shoreline. When oil is introduced into the littoral zone it becomes another factor in the dynamics of shoreline processes. The impact of the more significant effects of oil are discussed here briefly.

Oil on water dampens the surface waves, this is especially true of heavy or residual oils. The practice of spreading oil on the sea has long been used to dampen breaking waves during ship-rescue operations (C.H.S., 1970). In the near-shore zone, oil on the water can be important in reducing the height of breaking waves, particularly if wave heights are low. The feed-back effect of this is to reduce the ability of the breaking waves to mix or break down the oil. This then increases the likelihood that oil would be stranded on the shoreline as a continuous cover rather than as individual particles.

When a large volume of oil is deposited on a beach or in the intertidal zone the oil can act as a protective cover or can bind the sediments together. This then prevents or inhibits the ability of waves to redistribute sediments and the beach or intertidal zone can resemble an "asphalt pavement". In a low-energy environment this is of great significance as the beach and oil can become totally immobilized (Photo 47b, page 183). A secondary feed-back effect in this instance is that waves cannot then use the immobilized sediments as an abrasive tool to break down or to erode the oil. This aspect of oil preventing sediment redistribution is also discussed later (page 264). Where oil has been buried on a beach and is subsequently exposed (Photo 57, page 202), the exposed layer of oil is more resistant to erosion by waves than the adjacent beach. This oil layer can absorb some of the wave energy that would otherwise be used to redistribute the sediments, thereby reducing erosion on that part of the beach. In sandy backshore areas, a cover of oil would prevent sediment redistribution by wind action, although the oil itself can become buried.

Oil deposited on an ice surface can increase rates of melting or delay ice formation. Because of its dark colour, oil absorbs more incoming radiation than ice and its temperature is raised above that of the ice. This would cause melting of the adjacent ice (Glaeser, 1971). On a large scale, this could result in melting of an ice foot or part of the ice foot earlier than would be normal and would, therefore, increase the possibility of wave action on the shoreline. It is also theoretically possible that oil could prevent wave spray freezing on a beach if the temperature of the oil is greater than the freezing point, even if air temperatures are below the freezing point. This would then delay ice formation and the burial of the oil, and could again increase the possibility of wave action dispersing the oil.

SUMMARY

(1) *Oil dampens breakers and thereby reduces mixing or breakdown of oil on the water surface.*

(2) *A thick oil cover can prevent sediment redistribution, particularly in a low-energy environment, with a resulting decrease in rates of abrasion and erosion.*

(3) *Surface oil on ice can increase melting rates and lead to exposure of the shoreline to waves earlier than usual. Oil can delay ice foot development for a few days by preventing the freezing of waves on the beach.*

TABLE 13. Factors That Alter The Impact of Littoral Processes on Oil

Factors that INCREASE rates of physical breakdown and degradation of oil	Factors that REDUCE rates of physical breakdown and degradation of oil
Waves - increasing wave-energy levels - mix or breakdown oil in breaker, surf or swash zones - use sediments as abrasive tools - redistribute or erode oil on the shore - reflected waves mix or breakdown oil & may prevent oil reaching the shoreline	**Waves** - decreasing wave-energy levels - bury oil by beach accretion or by longshore migration of sediments - reduce temperature of oil - throw oil above the normal level of wave activity by the splashing action of breakers
Tides - concentrate wave energy when range is low - concentrate wave energy at high-water & low-water levels when range is high - use sediments as abrasive tools - redistribute or erode oil in the intertidal zone - if tidal range is large, oil layer is thinner as it is deposited over a wider area	**Tides** - dissipate wave energy over wider vertical band as range increases - spring tides deposit oil above normal level of wave activity - flood tides transport oil into low-energy lagoons or estuaries - redistribute sediments and bury oil in intertidal zone

Table 13 (cont'd)

Winds - increase rates of evaporation	Winds - redistribute sediments and bury oil on backshore - generate storm surges and oil deposited in lagoons (by over-wash) or in backshore - onshore winds trap oil on coast during surge, deposition then occurs above level of normal wave activity when water levels lowers
Ice - ice foot prevents oil deposition on shoreline - ice push breaks up stranded oil - ice foot prevents oil reaching the shoreline by reflecting waves	Ice - prevents wave generation and lowers wave-energy levels - ice foot can enclose oil - ice push can bury oil - ice push moves oil above zone of maximum wave activity
Sediment Budget - net loss of sediments leads to abrasion and breakdown of oil	Sediment Budget - net increase of sediments leads to burial of oil
Oil - can increase ice-foot melting and delay ice-foot formation	Oil - reduces breaker heights and therefore mixing or breakdown of oil - can prevent sediment redistrib-ution and therefore abrasion or erosion of oil

7.3.7 Discussion

The complex interactions that control shoreline dynamics are understood in principle, even though some of the explanations of the mechanics of energy transfer may be open to question. The effects of the various forces and factors (i.e., littoral processes) on stranded oil that have been discussed briefly in this section are summarized in Table 13. This table combines some aspects of the deposition, impact and persistence of oil by relating the various factors to the effect that they have on rates of physical breakdown and degradation.

7.4 COASTAL GEOMORPHOLOGY AND OIL ON THE SHORELINE

7.4.1 Introduction

Coastal geomorphology is related to the form of the littoral and backshore zones, and to the types of sediment that occur there. It is critical to remember that shorelines are a dynamic environment. The coastal zone is an interface of the land, sea and air and it is the complex interactions which occur within this zone that result in particular shoreline types and, at a larger scale, coastal environments.

Classifications of coastal landforms are, in general, geographical and are concerned with the characteristics of a shoreline in terms of erosion or accretion, the effects of long-term sea level changes or other similar regional parameters. These geographical classifications provide a general explanation of the features of shorelines. In terms of the impact and persistence of oil on the coast, this type of coastal classification for Canada would be too general and would not provide information on the process and form relationships that characterize the littoral zone.

The coastal geomorphology of Canada's shorelines is discussed in this section in terms of the basic shoreline types (cliffs, beaches, marshes, etc.) and the process factors that cause changes and that result in the actual morphology of that shoreline type. It would be impractical to discuss every combination of rock type, sediment size, wave environment and tidal range that could be found in Canada. The objective of the shoreline-type approach used in this section is to provide a basic outline of the variations in Canada's coastal geomorphology. This information must then be related to the section on littoral processes in order to assess the impact and persistence of oil on a particular section of coast. In this context, for example, it is necessary to relate the expected impact and persistence of oil at a particular site to the shoreline type (e.g., sand or pebble-cobble beaches, marshes, etc.), to the local wave characteristics and to the local tidal range as well as to the type of sediment in the littoral zone. Shoreline energy levels must be considered as they control the physical breakdown of stranded oil. For example, oil tends to collect in sheltered (low-energy) environments where rates of dispersal and degradation would be low. In addition, sediment type is a primary factor in determining the depth to which oil will penetrate a beach, but the frequency of erosion-deposition cycles and the stage of a beach in such a cycle determine the persistence of stranded oil.

Included in this discussion on the expected impact and persistence of stranded oil are general guidelines for onshore protection and clean-up operations. Only existing or proven clean-up methods are presented in this section, and further consideration of onshore protection and cleanup is given in Part 9.

7.4.2 Rock or Cliff Coasts and Oil

On coasts where there is little or no sediment accumulation in the littoral zone, shoreline processes act directly on the coast (Photo 58, page 203). The absence of sediment can be due to a deep nearshore zone, a limited supply of sediment, or a rapid removal of sediment. In all cases the effect is that the normal protective beach is not present to absorb incoming wave energy. Cliffs occur either as a result of high relief in the coastal zone or because the unresistant rocks or the unconsolidated material are rapidly eroded by littoral processes.

These types of shoreline are erosional, and are subject to both marine and subaerial processes. For example, one mechanism by which cliffs erode due to non-marine processes, if air temperatures are below 0°C, is by freeze-thaw action as water in the cliff freezes, expands and then melts. When this happens daily, the material is subject to constant stress and individual blocks of varying sizes break off the cliff face. This eroded material accumulates at the base of the cliff as a talus deposit (Photo 65) if the nearshore zone is not steep or if littoral processes cannot remove material faster than it is supplied. The latter is very common on arctic coasts and many cliffs in this environment have large talus accumulations that

Photo 65. Large accumulations of sediment (talus), eroded from the cliff face by weathering, have buried the lower section of the cliff, Cape Ricketts, Devon Island, N.W.T. (August 1968).

virtually bury the cliff (see also Photo 23, page 92).

Marine action erodes a cliff or rocky coast either by the hydraulic action of waves, by abrasion, or by corrosion from continuous wetting and drying of sections affected by wave spray. Plunging breakers are particularly effective in erosion as air is trapped and compressed when waves break directly on rock or cliffs. The high shock pressures generated by this process result in direct erosion or in a weakening of the rock by expansion along minor joints or cracks. If sediment is present at the base of a cliff this can be used as an abrasive tool by waves to erode the rock or cliff surfaces. The wetting and drying of water thrown up by breaking waves causes the chemical solution of cements that bind the particles together in sedimentary rocks.

Erosion results from the processes outlined above but can also occur in a more spectacular manner. Where waves are able to erode a notch at the cliff base, this undercutting can result in a large rock fall once an unstable situation is created (Fig. 45: 1a). This is most common where a protective beach apron is not present and where waves act directly at the base of the cliff (Photo 66). Where sediment accumulates in the littoral zone and absorbs wave energy, erosion results primarily from non-marine processes, such as freeze-thaw action (Fig. 45: 1b). Where cliffs are of unresistant material, slope failure

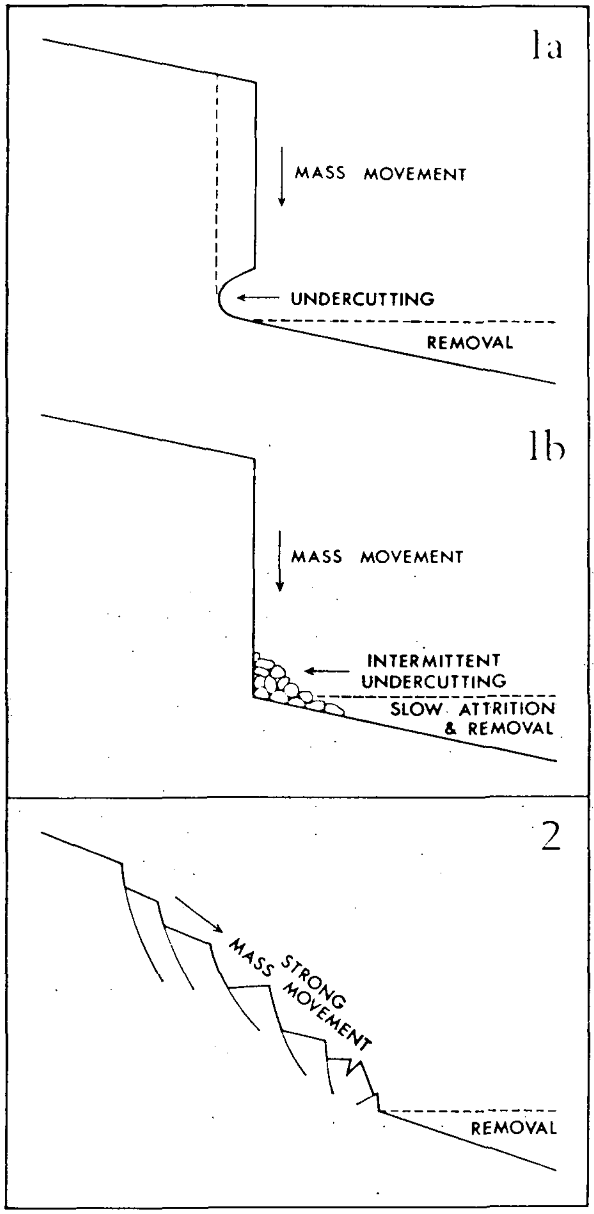


Figure 45. Cliff erosion can result from undercutting followed by a rock fall and sediment removal (1a) or by a rock fall or weathering of the cliff face followed by slow removal (1b). If the cliffs are composed of unconsolidated sediments or unstable rock, mass movement (slumping, slides, and landslips) can result (2) (from Davies, 1972).

Photo 66. Waves have eroded a notch at the high-water mark (arrow) on this cliff of unconsolidated glacial deposits in Chedabucto Bay, N.S.

can occur from undercutting or from internal weaknesses within the cliff, caused by factors such as groundwater erosion or sliding along beds of different material (especially in clays) (Fig. 45: 2).

The local nature of a rock or cliff shoreline depends primarily on the relief in the coastal zone and on the properties of the rock or unconsolidated material. Resistant rocks in areas of high relief tend to produce high, steep cliffs (Photos 33 and 58, pages 131 and 203). Outcrops of sandstone are relatively unresistant to erosion but tend to form steep cliffs because of high internal cohesion within the rock that prevents slope failure.

A major result of the erosion processes is the formation of a platform. This occurs in all cases where a cliff is eroded except when the nearshore zone is deep (Fig. 46). The actual nature and width of a platform depend on the rock or sediment type and on the internal structure of the material. Platforms are discussed more fully below (page 276).

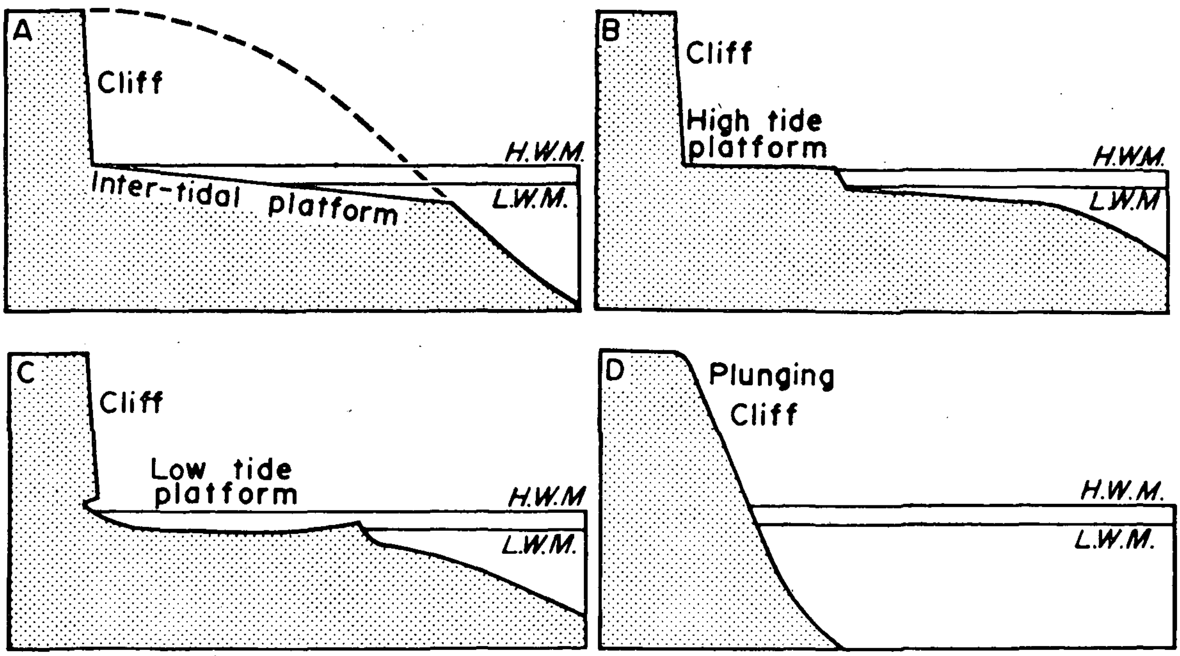


Figure 46. Cliff erosion results in the formation of a platform in the littoral zone (A, B, C) unless the rates of erosion are extremely low due to the resistant nature of the rock (D) (from Bird, 1969).

IMPACT OF OIL:

On steep coasts waves may be reflected and prevent oil from being stranded on the shoreline. If oil reaches the rock or the cliffs it tends to coat exposed surface areas and frequently is splashed onto the surfaces above the breaker or swash zones as the waves break. Oil does not adhere well to wet surfaces and, if deposited in the intertidal zone on wet rock during an ebbing tide, is frequently refloated and subsequently deposited at a higher level by the flood tide.

The angle of slope is important in determining the thickness of stranded oil. Where slopes are steep oil tends to float down the surface, due to gravity, and this results in a thinner, residual layer. Oil collects in crevices and rock pools due to this downslope movement and as the tide ebbs. This oil may be released later, either during a normal high tide or during a spring tide or storm surge. This is particularly evident in Photograph 67 which shows a low rocky coast with many surface irregularities that would act as traps and collect-

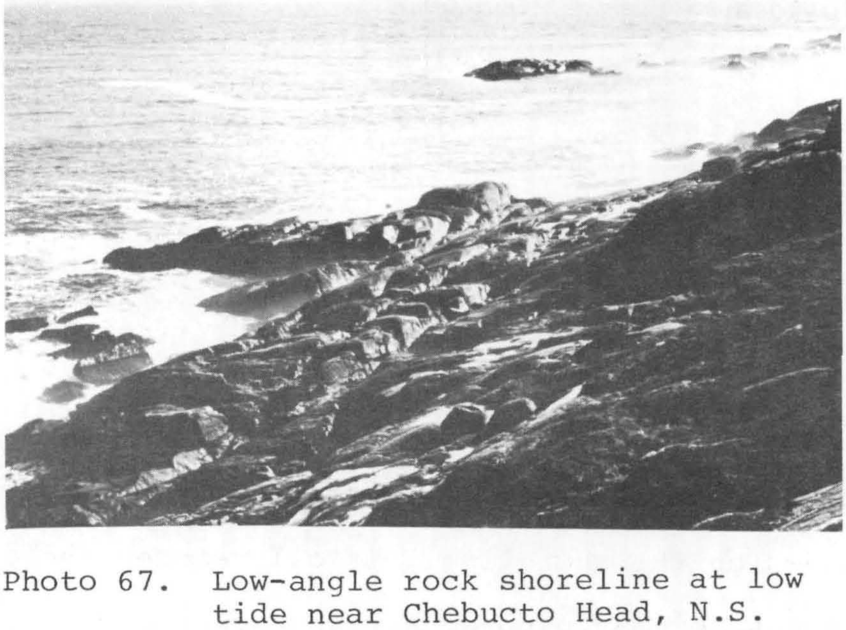


Photo 67. Low-angle rock shoreline at low tide near Chebucto Head, N.S. (see also Photo 37, page 136).

ing pools for stranded oil (see also Photo 37, page 136). If the rock or cliff has an intertidal beach (Photo 66), oil would be deposited above the high-water level only during storm surges or by the action of wave spray.

PERSISTENCE OF OIL:

Oil stranded in the intertidal zone would be abraded by wave action or would be weathered (Photo 68). If stranded above the normal limit of wave activity it would only be affected by

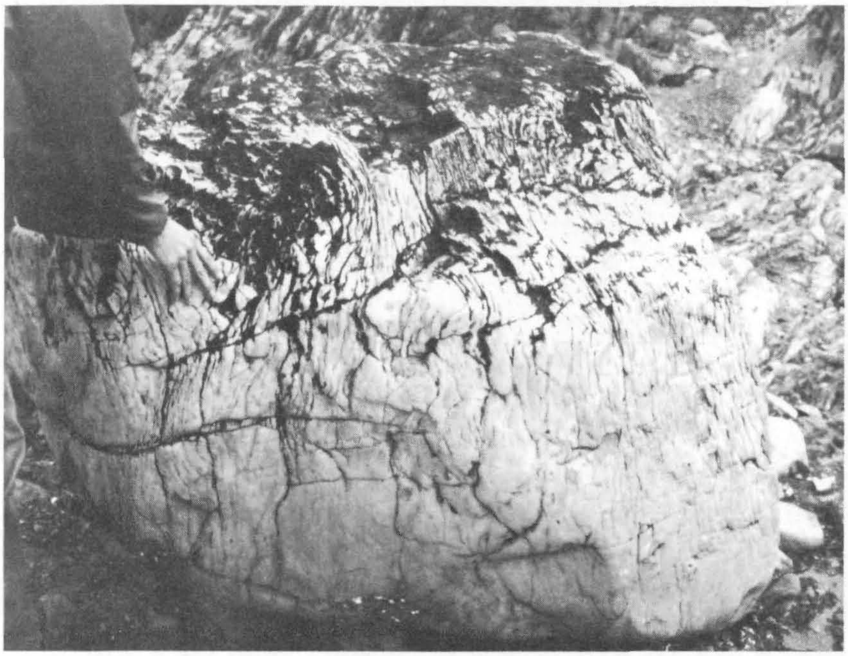


Photo 68. Oil on a large boulder at the high-water level on Crichton Island, Chedabucto Bay, N.S. The oil stranded on the rock was abraded and dispersed by wave action except on the upper parts which were rarely affected by wave activity. (Photo 3 1/4 years after the spill, May 1973 by J.R. Belanger, Bedford Institute) (c.f., Photo 92, page 299).

marine processes during periods of storm waves or high water levels, and rates of persistence would depend primarily upon weathering and cliff erosion. During the "Arrow" spill, oil was stranded during periods of spring tides at many sites. This oil was refloated during subsequent spring tides from pools and crevices and recontaminated adjacent shorelines.

On unresistant or unconsolidated cliffs, non-marine erosion would be important in determining the persistence of oil. As a cliff retreats due to normal erosion by waves or by weathering, oil would be carried downslope and be either buried in the talus accumulation or would be abraded and dispersed by wave action. The rate at which burial or dispersal would occur is clearly related to the rate of cliff erosion. Where marine processes are active in eroding a shoreline, or in removing talus deposits, the removal of oil would be rapid. On arctic coasts, characterized by large talus accumulations (Photo 65), the oil would be buried and would be subject to very low rates of abrasion and dispersal by waves.

Persistence of oil on rocky or cliffed coasts depends on the rates of natural erosion (which are high for low-resistance materials), on the levels of wave energy, and on the location of the oil. Contamination of a cliffed coast, composed of resistant rocks in a sheltered environment above the high-water mark would result in very low rates of degradation.

Conversely, oil on exposed coasts is removed rapidly if subject to wave action.

ONSHORE PROTECTION:

Little if anything can be done to protect this type of shoreline. If the gradient is low and cleanup is planned, sorbents could be spread on the surface before the oil is washed ashore. This would facilitate later removal of the oil. As oil does not readily adhere to wet surfaces, water could be sprayed on the rocks before the oil is washed ashore. This is only useful if the water does not evaporate. If air temperatures are below freezing, water sprayed onto rocks or man-made structures would freeze and the ice layers could prevent oil being stranded directly on the surface in question.

If there is a beach at the base of the cliff or rock outcrop, a dyke could be built by mechanical equipment pushing sediment up from the beach to prevent the oil being deposited in backshore areas.

CLEAN-UP METHODS:

Hydraulic dispersal (high-pressure or low-pressure hoses), steam cleaning or sandblasting can be used to remove oil from rock surfaces. These techniques only disperse the oil, which would then have to be collected and removed. If oil is deposited on unconsolidated material these techniques are not recommended as the cliff face would be washed away (e.g., Photo 66).

Where oil collects in pools or hollows it can be removed manually, with sorbents if available, or can be picked up with cans, buckets or portable vacuum skimmers (Berry and Wolfe, 1975). If planned this should be carried out before tides can release the oil to adjacent areas. Intertidal vegetation can be cropped effectively to prevent subsequent release of trapped oil, but this should only be carried out in consultation with biologists.

Usually cliff or rock coasts will be self-cleaning, except in low-energy environments. The primary clean-up requirements would be to collect oil that could be released at a later time during high water levels and that could then contaminate or re-contaminate adjacent shoreline areas.

CLEAN-UP GUIDELINES:

Manual removal by cropping oiled vegetation, by using buckets, cans or pumps, or by scrubbing can be effective on rocky or cliffed coasts. High-pressure hoses, steam cleaning or sandblasting should only be used on non-biologically sensitive resistant rocks or on man-made structures. Application of these techniques on unconsolidated or unresistant cliffs (Photo 66) could result in induced slumping, sliding or rock falls, which would be dangerous to personnel in the area. Low-pressure hoses incur less biological damage but again should not be used on unconsolidated or unresistant cliffs. This technique only disperses oil and is best utilized to transfer oil onto adjacent water surfaces for collection by skimmers. Unresistant cliffs should not require cleaning as natural marine or non-marine processes rapidly erode the cliff and therefore, disperse the oil into the intertidal zone. In low-energy environments where a beach is present at the base of an unconsolidated cliff, removal of contaminated beach sediment can cause erosion of the cliff (Photo 69). The beach protects the cliff by absorbing wave energy. Removal of oiled beach material would expose the cliff to direct wave action, and erosion would follow until sufficient material replaces that which was removed.

Photo 69. Cliff of unconsolidated material at Arichat, N.S. Initial removal of oil from the intertidal zone by a bulldozer removed the protective beach and cut a notch (arrow) at the base of the cliff. This could easily have led to erosion of the cliff and damage to property if remedial action had not been taken.

SUMMARY: Rock or Cliff Coasts and Oil

(1) *Shorelines are eroded by littoral (hydraulic action, abrasion or corrosion) and non-marine (freeze-thaw, rock falls or land slides) processes.*

(2) *Cliffs can be buried if marine processes are unable to remove sediments that accumulate at the base of the slope.*

(3) *On steep shorelines wave reflection may prevent oil reaching the rocks or cliffs. On low-angle slopes oil collects in pools and hollows as the tide ebbs.*

(4) *Oil in the intertidal zone is abraded if sufficient wave energy is available; above the limit of wave activity oil would be dispersed as the cliff faces are eroded by weathering processes.*

(5) *No effective protection methods can be recommended, except to spread sorbents on low-angle slopes or to spray water over the rock surface.*

(6) *Resistant rock surfaces and man-made structures can be cleaned with hoses, steam cleaning or sandblasting. These methods should not be used on unresistant or unconsolidated cliffs or in biologically sensitive environments.*

(7) *Low-pressure hosing can disperse oil from rocks and man-made structures onto adjacent water surfaces for collection.*

(8) *Manual removal from pools or hollows prevents recontamination of adjacent shorelines.*

(9) *Sediment removed from the base of the cliff exposed the cliff to marine action and, therefore, erosion.*

7.4.3 Beaches and Oil

Sediments in the littoral zone act as natural collectors of oil and in most cases the removal of oil from beaches is neither simple nor easy. In this discussion, distinctions are drawn between (a) sand and (b) coarse-sediment beaches, and (c) pocket or bay beaches and (d) barriers or "free beaches".

(a) Sand Beaches: The form of a sand beach is related to the action of waves and to the tidal range. Usually waves build up a flat berm above the high-water mark (see Appendix, page 401). The beach is subject to cycles of erosion and deposition as levels of incoming wave energy vary (page 187 f.f.). In addition, with each tidal cycle, small-scale phases of erosion and deposition during the ebb and the flood tides are common (Fig. 47). As sand-sized sediments are closely packed, and therefore the voids between the particles are relatively small, the backwash usually has a velocity nearly equal or equal to the swash, due to the low infiltration of water into the beach. Plunging breakers act somewhat differently and produce strong backwash velocities due to the downward motion of water from the wave crest.

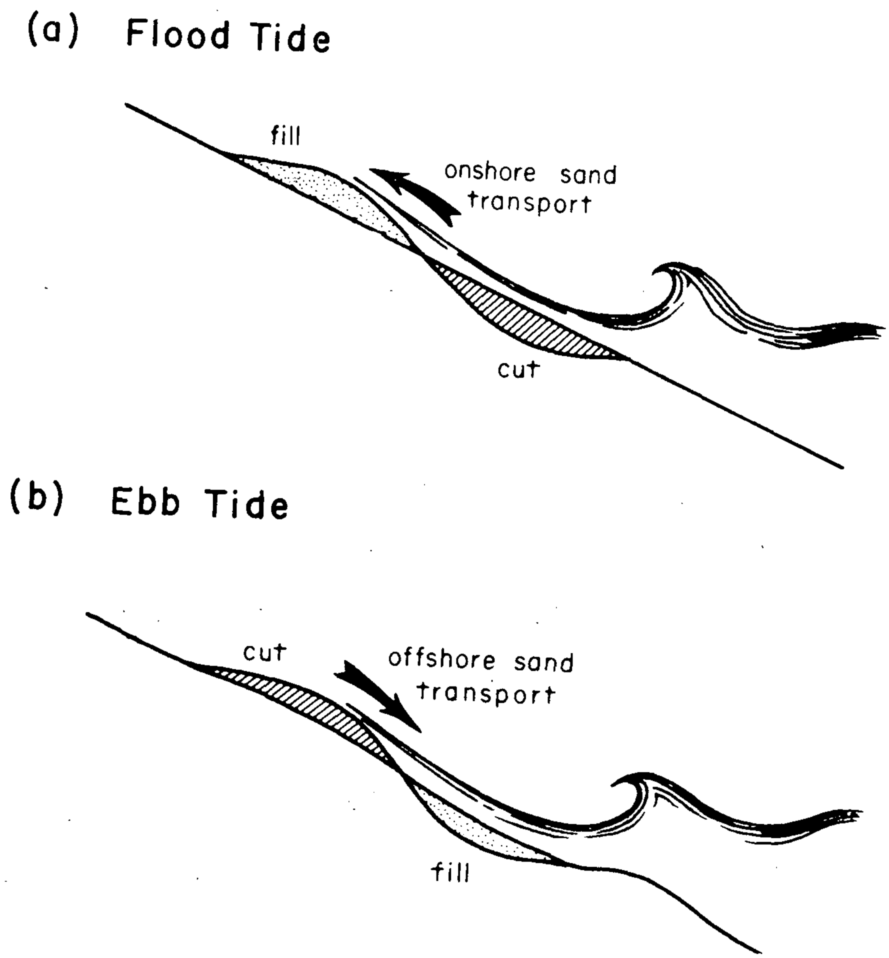


Figure 47. Small-scale erosion and accretion in the intertidal zone during the tidal cycle (after Komar, 1976).

IMPACT OF OIL:

The nature of oil contamination depends primarily on the type of oil. Free-flowing oils with low viscosities can penetrate the small pore spaces between particles. Heavy, more viscous, oils tend to remain on the sand surface (Photos 70 and 71) but with increases in temperature, and a corresponding decrease in the viscosity, these heavy oils are able to

Photo 70. Oil deposited on a sand beach above the high-water level (arrow), Hadleyville, N.S. (August 1970).

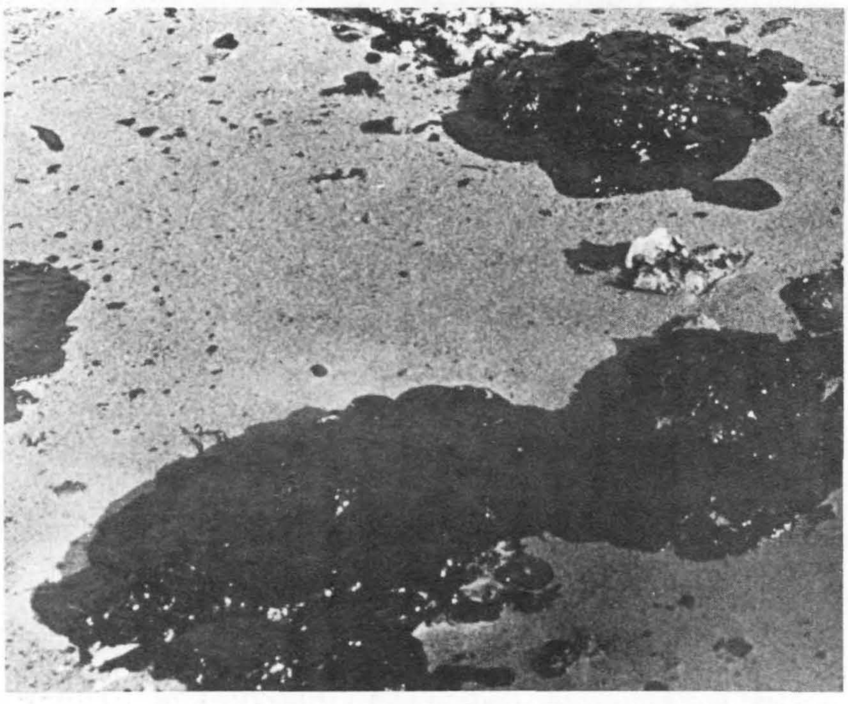


Photo 71. Fresh oil from the "Arrow" on the surface of a sand beach, Crichton Island, N.S. (Photo by G. Drapeau, March 1970).

slowly penetrate the surface sediments. If wave-energy levels are low or if the volume of oil washed ashore is high, the oil can coat the entire intertidal zone. Usually the process of erosion during an ebb-tidal phase with deposition at the turn of the tide and during the flood stage concentrates oil in the upper intertidal zone. If water levels are high due to spring tides, storm surges or high wave-energy conditions, the oil can be deposited on the berm above the limit of normal wave activity (Photos 59, page 211, and Photo 70).

PERSISTENCE OF OIL:

The timing of contamination is very important in the determination of the persistence of oil. As discussed earlier, oil deposited during an erosion phase can be buried as the beach recovers (Fig. 38, page 192) and then it can be exposed in the beach face during a subsequent period of erosion (Fig. 38(f) and Photo 51, page 193). Similarly, if the beach has a summer-winter cycle, timing is once again important (see page 194).

Oil deposited in the zone of wave activity is usually dispersed rapidly but where levels of wave energy are low, oil can persist for a long time as waves rarely modify the beach morphology. Similarly, oil deposited above the high-water mark is rarely affected by wave action as was evident on the sand beaches in the Straits of Magellan. On this shoreline, oil from the "Metula" remained above the spring high-water mark 2 1/2 years after the spill (Photo 59, page 211). It should be noted that the site in Photograph 59 is in a relatively sheltered wave environment. Wave action reworks and disperses the intertidal sediments at this location but, due to the short fetches (<50 km), high waves that could erode the backshore areas are not generated. In addition, on this coast the prevailing and dominant winds blow onshore, so that the oil was not buried by wind-transported sediments.

Where the cover of oil is thick, dispersal is slower. If the oil layer is not broken up by wave action it can be removed and dispersed slowly by erosion along scarps at the edges. These scarps can occur at the base or at the top of the oil layer. A scarp at the base of the oil layer is eroded by swash action whereas at the top of the oil layer (Photo 72) the scarp results from erosion by the backwash.

ONSHORE PROTECTION:

In areas of low tidal range the beach can be protected by construction of a dyke or windrow at the water level. This can be carried out by machinery pushing sand to the water line. In tidal areas a dyke could be built at or near the high-water level to prevent oil being deposited on the backshore. A dyke would be useful in the middle or lower intertidal zones only if it is sufficiently high so that it is not overtopped by the flooding tide; usually this is not practical. As wet sand

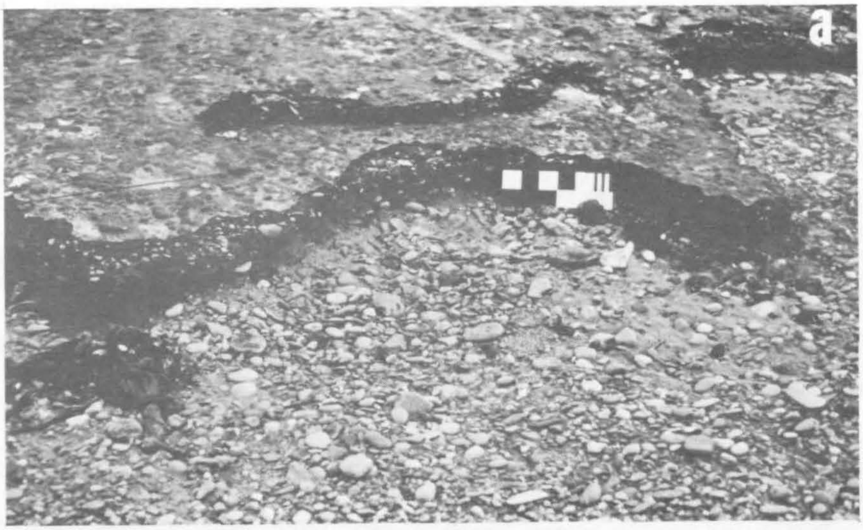


Photo 72. Erosion along the upper edge of an oil "pavement" by backwash action. South shore, Straits of Magellan, January 1977, in a sheltered environment with a mixed sand-pebble beach, 2 1/2 years after the spill; (a) is located by the arrow in (b).

makes a more effective dyke, the sediment from the intertidal zone should be used rather than dry backshore sand.

Sorbents can be spread over the beach at low tide if cleanup is planned. These would then mix with the oil as it is washed ashore and could make the subsequent cleanup easier. Sartor and Foget (1971) note that sorbents are much more effective if laid down prior to or immediately following the stranding of oil, as this reduces the penetration of the oil into the sediments.

Chemical or natural agents spread on a beach can prevent contamination but these are still in development or assessment stages (Foget *et al.*, 1977).

CLEAN-UP METHODS:

For small spills or in areas where vehicular access is not possible, manual removal using shovels, rakes, and plastic bags is an effective and recommended technique (Photo 73). This is a labor-intensive operation and can, therefore, be expensive.

Mechanical removal is a proven and recommended method for large spills on sandy beaches (Sartor and Foget, 1971). The actual technique would vary depending on the available equipment and on the bearing capacity of the beach sediments. The most efficient machines have been found to be a combination of graders and elevating scrapers Graders are used to form windrows which are then removed by the elevating scraper or

Photo 73. Manual removal of oil from a sand beach, Point Michaud, N.S., May 1970.

elevating scrapers can be used alone. If the bearing strength of the beach is low, tyre pressures may be lowered or flotation tyres may be necessary to prevent the equipment becoming stuck or mixing clean sediments with oil. Front-end loaders can be used to pick up smaller amounts or isolated patches of oil (Photo 70), but are not as efficient as graders and/or scrapers for large-scale cleanup, due to spillage from the bucket. Tracked front-end loaders are less preferable as the tracks tend to thoroughly mix oil and sediment. Bulldozers are the least preferred machinery, as it is difficult to control the blade accurately and sand spills around the blade edges. A set of recommended mechanical restoration procedures are outlined in Table 14.

TABLE 14. Recommended Mechanical Restoration Procedures for Sand Beaches (from Sartor and Foget, 1971).

RESTORATION PROCEDURE	METHOD OF OPERATION
A. Combination of motorized grader and motorized elevating scraper	Motorized graders cut and remove surface layer of beach material and form large windrows. Motorized scrapers pick up windrowed material and haul to disposal area for dumping or to unloading ramp-conveyor system for transfer to dump trucks. Screening system utilized to separate beach debris such as straw and kelp from sand when large amounts of debris are present.
B. Motorized elevating scraper	Motorized elevating scrapers, working singly, cut and pick up surface layer of beach material and haul to disposal area for dumping or to unloading ramp-conveyor system for transfer to dump trucks. Screening system utilized to separate beach debris such as straw and kelp, from sand when large amounts of debris present.
C.* Combination of motorized grader and front end loader	Motorized graders cut and remove surface layer of beach material and form large windrows. Front end loaders pick up windrowed material and load material into following trucks. Trucks remove material to disposal area or to conveyor-screening system for separation of large amounts of debris from sand.
D.* Front end loader	Front end loaders, working singly, cut and pick up surface layer of beach material and load material into following trucks. Trucks remove material to disposal area or to conveyor-screening system for separation of large amounts of debris from sand.

* Utilize restoration procedures C and D only in instances where motorized elevating scrapers are not available. Operations of front end loaders on oil-contaminated beach areas should be kept to a minimum.

In cases where it is not necessary to remove the oil, machinery can be used to <u>push the oil and contaminated material into the intertidal zone</u>. Wave action will subsequently abrade and disperse the oil as the sediment is moved back up the beach. In this way rates of dispersal and degradation are increased without the necessity of removing any sediment from the beach. This procedure may have to be repeated to fully disperse the oil.

In sheltered environments where oil coats the entire intertidal zone and where cleanup is not necessary, machinery can be used to break up the oil cover and to expose larger surface areas of the oil, thereby increasing the rates of degradation. For spills that involve light-grade oils, which rapidly penetrate the beach, a mechanical rake or harrow can be used to turn over the beach sediments in order to expose the oil and, therefore, accelerate rates of evaporation.

Sand-cleaning machines have been developed for the removal of oil, but these have only been used in experimental situations or for minor spills. Mobile equipment has been developed for removing tar lumps from the surface of beaches using screens or sieves and these are discussed below (page 348).

CLEAN-UP GUIDELINES:

In all cases the objective of the clean-up programme should be to remove as much oil and as little beach material as possible. To achieve this it is advisable to remove the oil as soon as possible after the spill reaches the beach, before the oil can penetrate deeply into the sediments. The use of sorbents spread on the beach before the oil is stranded can prevent the penetration of the oil into the beach. Beach cleanup, however, should not be attempted until all danger of recontamination is passed, otherwise it may be necessary to re-clean the same beach. This is particularly important if the sediment supply to the beach is limited (see pocket beaches, page 271).

The beach berm acts as a natural dyke to protect backshore areas and the removal of large volumes of sediment from the berm on any beach permits waves to wash-over the beach crest. This can lead to backshore erosion or flooding if sufficient time has not elapsed for natural replacement of the removed sediment. If removal of sediment from the beach crest is necessary, it is advisable that the material be replaced by an equal volume of the same-sized sediment. This can be achieved using machinery to push material from backshore areas to rebuild the natural berm.

SUMMARY: Sand Beaches and Oil

(1) *Only light-grade oil penetrates sand beaches.*

(2) *Oil is usually deposited on the upper parts of the beach; in low wave-energy environments or if large volumes of oil are washed ashore, the oil can coat the entire intertidal zone.*

(3) *Normal cycles of beach erosion or deposition will cause removal or burial of stranded oil. Buried oil degrades very slowly.*

(4) *Dispersion and degradation rates in the intertidal zone are controlled by wave-energy levels.*

(5) *Onshore protection using sorbents or construction of dykes can be effective.*

(6) *Manual removal is recommended for small spills; graders and elevating scrapers are recommended for large spills.*

(7) *Evaporation of light-grade oils can be accelerated by mixing of the surface sediments.*

(8) *If cleanup is not required oil can be pushed into the intertidal zone for reworking by waves or the oil cover can be broken up by machinery to increase rates of degradation.*

(9) *If large volumes of sediment are removed these should be replaced. Berms can be rebuilt using backshore sediments.*

(b) Coarse-Sediment Beaches: Due to the large spaces between sediments on this type of beach (pebbles-cobbles-boulders), swash infiltrates rapidly and backwash velocities are, therefore, usually low. As a result of this and the fact that the large size of the sediment particles gives a higher angle of repose (q.v.), coarse-sediment beaches have a narrower and steeper beach-face slope than sand beaches. A second effect of sediment size and the predominance of swash over backwash, is the construction of a storm ridge landward of the berm (Fig. 41, page 198). This ridge is built by swash action during periods of storm waves, that pushes material up the beach. This ridge is a natural dyke that is only breached or overwashed during major storms.

These beaches are subject to cycles of erosion and deposition as discussed above (page 188) with the major difference being that during storms material is removed seawards by swash and is pushed over the berm to form the storm ridge (Photo 74, Fig. 41, page 198, and Photo 54, page 199). If there is a net loss of material from the intertidal zone due to low rates of sediment input from alongshore, this results in a slow net landward movement of the beach system.

Photo 74. Pebble-cobble beach with berm and storm ridge (A), debris (B), and overwash deposits (C), at Scots Bay, N.S., Bay of Fundy, (see also Photo 54, page 199).

The shape of the pebbles, cobbles or boulders can often be used as an indicator of wave-energy levels. In sheltered or low-energy environments the sediments tend to be angular or have few rounded edges (Photo 75). This is true even if the

Photo 75. Angular rock fragments in the intertidal zone on a low-energy beach, Arichat Harbour, N.S.

source material is unresistant sedimentary rock fragments, and is particularly common on arctic beaches (McCann and Owens, 1969). As levels of wave energy increase, abrasion of sediment particles against each other results in very rounded material with no edges or flat faces (c.f., Photo 55, page 199, and Photo 75).

Another indicator of energy levels on beaches is the degree of sorting (i.e., the degree to which different sizes of sediment are preferentially transported and deposited). On low-energy coasts, sediments are usually a poorly-sorted mixture of sands, pebbles, cobbles and boulders (Photos 66, 72a and 75). As energy levels increase, sorting of the material also increases and the beach is composed of only one size of sediment (Photo 55, page 199, and Photo 73) or the sediments have a distinct zonation across the beach (Photo 54, page 199, and Fig. 41, page 198).

IMPACT OF OIL:

The impact of oil on coarse-grained beach sediments is to penetrate into the material through the large spaces between individual particles. The actual depth of penetration varies depending on the size of the spaces and on the viscosity of the oil. On low-energy coasts, the sediments are usually poorly sorted and the spaces between the larger particles are filled with sand so that penetration is prevented. As energy levels and sorting increase, and only pebbles and cobbles occur on the beach, the size of the spaces and the penetration of the oil increases. In Chedabucto Bay, Bunker C oil was found at depths up to 1.5 m below the surface on cobble beaches shortly after the oil was stranded.

Except where large amounts of oil are washed ashore (Photo 46, page 182), deposition occurs primarily on the upper beach face and on the low-tide terrace (Photos 76 and 77). Deposition on the upper beach face occurs during the slack water period at the turn of the tide or above the intertidal zone during periods of high-water levels when waves overtop the beach crest (as in the case of Photo 76). Deposition on the low-tide terrace

Photo 76. Oil deposited between the beach crest and storm ridge at Hadleyville, N.S., August 1970. The arrow indicates the normal high-water level.

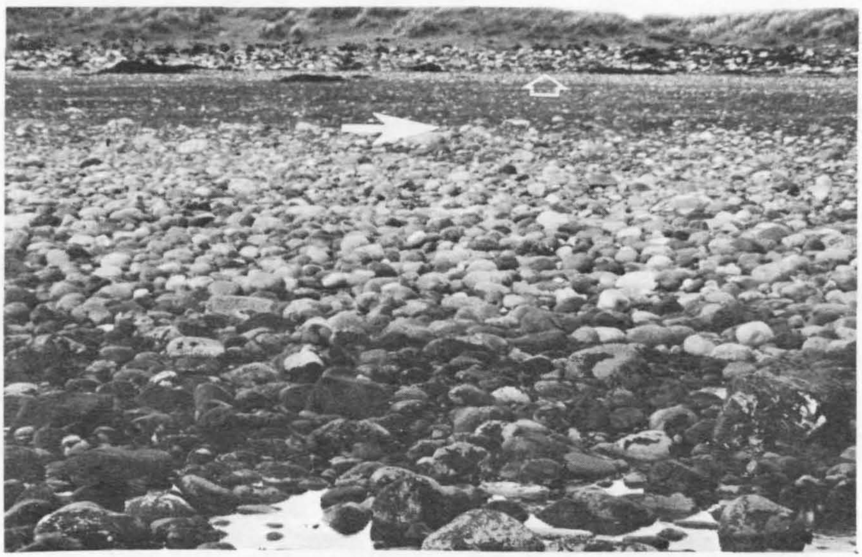


Photo 77. Oil on the low-tide terrace of a cobble beach, north shore, Straits of Magellan, January 1977. The solid arrow marks the junction of the beach face and low-tide terrace, the open arrow indicates the normal high-water level.

occurs as the tide ebbs and swash action washes oil across the pebble or cobble sediments. Oil is trapped in the voids between the particles and if the sediments are dry, will readily adhere to the sediment surfaces. If deposition occurs on the central beach-face slope, the amounts of oil stranded there are usually lower than on the upper and lower parts of the intertidal zone as the water level changes more rapidly over this part of the beach.

PERSISTENCE OF OIL:

Oil stranded on the beach-face slope is usually abraded and dispersed rapidly by the constant movement of sediments, unless the oil layer is very thick and/or wave-energy levels are low. Photo 47a (page 183) shows a cobble-boulder beach less than 3 months after being heavily oiled. In this example, the beach-face slope is virtually clean. On the low-tide terrace oil persists because of the low rates of sediment redistribution and because of the lower wave-energy levels that result from a predominance of spilling breakers across the terrace during low tides (Fig. 34, page 180). In addition, rates of erosion and abrasion are low as oil fills the voids and inhibits or prevents sediment movement. When this occurs the surfaces of the pebbles or cobbles are often abraded and cleaned of oil but the oil remains unaffected by abrasion in the spaces between the sediments (Photo 78). On these low-

Photo 78. Part of an "asphalt pavement" in a low-tide terrace in the Straits of Magellan, 2 1/2 years after the spill. Oil has filled all the spaces between the cobbles but has been abraded from the exposed upper surfaces.

tide terraces, or in a sheltered wave environment with a thick oil cover, the sediments can become immobilized and resemble an "asphalt pavement". Dispersal of the oil then occurs very slowly as the result of erosion of scarps along the edge of the oil cover (Photo 79)

Above the high-water mark oil remains unaffected except by storm-wave activity. As material is pushed up the beach during periods of high levels of wave energy this can result in burial of the oil (Photo 56, page 200, and Fig. 42, page 201). Burial and exposure of one or more oil layers in the upper beach face can occur if oil is washed ashore over a

Photo 79. Part of an "asphalt pavement" in the upper intertidal zone on Crichton Island, N.S., 3 1/2 years after the spill (Photo by J.R. Belanger, Bedford Institute).

period of time which includes several cycles of storm-wave action (Photo 57b, page 202).

Light grades of oil penetrate deeply into the beach sediments but may be washed out by swash that returns seaward below the beach surface.

Rates of change on coarse-sediment beaches are lower than on sand beaches, due to the higher amounts of energy required to move these larger-sized sediments. As a result, for beaches with the same levels of incoming wave energy, rates of abrasion and dispersion of oil are lower on coarse-sediment beaches when compared to sand beaches.

It is possible to obtain an estimate of energy levels on a beach, and therefore an estimate of rates of abrasion, from the shape and sorting of the beach material. As roundness and sorting increase, so the expected rates of abrasion and dispersion increase.

ONSHORE PROTECTION:

No effective protection methods can be recommended but sorbents spread over the beach can reduce the penetration of oil. This technique is less effective if the spaces between the sediments are large and collection of the oil-sorbent mixture is frequently a difficult operation. Dykes can be built in the same manner as described above (page 251) but are less effective than on sand beaches as oil penetrates through voids into the sediments. However, dykes at the high-water mark can protect backshore areas by acting as collectors of oil and thus preventing it from reaching sensitive areas such as marshes (Photo 54, page 199).

CLEAN-UP METHODS:

Removal of oil from coarse-sediment beaches is difficult due to the deep penetration of the oil. As a result of this penetration and the size of the sediments the oil-sediment ratio is very low and large volumes of material are removed for relatively small amounts of oil. Owens (1971) found that samples collected from the intertidal zone of a contaminated pebble-cobble beach in Chedabucto Bay contained only 4% to 5% of oil by volume.

Mechanical equipment is difficult to use on these beaches because of the low traction provided by the sediments. Graders and scrapers cannot be used and front-end loaders are the only effective equipment, although their efficiency is low. In Chedabucto Bay, front-end loaders were used to remove layers of oil on the upper beach successfully when handled carefully (Photo 80). The bucket was used to skim the surface sediments and care was taken to remove only small amounts of material at a time. A front-end loader is designed to move large volumes of material but, as the bucket was only partially filled to avoid spillage, the operation was inefficient in terms of the uses for which the equipment was designed.

Photo 80. Front-end loader carefully removing a thin (10-20 cm) layer of oil and sediment, Indian Cove, N.S.

If removal of the oil is not required the contaminated sediments can be pushed down the beach in order to allow waves to abrade and disperse the oil as the material is pushed back up the beach. This is particularly useful if the oil is stranded above the high-water mark beyond the normal limit of wave action, but the operation may have to be repeated once or more to effectively disperse all the oil on the sediments. In cases where oil coats the intertidal zone, or the low-tide terrace, machinery can be used to break up the oil cover. When the oil and sediments form an "asphalt pavement" this is recommended as it remobilizes the beach material and increases rates of degradation and dispersion.

Manual removal can be used if the volume of oil on the beach is not great and if the oil is on the surface. This is a slow process and is labor intensive but avoids the problem of large-scale sediment removal.

CLEAN-UP GUIDELINES:

As rates of transport are relatively low on pebble, cobble or boulder beaches due to the large size of the sediments, rates of replacement of removed material are also low. These rates decrease as the size of the material increases. In principle, therefore, any material removed should be replaced by sediment of a similar size. Non-replacement of material taken from the berm or storm ridge can result in waves washing over the beach crest, moving the beach landward and flooding or eroding backshore areas. An example of beach erosion caused by sediment removal is given in Figure 48. This set of beach profiles from Indian Cove in Chedabucto Bay shows (a) the amounts of sediment removed, and (b) the effects of the removal after a 12-month period. In sections of this beach the crest moved landward as much as 20 m. Subsequent profiles in 1973 show that the beach stabilized at the May 1971 position (Owens and Rashid, 1976).

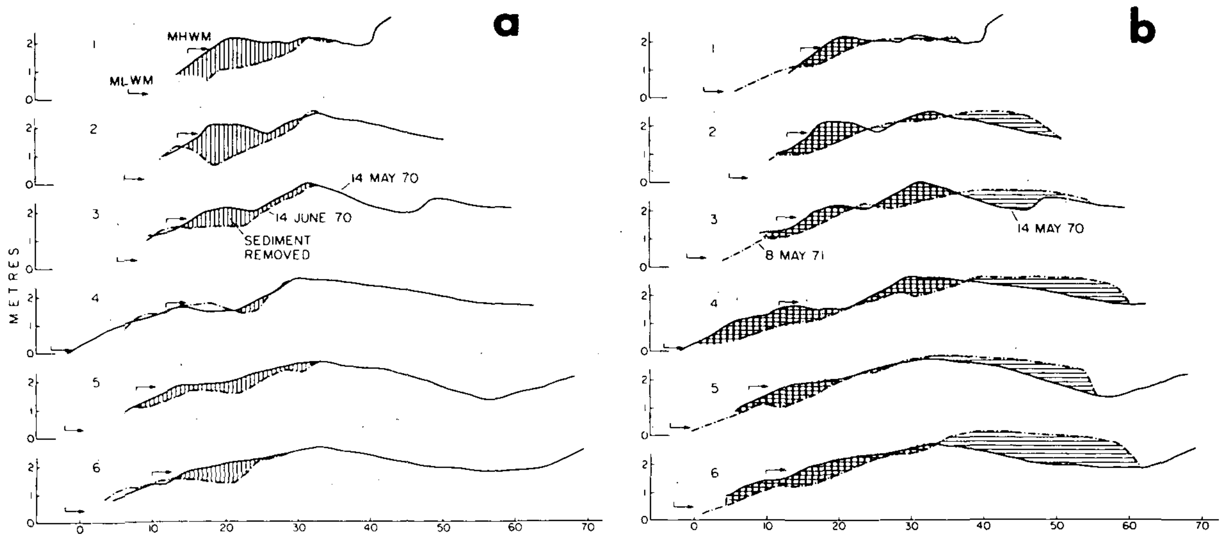


Figure 48. A sequence of profiles across the beach at Indian Cove, N.S. The first two profiles (a) are the beach before (14 May 1970) and immediately following (14 June 1970) sediment removal during a clean-up programme. A subsequent survey (b) one year later (8 May 1971) illustrates the retreat of the beach crest. The horizontal shading indicates areas of net sediment gain, the cross-hatch indicates net sediment loss (after Owens and Rashid, 1976).

Replacement of material removed from the upper beach or storm ridge could be achieved by pushing overwash sediments from the backshore into the removal area (from area (c) in Photo 54, page 199, and Photo 74, page 259). This would effectively prevent waves washing over the top of the beach.

SUMMARY: *Coarse-Sediment Beaches and Oil*

(1) Sediment shape and sorting are indicators of energy levels. Angular, poorly-sorted material reflects low-energy environments; rounded, well-sorted material occurs in environments with higher energy levels. This information can be related to the expected persistence of oil.

(2) Oil penetrates into beaches that have large open spaces between particles.

(3) Oil is usually deposited on the upper beach or on the low-tide terrace; where energy levels are low or if large volumes of oil are washed ashore, oil can contaminate the entire intertidal zone.

(4) Oil that is buried, that forms an "asphalt pavement", or that is deposited on the berm or the storm ridge is only slowly abraded and degraded.

(5) Sorbents can reduce penetration of the oil and can facilitate cleanup. Dykes can prevent or reduce oil deposition on the backshore.

(6) *Manual removal of oil is recommended for small spills; mechanical removal (front-end loaders) for large spills.*

(7) *If material is removed it should be replaced; this can be done by using sediment from the backshore area.*

(8) *Oil can be dispersed by wave action if it is pushed into the intertidal zone and an "asphalt pavement" can be broken up by machinery. This increases the rates of natural degradation.*

(c) Pocket Beaches: The impact, persistence and cleanup of oil depends on sediment type and energy levels and these aspects are discussed in the sections above. A few additional considerations, however, are presented here that relate to this shoreline type.

This type of beach occurs on rock or cliff coasts. Beaches form in bays or coves where sediment collects due to local erosion (Photo 81) or to interruption of a longshore sediment transport system. The latter can occur on a large scale as in the Bay of Fundy (Fig. 49). These two examples illustrated in Photograph 81 and Figure 49 show that pocket or bay-head beaches can occur on widely different scales.

In the same manner that pocket beaches act as collectors of sediment, they can also act as collectors of oil which would be

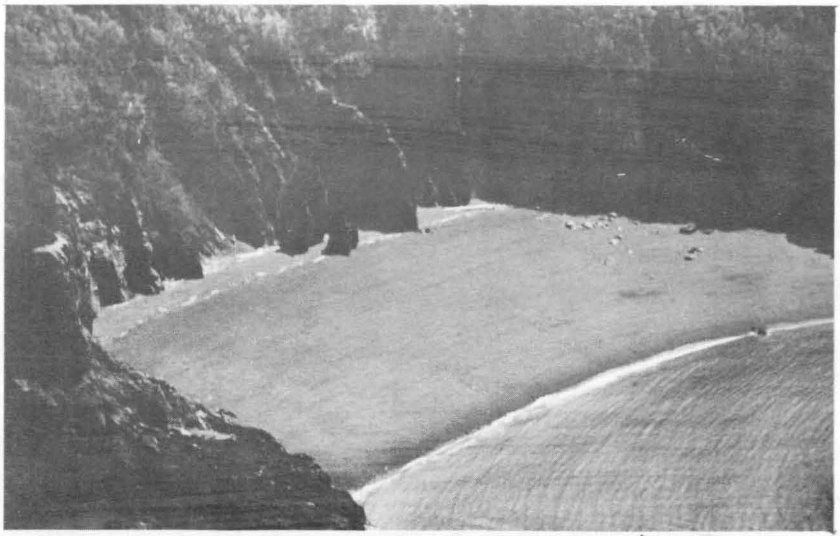


Photo 81. Pocket beach on a rocky, cliffed shoreline, south coast, Chignecto Bay, N.S.

trapped in these bays or coves. In cases where the margins of a bay are rocky or steep, oil would not be stranded there if waves are reflected but would be deposited on the bay-head beach. If oil is stranded on the adjacent rocky shores there is a danger of later contamination or recontamination of the bay-head beach if the oil is released by normal or spring high tides.

With onshore winds or storm waves, water levels can be raised as water is piled up against the beach in bays or coves. Oil on the water under these conditions would be trapped and would probably be deposited above the high-water mark and possibly washed over the berm or storm ridge (Photo 74, page 259).

Pocket beaches usually have a low rate of sediment input, as they occur in areas where rock headlands interrupt longshore

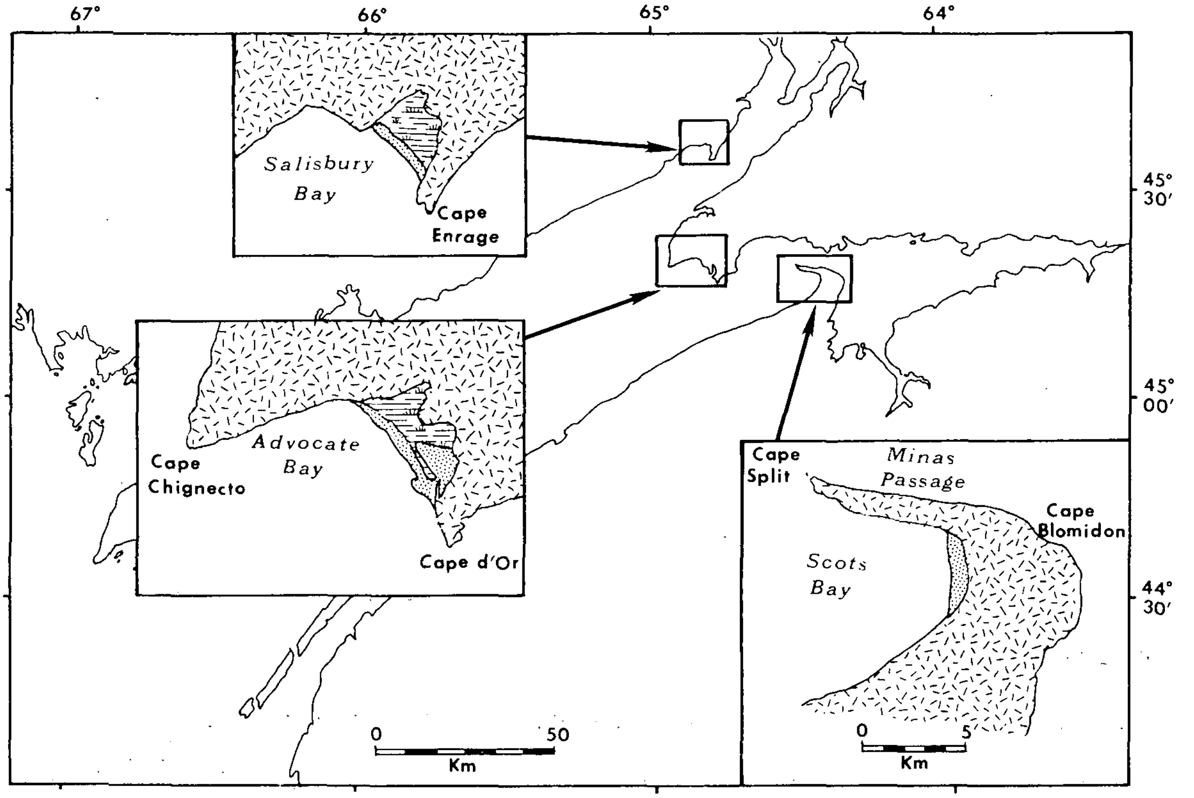


Figure 49. Large embayments with pocket beaches in the Bay of Fundy. Beaches are indicated by the dot pattern. Figure 41 (page 198) presents an idealized profile across one of these pocket beaches.

transport, so that any material removed is only slowly replaced. This was the case in the Indian Cove cleanup in Chedabucto Bay (Fig. 48, page 269) where material was removed and a rapid retreat of the beach followed. Material removed from this type of beach should, therefore, be replaced.

SUMMARY: Pocket Beaches

(1) Pocket or bay beaches are potential traps for oil.

(2) *These beaches can be recontaminated by oil released from adjacent rock shorelines.*

(3) *Rates of sediment input are usually low, so that it is advisable to replace any sediment removed during cleanup.*

(d) "Free Beaches": The impact, persistence and cleanup of oil depends on sediment type and energy levels and these aspects are discussed in the sections above. A few additional considerations, however, are presented here that relate to this shoreline type.

This type of beach is one in which the longshore transport of material in the littoral zone is not interrupted by cliffed sections or by rock headlands (e.g., Photo 8, page 39). Shoreline changes are usually more rapid on this type of beach as the rates of longshore sediment transport are greater than on pocket beaches.

The major types of "free" beaches are spits, barrier beaches and barrier islands. Frequently these are backed by lagoons (Photo 8, page 39) that in tidal areas are connected to the sea through inlets (page 212). Barrier islands ("free" beach systems that are not attached to the land) may migrate slowly alongshore. The dynamics of barriers or spits often involve (a) overwash processes (Photo 53, page 197) as storms breach the dune systems, and (b) the transport of sediment as rhythmic features migrate alongshore (page 195). In low-energy environments, barriers and dunes are usually low (Photo 44, page 156) so that the infrequent storms inundate backshore areas, particularly if these are associated with a rise in the water level. In these cases oil can be carried over the beach into sheltered backshore marshes or lagoons.

On these coasts that have a "free" transport system, sediment removed from one section may be replaced by the longshore movement of material. This would, however, interrupt the local sediment budget as deposition of replacement material would cause a depletion of sediment in downdrift sections (i.e., sections towards which the material is moving). An example of this is given in Figure 44 (page 226) which shows the interruption of longshore sediment by construction of a groyne. This interruption of the normal longshore movement of material invariably leads to erosion in immediate downdrift sections. Care must be exercised in the removal of sediment during cleanup to prevent adjacent erosion.

SUMMARY: "Free Beaches"

(1) *These beaches are characterized by the uninterrupted longshore transport of sediments.*

(2) *Barriers and spits are often backed by sheltered lagoons or marshes.*

(3) *Oil can be carried into sheltered areas by overwash*

or through tidal inlets.

(4) *Sediment removal can result in loss of material to downdrift sections that would lead to erosion.*

7.4.4 Platforms, Intertidal Flats and Oil

Intertidal shorelines are characteristic of most tidal environments. On the landward margin of the intertidal zone they may give way to beaches, rock outcrops or cliffs. However, they constitute a distinctive shoreline type that is only exposed during a relatively short period in the tidal cycle.

These intertidal shorelines occur in areas where either the coastal gradient is low or where backshore erosion has produced an intertidal platform (Fig. 46, page 239). The following discussion considers initially rocky intertidal shorelines, followed by consideration of each of the major types of intertidal sediments.

The intertidal platforms referred to in this discussion vary in width from a few metres up to as much as 15 kilometres. The term intertidal flats refers to wide sections of shoreline exposed at low tide that are greater than 0.5 km wide. Low-tide terraces are frequently narrow and usually less than 0.5 km wide and these occur where littoral processes have been effective in sorting different sized-sediments; usually with coarse material on the beach face-slope and either finer or coarser material on the terrace surface (depending on the source of the sediments) (e.g., Fig. 41, page 198, and Photo 77, page 262).

(a) Rock Platforms: These platforms are rarely completely devoid of sediments, as the products of erosion from the rocks collect in hollows and depressions where they are used as abrasive tools. The main feature of intertidal rock shorelines is that sediments do not provide a protective cover and wave- and tide-induced processes act directly on the rock surfaces (Photo 82). Frequently flora (algae or "seaweed") and fauna cover the intertidal rock surfaces (Photo 83) and there are many biologically-rich tidal pools that do not drain completely at low tides.

During high tides waves break on the upper intertidal zone (Fig. 34c, page 180) and at low tide the platforms are above the

Photo 82. Wide (1 km) rocky intertidal platform at low tide, Straits of Magellan.

Photo 83. Intertidal rock platform (c. 150 m wide), Bay of Fundy, east of Digby Gut, at low tide. The rock surface is almost completely covered by algae.

water level. Levels of wave activity are usually low, except during periods of storms, as the ebbing and flooding tides rapidly cross the flat platform surfaces.

IMPACT OF OIL:

Oil can be stranded on rock surfaces or in hollows, crevices and tidal pools as the tide ebbs. Unless the rock surfaces are dry or vegetated, much of this oil would be refloated with the rising tide and transferred to higher intertidal zones or to adjacent shorelines. Heavy oils can be deposited on the platforms and are not refloated by subsequent tides. Oil is often trapped or adsorbed by intertidal vegetation (Photo 84) and is subsequently released by wave- or tide-induced currents when covered during flood tides.

Photo 84. Intertidal algae on rocks near Chedbucto Head, N.S.

PERSISTENCE OF OIL:

The physical breakdown and dispersion of oil on rock platforms is related to the type of oil and to the levels of energy. Rates of abrasion are lower than on rock outcrops in the upper intertidal zone as wave energy is concentrated there during high-tide slack periods. Oil trapped in crevices or hollows that contain coarse sediments can form local patches of "asphalt pavement" that abrade or erode very slowly (Photo 85).

ONSHORE PROTECTION:

Sorbents could be spread over the rocks to prevent deposition, but this is not practical if the platform is very wide. Generally there is little that can be done on this type of shoreline.

Photo 85. Oil-sediment mixture in intertidal rock crevices 3 1/2 years after the spill from the "Arrow", Crichton Island, N.S. The white scale is 8 cm in length. (Photo by J.R. Belanger, Bedford Institute).

CLEAN-UP METHODS:

Dispersion by hoses, steam or sandblasting can disperse oil from rock surfaces, however, these techniques can be harmful to flora and fauna. Low-pressure hosing can be used as the adverse effects are less with this method. Oil can be removed manually from tidal pools using cans, buckets or vacuum skimmers to prevent redistribution by subsequent rising tides. Intertidal vegetation can be cropped manually to prevent later release of the oil. This should be avoided unless necessary, as the algae recover more rapidly under natural conditions than if cropped (Eidam et al., 1975).

CLEAN-UP GUIDELINES:

A major problem in attempting to clean up this and all intertidal shorelines is the short duration of time available for such operations due to the tides. In addition, the slippery rocks and vegetation make this a difficult environment in which to work. Except for manual removal and low-pressure hoses, no suitable methods are available or recommended for cleanup and if large areas are contaminated the various limiting factors combine to make the task very difficult and frequently impractical. If low-pressure hoses are used to disperse oil the application of sorbents would assist in containment of the oil for later collection during the flood tide stage by skimmers. Cropping can be useful to prevent recontamination but this should be carried out only under guidance from biologists.

SUMMARY: Rock Platforms

(1) Intertidal rock platforms are generally devoid of sediment and often covered with flora and fauna.

(2) Oil is trapped or collects in hollows and pools during the ebb tide and is frequently released by rising water levels.

(3) Manual cleanup can be applied to remove oil from hollows and pools in order to prevent later contamination of adjacent shorelines.

(4) Low-pressure hoses can disperse oil from rock surfaces. If the dispersed oil is refloated by the flood tide it should be removed from the water surface.

(5) The intertidal zone is only exposed for short time periods during each tidal cycle and access to and movement on the platforms is often difficult.

(b) Platforms Covered by Coarse Sediments: Sediments on a platform (Photos 40 and 47, pages 140 and 183) protect the rock surfaces from abrasion and erosion, unless the layer of material is thin in which case the sediments can become an abrasive tool. As rates of wave energy decrease and as the sediment size increases the ability of littoral processes to move sediments decreases, resulting in lower rates of abrasion.

IMPACT OF OIL:

Oil deposited on coarse sediments by the ebbing tide would penetrate the spaces between particles and would likely form an "asphalt pavement" (Photo 79, page 265). Light-grade oils would probably be flushed and refloated during a flooding tide.

PERSISTENCE OF OIL:

Except for the light grade of oils, persistence of large volumes of oil would be high even on exposed coasts. As oil penetrates the sediments it becomes protected from wave and tidal processes and little surface area is exposed to degradation or abrasion (Photo 78, page 264). In addition, oil in the sediments would be covered by the tides for most of the time and this greatly reduces rates of weathering.

Breakup of oil-sediment "pavements" occurs as sediment movement exposes edges of the oil cover that are then slowly eroded (Photo 79). If the oil deposited on the sediment is not thick and a "pavement" is not formed, abrasion and degradation rates are higher because the sediments are not immobilized.

ONSHORE PROTECTION:

No effective methods of protection can be recommended. Sorbents could be used to contain and mix with the oil for later collection. This method could reduce the penetration of the oil into the sediments.

CLEAN-UP METHODS:

If cleanup of contaminated areas is required, mechanical equipment can be used to break up the oil-sediment layers in order to increase rates of dispersion and abrasion. Actual cleanup is not possible without removal of sediments. This would be a difficult operation and would involve removal of large volumes of sediment for relatively small amounts of oil.

Manual techniques could be used to remove small patches of surface oil. Hoses could be used to disperse the oil onto the water for subsequent collection using sorbents or, during the flood-tide stage, skimmers.

CLEAN-UP GUIDELINES:

As no effective techniques are available for clean up, this should not be attempted unless absolutely necessary. Dispersion and degradation rates can be increased by breakup of the oil cover using machinery, but again this should only be attempted if necessary.

SUMMARY: Platforms Covered by Coarse Sediments

(1) Coarse sediments are moved only in high-energy environments. Rates of sediment movement are usually low.

(2) Oil penetrates spaces between particles and heavy oils lead to the formation of "asphalt pavements".

(3) No effective clean-up methods are available but machinery can be used to break up the "pavements" and manual methods can be employed to remove oil.

(4) The time available to carry out work in the intertidal zone is limited to short periods during low tides.

(c) <u>Platforms with Intertidal Sand Flats</u>: Where extensive intertidal sand deposits are exposed on low-tide platforms the rates of sediment transport are related to wave- and tidal-energy levels. Sediment redistribution is often in the form of migrating sand waves (Photos 12 and 41, pages 57 and 141). These migrating sand waves of different sizes result in local erosion and deposition of surface sediments. Frequently at low tide the troughs between the sand waves are wet or contain standing water. Sand waves are typical of areas where wide intertidal flats are exposed and where there is an abundant supply of sediment, as in parts of the Bay of Fundy.

On beaches where a variety of sediment sizes are supplied to the littoral zone and where sufficient wave energy is available to sort this material, sand is usually deposited on the low-tide terrace whereas the coarser material is transferred to the beach-face slope and the upper parts of the beach. The sandy low-tide terraces are usually flat and have a high water content.

IMPACT OF OIL:

The deposition of oil on intertidal sands is largely dependent on whether the surface is dry or wet. If the sands are wet any stranded oil would probably be refloated by a rising tide. As sandy low-tide terraces are usually water-saturated, oil would not penetrate the surface sediments because the spaces between particles would be filled with water.

On wide intertidal flats the movement of sand waves on the surface would result in alternate burial and exposure of oil as these features migrate due to wave and tidal currents. Where sediments are moved by wave or tidal processes an oil cover would tend to be broken up into small particles which would then be rolled about and abraded.

PERSISTENCE OF OIL:

Provided that the oil is not buried, rates of abrasion, degradation and dispersion would be rapid if sufficient energy is available. Buried oil would degrade very slowly and would only be dispersed upon subsequent exposure.

ONSHORE PROTECTION:

No effective methods are available to protect sandy intertidal flats or low-tide terraces. In the latter case, sorbents could be spread on the surface at low tide. These would be mixed with the oil and would be moved onto higher parts of the beach during a rising tide for later collection.

CLEAN-UP METHODS:

Small patches of oil can be removed manually with rakes or shovels. Larger amounts of oil could be cleaned by machinery, provided that the sand is not wet and that traction is adequate. If the surface has sand waves or is irregular the effectiveness of the machinery decreases, but front-end loaders could be used to remove patches of oil.

<u>*CLEAN-UP GUIDELINES:*</u>

On wide intertidal sand flats, clean-up operations could be hazardous due to rapidly rising tides and to the presence of soft patches of sand. Cleanup on these wide flats is not advisable unless absolutely necessary. If oil is deposited on sandy, low-tide terraces cleanup can be effected using mechanical or manual methods, or the oiled sand could be pushed to the low-tide level to be dispersed and abraded by wave action during the flood tide.

<u>*SUMMARY: Platforms with Intertidal Sand Flats*</u>

(1) Wide intertidal sand flats are usually characterized by migrating sand ripples or sand waves. Sand on low-tide terraces has a flat surface but is frequently water-saturated.

(2) Oil would be refloated by flooding tides if the sand is wet. If oil deposition occurs, the sand could be subject to erosion and burial in areas of wave and tidal activity.

(3) Only light oils would penetrate dry sand deposits; heavier oils could be removed by machinery if the surfaces of the sand are flat.

(4) *Wide intertidal sand flats would be very difficult to clean but oil could be removed from low-tide terraces by mechanical or manual techniques.*

(5) *Care should be exercised to prevent personnel and machinery from becoming stuck in soft sand patches.*

(d) Platforms with Intertidal Mud Flats: Wide mud flats (Photo 39, page 138) usually develop in sheltered environments. These flats are often deeply incised by a network of creeks and channels (Photos 86 and 87). Intertidal muds are usually water-

Photo 86. Wide intertidal mud flats backed by marsh in a sheltered, low-energy environment. The flats are dissected by numerous creeks when exposed at low tide, south coast, Straits of Magellan.

Photo 87. Wide (5 km) intertidal mud flats in an environment where the sediments are actively redistributed by tidal and wave action, south coast, Straits of Magellan.

saturated even when exposed at low tide and this results in very low bearing capacities that are frequently insufficient to support the weight of a person. Due to the small size of the sediments, muds are readily transported by minimal wave or tidal current activity and are often redistributed in suspension.

IMPACT OF OIL:

Only the very light grades of oil would penetrate even dry mud deposits, as the spaces between particles are extremely small. As these muds are usually water-saturated, the oil on the surface would probably be refloated by a flooding tide. Oil deposited on the surface may also be subject to burial as sediments are redistributed when the flats are covered by the tides.

PERSISTENCE OF OIL:

Except for heavy residual patches, oil on the surface would probably be refloated by flooding tides. If buried, the rates of degradation would cease as oxygen necessary for the weathering processes would be cut off until the oil was re-exposed.

ONSHORE PROTECTION:

On wide mud flats nothing can be done to protect the intertidal zone against contamination. Oil on a muddy low-tide terrace could be mixed with sorbents, if they are laid down before the oil is washed ashore. The sorbent-oil mixture would be more easily removed than if no sorbent were spread on the mud flats.

CLEAN-UP METHODS:

No effective methods can be recommended. Small patches of oil can be removed manually. If the area is accessible and if the bearing capacity is sufficient, machinery could be used to remove larger accumulations from low-tide terraces, but this is not recommended.

CLEAN-UP GUIDELINES:

Muddy environments are a risky area both for personnel and machinery, due to the low bearing capacity of the sediments and the speed at which the tide floods over wide flats. It is doubtful that clean-up operations could be effective in the event of a large spill, except for narrow low-tide terraces, but if action is absolutely necessary extreme caution should be exercised.

SUMMARY: Platforms with Intertidal Mud Flats

(1) *Access and travel in muddy environments is difficult and may be dangerous.*

(2) *Except for heavy and residual oils, oils would be refloated by flooding tides.*

(3) *Buried oil would not be degraded until re-exposed.*

(4) *Cleanup would be difficult and it is not advisable unless necessary.*

7.4.5 Backshore Areas and Oil

Oil stranded or deposited in sheltered areas or above the level of normal wave activity is degraded and dispersed slowly as energy levels are low in these environments. Oil tends to collect in sheltered locations, such as lagoons, and once stranded there it would be subject to low rates of abrasion and dispersal by littoral processes. Deposition above the level of normal wave activity occurs when oil is washed ashore during spring tides or storm surges. In areas where there is debris, trash or log accumulations, this can present added difficulties for clean-up operations.

As these shoreline environments are frequently biologically productive and sensitive, as well as difficult to clean up, every attempt should be made to prevent oil on the water from reaching the shorelines. Clearly this is difficult during periods of storm-wave activity or if tidal currents are strong, but at other times inlets or estuaries can be boomed and the oil can be removed from the water surface. The phrase "prevention is better than cure" is particularly apt for these shoreline environments.

(a) Debris, Dunes and Overwash Deposits: The impact and persistence of oil in these environments is considered above in the section on littoral processes (pages 197 and 216). The only additional considerations are the effects of oil becoming mixed with debris in backshore areas and a caution on the use of vehicles in vegetated areas.

Debris and trash floating on the water surface are deposited at the upper limits of wave action or of storm surges (Photos 88 and 89). As such, these lines of debris can be useful indicators of the maximum limits of water levels, and therefore, indicators of the maximum elevations or distances inland that stranded oil could be expected to be deposited at times of high-water levels. In lowlying areas or marsh and deltaic environments, these debris lines are often considerable distances inland from the normal high-water mark. On the Beaufort Sea coast

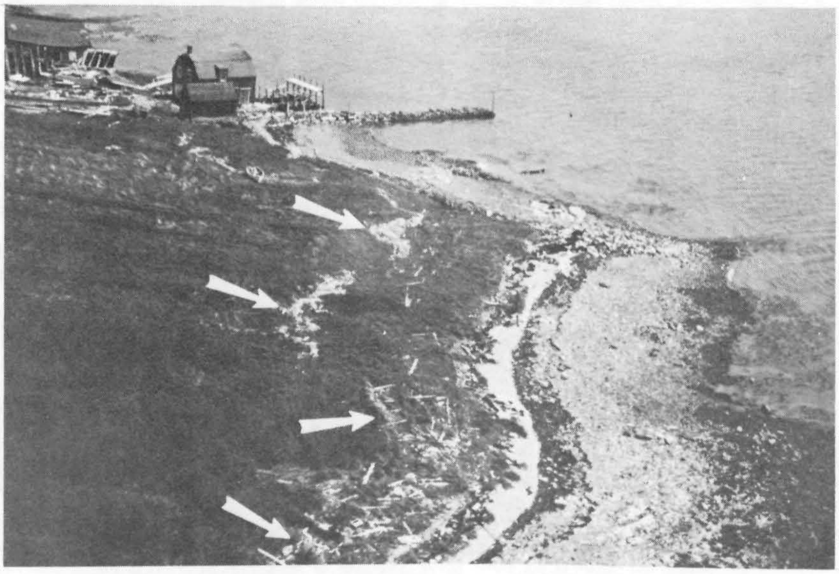


Photo 88. Debris lines (indicated by arrows) in a sheltered environment, Annapolis Basin, N.S.

Photo 89. Log accumulations above the high-water level, Long Beach, west Vancouver Island, B.C. (December 1976).

debris lines are common on top of tundra cliff surfaces.

When oil becomes mixed with debris (e.g., wood, railroad ties, plastic bottles, dead seals and old fishing nets) or stranded logs and trees, the difficulties are increased. A spill of 156,000 gallons of oil in Oakland Harbour resulted in removal of a total of 1280 cubic metres of oil-soaked trash and debris. It was estimated that the 1280 cubic metres included only 3,000 gallons of oil (Hanson and Kochis, 1975). This gives an approximate 100:1 ratio of debris and trash to oil.

On a shoreface with large amounts of logs or trees stranded above the high-water mark the problem would be complicated by the size and weight of the debris (Photo 89). If the construction of a dyke seaward of the debris is possible, to prevent oil mixing with the logs, this would alleviate the problem.

On sandy backshore areas with vegetation or dunes the traffic of vehicles and machinery should be restricted to existing roads or tracks in order to prevent damage to the vegetation. If no roads are present, vehicles should be restricted to as few access routes as possible during a clean-up operation and, if available, mats could be used to improve traction as well as reduce damage. Failure to control access could result in severe damage to the vegetation. Where this has occurred in the past, wind erosion on sections where the vegetation has been trampled or stripped has led to the formation of "blowouts" before the vegetation could recover. A blowout is an erosion hollow or depression caused by the removal of sand by wind. Once formed a blowout can become enlarged and can cause severe erosion in adjacent areas of vegetation or dunes. If the blowout extends to the edge of the beach, subsequent high-water levels could result in overwash through the depression and erosion and inundation of backshore areas.

SUMMARY: Debris, Dunes and Overwash Deposits

(1) Debris lines indicate maximum high-water levels.

(2) Oil-soaked debris is more difficult to remove than sediments alone, especially if the debris consists of logs or trees and the debris to oil ratio is high.

(3) Dykes constructed before the oil reaches the shoreline can prevent mixing of oil and debris.

(4) Vehicular traffic on vegetated backshore areas or dunes should be restricted to a minimum or should follow existing access routes. Mats can reduce damage to these areas.

(5) Damage to backshore vegetation can lead to erosion by wind action, and possibly subsequent overwash and flooding of backshore areas.

(b) Lagoons. The impact, persistence and cleanup of oil depends on sediment type and energy levels and these aspects are discussed in the sections above. A few additional considerations, however, are presented here that relate to this shoreline type.

Oil stranded in lagoons is subject to low-energy conditions (Photo 47a, page 183). In this environment the only mechanical energy inputs are from small, choppy waves generated in the lagoon and from the rise and the fall of the water level (usually the tides). Photograph 90 presents two views of the landward side of the cobble spit shown in Photographs 47a and 47b and Figure 35 (pages 183 and 184) at (a) 2 months after the spill, and (b) 3 years after the spill from the tanker "Arrow" in Chedabucto Bay. From Photograph 47b and from Figure 35 it is evident that after 3 years of degradation and weathering a 100% oil cover still coated the cobbles and that on the sand/mud lower intertidal zone the cover was approximately 50%. More recent observations (1976) indicate that the situation is similar 6 years after the spill and on the basis of present rates of weathering it is estimated that this oil could persist as long as 75 years (J. Vandermeulen, Bedford Institute, pers. comm).

In lagoonal environments where pebble-cobble sediments occur, an "asphalt pavement" is readily formed (Photo 47b) and

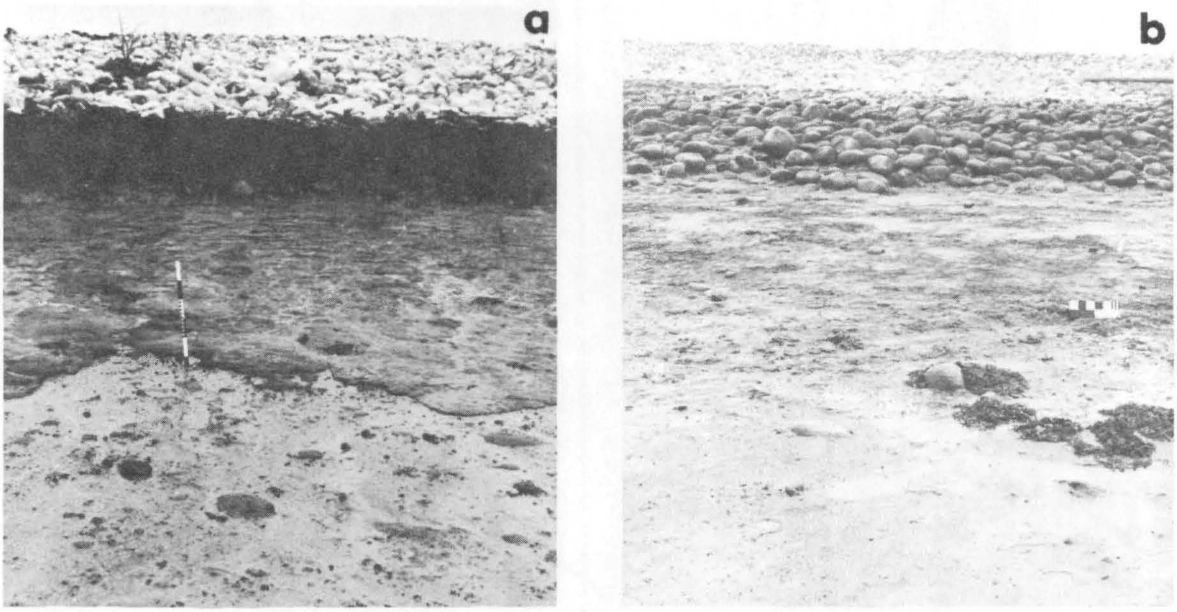


Photo 90. Oil in the intertidal zone on the lagoonal side of the spit at Black Duck Cove, N.S. Both photographs are at approximately the same location at low tide: (a) May 1970, scale is graduated at 10-cm intervals; (b) May 1973, scale is 30 cm in length (c.f., Fig. 35, page 184). The upper limit of the oil is the high-tide level. The location of this site is marked by the arrow on Photo 47b, page 183 (from Owens and Rashid, 1976).

will persist for a long time. Rates of mechanical abrasion and degradation are extremely low as little surface area of the oil is exposed. In addition, rates of weathering are low as the oil is covered by water except during short low-tide periods. In parts of the lagoon at Black Duck Cove in Chedabucto Bay (Photo 47a), the oil had a fresh, shiny appearance and was liquid three years after being stranded (Photo 91), and oil still covered intertidal rock surfaces (Photo 92).

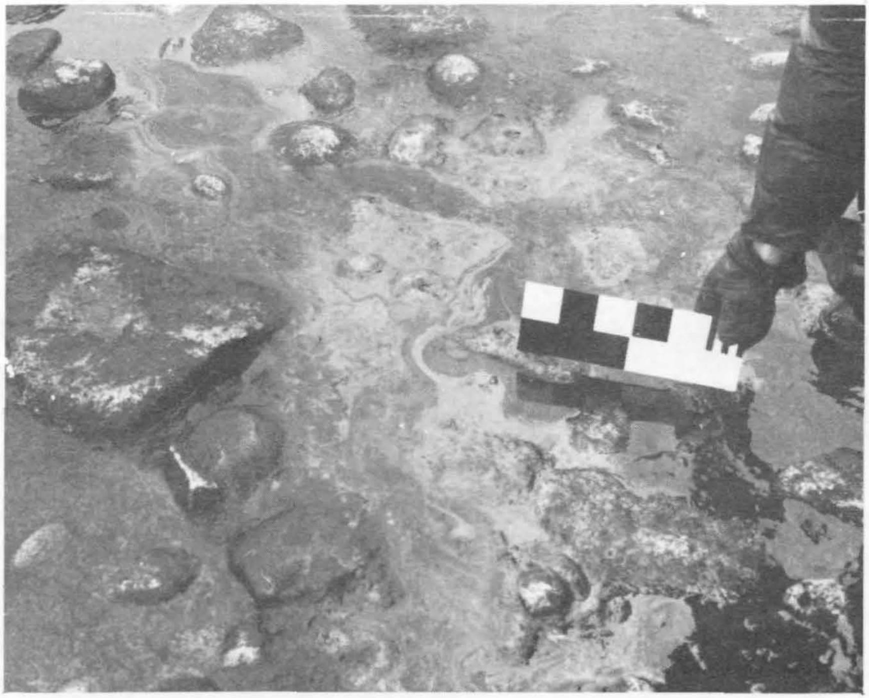


Photo 91. Thick (up to 5 cm), mobile oil deposits in the intertidal zone at Black Duck Cove, N.S., May 1973, 3 years after the oil was stranded in this sheltered lagoonal environment (Photo by J.R. Belanger, Bedford Institute).

A similar situation was observed in lagoons near the "Metula" spill area in the Straits of Magellan. In these environments oil stranded in the intertidal zone was present to depths up to 50 cm after 2 years, even though the surface appeared oil-free due to the deposition of a layer of mud on the surface of the oil (Photo 93).

Protection of these sheltered environments is a high priority to prevent this type of contamination. If oil does become stranded it can be removed manually, or if an "asphalt

Photo 92. Large boulder in Black Duck Cove, N.S., May 1973, at low tide. The oil still coated the rock surface 3 years after the spill (Photo by J.R. Belanger, Bedford Institute).

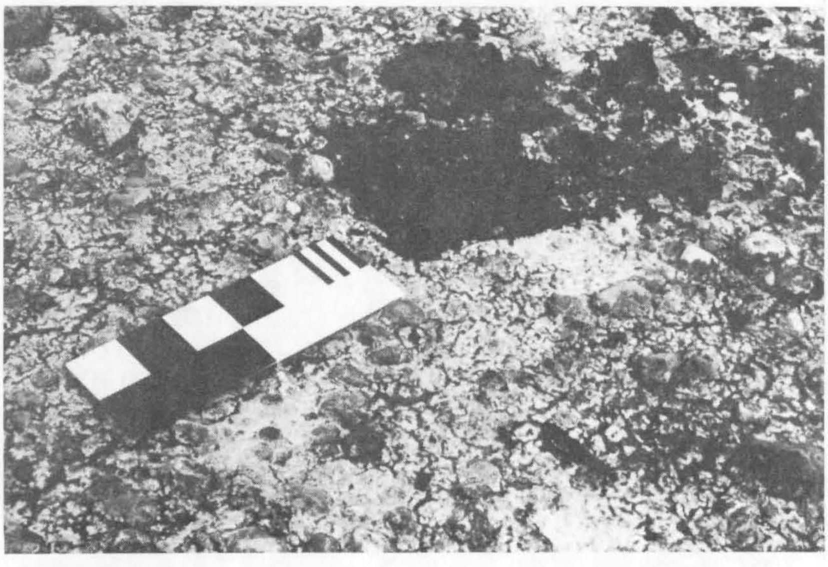


Photo 93. Oil covered by a thin layer of mud in a lagoonal environment, south shore, Straits of Magellan, January 1977.

pavement" is created, by oil mixing with coarse sediments, this can be broken up by machinery to increase rates of dispersion and degradation.

Although the oil has a considerable effect on the productive biological systems of lagoonal environments, some evidence was observed in Chedabucto Bay that the flora had adapted to the new environmental conditions (Photo 94).

Photo 94. Oil layer at the high-water level in the lagoon at Black Duck Cove, N.S., with flowering plants growing through the oil (May 1973).

SUMMARY: Lagoons

(1) Oil tends to collect in sheltered environments, such as lagoons, where mechanical energy levels are low.

(2) Oil stranded in lagoons can be expected to persist

for long periods due to the low rates of dispersion and degradation.

(3) *Oil deposited in the intertidal zone is only exposed during the short periods of low tide.*

(4) *Lagoons can be protected by booms across their entrances, if conditions permit.*

(c) Marshes and Deltas: In sheltered environments marshes develop as vegetation encroaches on the sediments of the upper intertidal zone. The vegetation traps water-borne sediments during high tides and the marsh continues to build up until it is flooded only by high spring tides or during storm surges. The edge of the marsh can be a zone where vegetation is slowly encroaching on the upper tidal flats (Photo 95) or on old marshes the edge can be a scarp that is eroded by waves at the limit of normal high tides (Photo 96). In addition, some marshes have been dyked by man for reclamation (Photo 96). The characteristic form of marsh is one of a flat, vegetated surface above the normal high-water level that is dissected by muddy, non-vegetated creeks and channels (Photo 97). In areas of high tidal range these creeks are frequently very deep, have strong tidal currents at the turn of the tide and dissect the marsh making access to some areas very difficult (Photo 97). Often the creeks or channels have levées on their margins which are slightly above the general level of the marsh surface.

Photo 95. Large marsh that is gradually encroaching onto the adjacent intertidal mud flats, Punta Catalina, Straits of Magellan.

Photo 96. Intertidal mud deposits, eroding marsh edge, and dyke; north shore, Annapolis Basin, N.S.

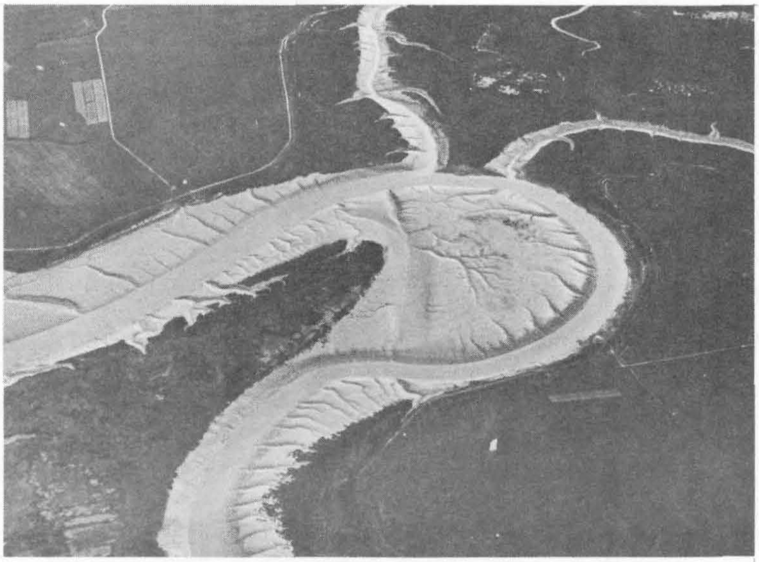


Photo 97. Tidal channel at low tide, Head of Cobequid Bay, N.S. The adjacent marshes have been dyked and reclaimed for agriculture.

Changes to marshes usually take place at a slow rate, as these are sheltered environments in terms of wave energy. The primary mechanical energy inputs are related to tides. Marshes are extremely productive environments in terms of both flora and fauna, which make them biologically susceptible and sensitive to oil contamination.

Deltaic environments are similar to marshes in many respects. Even though freshwater river discharge controls the morphology of the channels and the sedimentation patterns, deltas are subject to inundation by storm-surges, tides and by high river levels. The lowlying areas between the river channels are usually marsh environments (Photo 11, page 55).

IMPACT OF OIL:

The distribution of oil being washed ashore in a marsh area depends primarily on the water level. If tides are normal the oil is deposited on the adjacent mud flats and in the tidal creeks. As these are areas of water-saturated sediments the oil does not usually penetrate and can be refloated by subsequent high tides. This refloated oil could be redeposited by the next ebb tide or could be moved to other locations or seawards. If water levels are high, due to spring tides or storm surges, the oil can be refloated from mud flats and creeks and deposited at higher levels or can be carried directly onto the marsh surface.

Deltaic areas can be contaminated if storm surges or tides override the effects of river discharge. Wind-driven slicks can be moved onshore if the velocity of river currents is low. As in marshes, the actual impact of oil depends on water levels at the time the oil is stranded.

Following the spill from the "Metula", oil was washed ashore and stranded in some marsh areas at times of spring tides (Photo 98) (Hann, 1975). The marsh surface was completely inundated and oil was carried to and deposited on the highest parts of the marsh, up to 4 or 5 km inland in some cases (Photo 99). In Photograph 99, oil was stranded at the landward and vertical limit of the spring tides (open arrow) and on the channel-margin levées (solid arrow). Oil deposited on the

Photo 98. Oil stranded in the upper parts of a marsh during spring tides. The small arrow to the right indicates normal high-water mark. The larger arrow is the limit of spring high water, south shore, Straits of Magellan, January 1977.

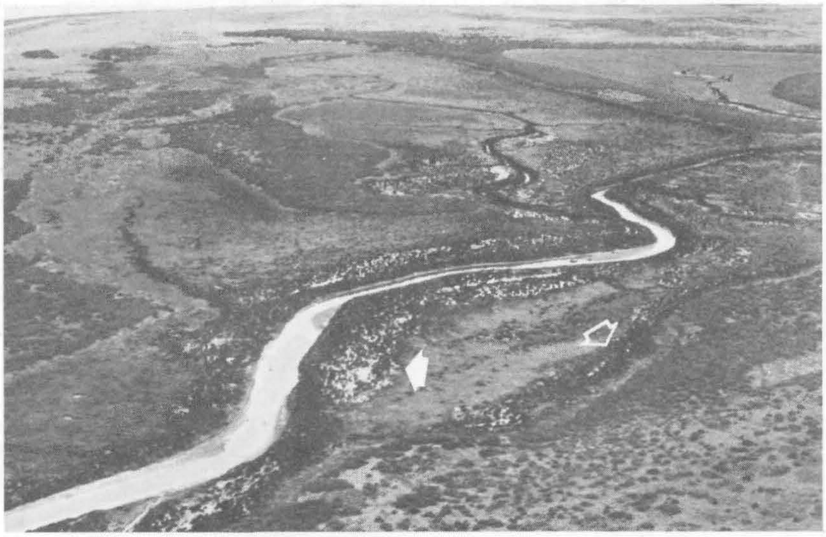


Photo 99. Marsh on the south coast of the Straits of Magellan, January 1977. The open arrow indicates the maximum landward and vertical distribution of the oil. The solid arrow indicates oil stranded on the channel-margin levées.

marsh surface was refloated by later spring tides and recontaminated the highest areas of the marsh. The marsh surfaces themselves remained virtually oil-free (Hann, 1975) (Photo 100). Floating oil was, however, trapped by clumps of vegetation or bushes and as the water ebbed this oil flowed down the vegetation and was deposited in patches around the clump as well as on the vegetation itself (Photo 100).

Photo 100. Ground view in same marsh as in Photograph 99. The open arrow indicates the most landward oil and the solid arrow marks oil on a channel-margin levée. Note the oiled clumps of vegetation on the marsh surface.

Oil washed into a lagoon and marsh area following the spill from the "Golden Robin" in Baie des Chaleurs was not deposited above the normal high-water mark as it was stranded at a time of neap tides. In this case the oil was deposited only on the marsh edges and in tidal creeks (Photo 60, page 213, and Photo 101).

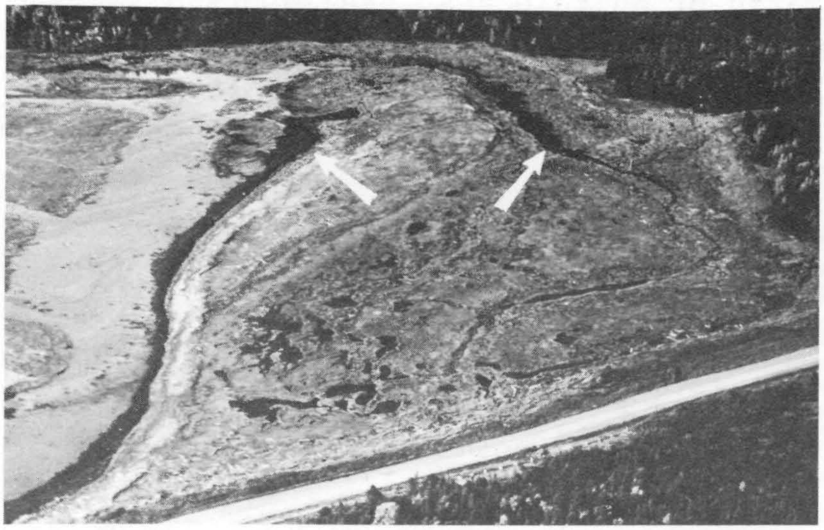


Photo 101. Oil (indicated by the arrows) trapped in creeks and against the marsh edge at high tide, Baie des Chaleurs, October 1974.

The effect of oil on marsh vegetation depends on the type of oil and the vegetation. Light oils are more toxic than heavy or residual oils and can penetrate marsh sediments (Westree, 1977). As the sediments in a marsh, on the adjacent mud flats, or in tidal creeks are fine-grained muds and are usually water-saturated, only light-grade oils can penetrate into the sediments. Marsh vegetation, such as *Spartina*, acts as a sorbent and can trap large quantities of oil. In addition, the impact of oil on the biological productivity of a marsh is less during autumn and winter months (Cowell, 1971).

PERSISTENCE OF OIL:

In these sheltered environments wave action has little effect on oil except where the oil is stranded near the high-water mark on the marsh or delta edges. As inputs of mechanical energy are low, the oil is abraded and dispersed slowly. In creeks or channels, strong river currents or strong tidal currents at the turn of the tide can abrade and disperse oil more rapidly. On the marsh itself mechanical energy is minimal but as this is a very active bio-chemical environment, rates of degradation are high, except for asphaltene residues, and recovery is usually rapid. Cowell (1971) notes that most marshes recover from a single spill in 1 or 2 years. If the oil is buried, however, degradation will stop and the oil may persist for many years under these anaerobic conditions.

ONSHORE PROTECTION:

The presence of dykes on reclaimed marshes protects those areas from stranded oil. In delta channels natural levées afford some protection, except during periods of high-water levels. Deltas or unreclaimed marshes can be protected if (a) the areas are accessible, (b) if material is readily available to construct dykes, and (c) if this can be carried out without damage to vegetation by the mechanical equipment. This dyke construction would only be necessary if spring tides or storm surges are predicted. For extensive delta or marsh areas this type of protection is usually impractical. Offshore protection for these environments should receive a high priority.

CLEAN-UP METHODS:

If oil is stranded on the marsh or delta edge or in creeks it can be removed manually with skimmers, rakes or shovels. Great care must be exercised in the implementation of manual removal techniques to prevent oil being compacted or trampled into the sediments (Westree, 1977). Where vegetation has been covered by oil this can be cropped if necessary by machinery or manually and is probably not harmful to most plant species (e.g., *Spartina* and *Juncus*; Baker, 1971). If floating mechanical weed-cutters cannot be used, cropping with sickles or scythes is effective as long as oil is not trampled into the sediments. Contamination of a marsh has less severe effects if this occurs during autumn or winter months and cropping or controlled burning at this time can be successful (Wardley Smith, 1968; Westree, 1977).

Biologically the most acceptable clean-up method is the use of low-pressure hoses to disperse the oil that is then contained by booms and removed from adjacent water surfaces (Westree, 1977). In addition, sorbents can be used providing that they are then recovered. This again can be achieved using low-pressure hoses to flush the material onto adjacent water surfaces for collection.

CLEAN-UP GUIDELINES:

Machinery should not be used on marshes as this can cause extensive damage to the vegetation. Similar damage can result from personnel traffic, particularly if this results in spreading or burial of the oil. The use of mats is recommended if vehicular or personnel traffic is high as these would reduce damage caused by the restoration programme. Oil deposited on the marsh edge, in tidal creeks or in delta channels should be removed to prevent subsequent refloating and contamination of higher areas during spring tides.

These environments are extremely sensitive ecologically and a high priority should be given to offshore and onshore protection. Clean-up operations can be carried out effectively using well-supervised manual techniques but should only be carried out in consultation and with the advice of biologists in order to prevent more damage than that caused by the oil itself.

SUMMARY: Marshes and Deltas

(1) Marshes and deltas are only flooded during spring tides, storm surges or at periods of maximum river discharge. At other times oil would be stranded on the marsh or delta edge or in tidal creeks and channels.

(2) Marshes generally recover naturally as degradation by bio-chemical processes is relatively rapid.

(3) Protection of these environments should have a high priority in contingency planning.

(4) Manual removal of the oil, flushing with low-pressure hoses, use of sorbents, controlled burning or cropping of contaminated vegetation can be effective. The use of low-pressure hoses is preferred over the other methods.

(5) Machinery should not be used, except for floating aquatic weed-cutters.

PART 8 - COASTAL ENVIRONMENTS OF CANADA AND OIL SPILLS

The preceding parts of this report provide information both on the coastal process and morphology characteristics of Canada and on the relationships between littoral processes, shoreline morphology and oil. This information can be used at the general (regional) and at the local (site specific) levels for contingency planning or for operational response. As there is such a wide range of geologic and oceanographic environments within Canada this section presents some regional aspects of oil on the shoreline that should be considered for planning and clean-up programmes in the four regions (Fig. 2, page 8).

8.1 THE PACIFIC COAST

The climate of British Columbia is one of warm summers and cool winters (Fig. 3 and Table 3, pages 13 and 15) so that bio-chemical degradation of oil occurs at a relatively high rate throughout the year, when compared to the rest of Canada. Water temperatures range between 4°C and 20°C (Herlinveaux, undated) and this is a factor in promoting weathering of oil by chemical or biological processes in the littoral zone.

Green et al., (1974) observed that 90% to 95% of a small spill of heavy fuel oil in Alert Bay had been physically removed or weathered within one year in this sheltered wave-energy environment. Where this oil had not been subject to the physical action of littoral processes, *in situ* weathering had produced an asphalt-like residue.

Energy levels, related to tides and waves, vary considerably throughout the region so that rates of physical dispersion and degradation differ greatly between exposed and sheltered environments. Where tidal currents are strong or where levels of wave activity are high, slicks on the water would be dispersed and emulsified thus distributing the oil over wide areas. The high wave-energy levels on exposed coasts would result in rapid physical abrasion and dispersion of the oil.

The beaches on the exposed outer coasts are subject to a "summer-winter" cycle of accretion and erosion. Any oil stranded in spring months would probably be buried and not exposed until late autumn or winter months.

Fog is common in many parts of the region particularly during summer months. This would be a problem for surveillance of slicks. Onshore protection operations would be hampered if the location and direction of movement of the slicks could not be monitored.

A problem peculiar to these coasts is the presence of large volumes of logs in the upper intertidal zone and on the backshore (Photo 89, page 293). Ricker (1974) notes that following a spill of light fuel oil in Burrard Inlet, oil soaked into the logs so that backshore areas were protected from contamination. This advantage could be offset if it is decided to remove or burn the contaminated logs. The size, weight and large number of logs (Photo 102) would make this operation difficult. In particular, burning would be difficult if the logs are wet.

Photo 102. Attempted burning of oil-contaminated logs, Long Beach, Pacific Rim National Park, Vancouver Island, B.C. (Photo by C.W. Nichol).

The rocky sections of the coast are frequently characterized by extensive <u>kelp beds</u>. Oil would likely collect in this nearshore vegetation and, if not removed, could later be dispersed by wave and current action to contaminate adjacent shorelines.

SUMMARY: The Pacific Coast

(1) *The relatively warm climate and water temperatures encourage bio-chemical degradation of stranded oil.*

(2) *Fog could hamper surveillance of slicks and onshore protection.*

(3) *Log debris may protect backshore areas but could be difficult to remove or burn.*

(4) *Oil could be trapped by kelp beds and subsequently released to be stranded on adjacent shorelines.*

8.2 THE ARCTIC COASTS

Recent research related to spills in arctic environments has largely focussed on the containment and removal of spilled oil from ice-infested waters. This emphasis is understandable due to the difficulties of shoreline cleanup. Although oil ages in arctic environments, even in winter months and if the oil is snow-covered (McMinn and Golden, 1973), the rates of weathering are very low due to the low temperatures throughout the year (Fig. 3 and Table 3, pages 12 and 15). Sittig (1971) notes the degradation by microbial action in arctic regions is slowed because bacterial metabolism is lower and because the oil is more viscous due to the low temperatures.

Inputs of thermal energy decrease as latitude increases and available amounts of mechanical energy due to wave action decrease as the length of the open-water season decreases.

Most sections of the Canadian Arctic coasts have short fetch distances which further reduce potential wave generation during ice-free months. Energy levels can be high on the coasts of Hudson Bay, Davis Strait and Baffin Bay due to storm-wave activity, but elsewhere wave-energy levels are very low. Oil stranded on ice-free beaches would be dispersed and degraded only during infrequent periods of storm waves.

Throughout the arctic region ice plays an important role in oceanographic and littoral processes for at least 6 months each year (Figs. 5 and 6, pages 25 and 26). Sea ice can contain oil on the water and the presence of an ice foot can protect the shoreline from contamination. However, if oil is on a beach and is not removed it can become enclosed within an ice foot and not be exposed until the following summer.

Onshore protection can be provided during ice-free periods for beaches, rock or man-made surfaces by water spraying if temperatures are below freezing. The artificial protection provided by the layer of ice would prevent oil adhering to the sediments or rocks. The oil could then be flushed onto the adjacent water surface by high- or low-pressure hoses and contained there for collection. This technique has not been field-tested but is theoretically feasible.

Many arctic beaches have pebble-cobble sediments but the presence of ice within the beach limits depths of oil penetration. The depth to which the beach thaws (the frost table) is related to thermal energy levels and to the size of the sediments. In coarse sediments the beach can thaw to greater depths than in finer material, as warm air can penetrate the large spaces between the particles. It is known that the level of the frost table fluctuates, depending on air temperature, water levels and wave activity (Owens and Harper, in preparation), and oil that penetrates the beach could be alternately enclosed or exposed on a daily or seasonal basis.

The Arctic is virtually uninhabited so that in most cases equipment and manpower would have to be brought into an area affected by a spill. Logan et al., (1976) state that "the logistical base to support an effective oil spill countermeasures operation is not available in the areas adjoining the Beaufort Sea". This is one of the most "populated" regions of the Arctic: the problem elsewhere is even more acute. Accessibility to many sites would be difficult, even for light aircraft in ideal conditions. In addition, few of the arctic coasts have been studied at even a reconnaissance level so that basic information on shoreline types and coastal processes is not available for most areas.

For the Beaufort Sea, information related to oil spills is provided by a series of reports published by Environment Canada (see Logan et al., 1976; Milne, 1976; and Milne and Smiley, 1976).

SUMMARY: The Arctic Coasts

(1) *Natural degradation rates and littoral zone energy levels are very low throughout the year.*

(2) *Ice on the sea or on the beach is present in all areas for at least 6 months each year.*

(3) *Water sprayed on a surface with ambient temperatures below freezing could form a protective layer of ice. This could protect surfaces from contamination and assist removal of the oil.*

(4) *Oil penetration into sediments is limited by ice within the beach.*

(5) *The logistics of an arctic spill cleanup are considerably more difficult than elsewhere due to the limited accessibility and the low (often absent) population density.*

(6) *Many sections of the coast are unexplored or relatively unknown in terms of shoreline types and processes.*

8.3 THE ATLANTIC COAST

The major spill from the tanker "Arrow" during spring 1970 in Chedabucto Bay has provided considerable baseline information for the impact and persistence of oil in this region (Task Force, Operation Oil, 1970). In many sheltered shorelines affected by this spill of Bunker C oil, the oil is still present (summer 1976) in large quantities (Photo 91, page 298). The region has a climate of warm summers and cold winters (Fig. 3 and Table 3, pages 12 and 15) so that natural weathering rates are relatively low in winter months.

The effects of ice in the littoral zone of this region increase from south to north (Fig. 6, page 26) but are important throughout the region. Although outer Nova Scotia and southern Newfoundland are essentially ice-free (Fig. 8, page 34), ice is present in sheltered locations during most winters.

Wave-energy levels on the exposed rocky coasts are high so that physical abrasion and dispersion of stranded oil would be rapid on these shorelines. Within the Gulf of St. Lawrence the long sections of sand barrier beaches are important recreational areas. Contamination of these shorelines would probably require cleanup and this could be achieved effectively with available methods. The Bay of Fundy (Owens, 1977a) and the St. Lawrence estuary would be more difficult sections to clean up due to the great variety of shoreline types and the high tidal ranges.

Slick surveillance and subsequent clean-up response and onshore protection could be hampered by the frequent fogs that are common in many areas of this region between May and August, particularly on those coasts that are directly adjacent to the North Atlantic.

SUMMARY: The Atlantic Coast

(1) *Rates of weathering are relatively low in winter months.*

(2) *Contamination of recreational sand beaches would probably require a clean-up response. Restoration of these shorelines could be effective.*

(3) *Fog could hamper slick surveillance and shoreline protection in summer months.*

8.4 THE GREAT LAKES

One of the critical factors in the distribution and persistence of oil in this region would be the water level at the time the oil is stranded. In this non-tidal environment beaches do not usually develop very much above the mean water level and are, therefore, relatively easily overwashed during storm surges. Should a spill occur at times of high water levels then many backshore areas would be subject to contamination, e.g., the coast of Lake St. Clair. Similarly, high water levels accelerate rates of erosion of the unresistant till cliffs of Lakes Erie and Ontario. Oil that is stranded on a beach at the base of these cliffs, if not removed, could be buried by sediment accumulation resulting from cliff erosion.

Although the winter months have a cold climate, high temperatures (>20°C) in summer months (Fig. 3 and Table 3, pages

13 and 15) would give high rates of weathering. Wave energy levels are generally low due to the short fetches within the lakes but this is offset by the short-term stability of lake levels that would concentrate wave energy over a narrow, vertical band. Therefore, except in sheltered environments, stable lake levels would be an important factor in the rate of physical abrasion and dispersion of oil stranded within the limits of normal wave activity.

SUMMARY: The Great Lakes

(1) *Water level variability is an important factor in predicting the impact of spilled oil.*

(2) *Natural weathering would be relatively rapid in summer months.*

(3) *Dispersion by waves is limited by low wave-energy levels but available wave energy is usually restricted to a narrow, vertical band.*

8.5 DISCUSSION

The primary factors that would control the impact, distribution and persistence of oil on Canada's coasts are the levels of wave energy and the tidal range. High-energy coastal environments such as the exposed shores of British Columbia and the Atlantic Provinces are in marked contrast to the sheltered environments of the Great Lakes and the northern arctic islands. The majority of the coasts of Canada are low-wave energy environments. Superimposed on the distribution of wave energy is the great variation in tidal ranges. Canada has many macro-tidal environments (range >4 m: Bay of Fundy, St. Lawrence estuary, Ungava Bay and Frobisher Bay), as well as many micro-tidal areas (range <2 m: Gulf of St. Lawrence, the Beaufort Sea and the Great Lakes).

A secondary factor that must be considered is the role of ice that affects approximately 90% of the coastline. Coupled with the effects of ice are the generally low air and water temperatures that produce low rates of weathering. Only the coasts of the Great Lakes have mean monthly summer temperatures greater than 20°C.

In terms of clean-up operations, there is a great variety of shoreline types but rocky coasts and pebble-cobble beaches predominate.

PART 9 - THE RESTORATION OF CONTAMINATED SHORELINES

9.1 THE DECISION TO CLEAN UP

The response to major coastal oil spills has ranged from complete shoreline clean-up programmes ("Torrey Canyon"; "NEPCO 140"), or partial restoration ("Arrow"), to no cleanup ("Metula"). No two spills are alike and in each case a variety of factors must be considered before any action is taken. Contingency planning and training are necessary to provide the infra-structure for reaction and response. However, even with carefully prepared contingency plans available, clean-up decisions cannot be made until the expected or actual impact of a spill is assessed at the time of the event.

The decision to initiate a clean-up programme and the way in which a programme is implemented depend on three groups of factors (Table 15). The first factor in the decision-making process is whether or not a restoration operation is necessary. The consideration of the socio-economic, aesthetic and ecological desirability of a clean-up programme involves many diverse factors. A major spill in a populated region (e.g., the Santa Barbara or the "NEPCO 140" spills) would be treated in a very different manner from one in an isolated and uninhabited area (e.g., the "Metula" spill).

TABLE 15. Factors Related to Clean-Up Decisions

Requirement Aspects	1.	Socio-Economic Desirability
	2.	Aesthetic Desirability
	3.	Ecological Desirability
Environmental Aspects	4.	Rates of Natural Dispersion
	5.	Rates of Natural Degradation
	6.	Geological Sensitivity of Shoreline
	7.	Ecological Sensitivity of Shoreline
Practical Aspects	8.	Effectiveness of Available Clean-Up Methods

The second group of factors (Table 15) relate to the environmental aspects of a spill. These include the rates at which the oil on the shoreline would disperse and degrade naturally and the geological and ecological sensitivity of the contaminated environment. Natural dispersion and degradation are a function of the climate, the littoral zone energy levels and the nature of the shoreline. Environmental sensitivity factors include flora, fauna (habitats, migration routes, etc.) and shoreline characteristics (littoral processes, sediment movement, etc). These factors would determine which sections of a contaminated coast would have a higher priority for protection or for restoration as well as the most appropriate methods of restoration.

The final set of factors in the decision-making process is consideration of the effectiveness of a clean-up programme in terms of the objectives of the operation. This involves not only an assessment of existing methods and techniques but also their availability and applicability in a given location. This third aspect of the response analysis is particularly important in terms of the efficient allocation of available resources.

Once a clean-up response has been initiated and implemented, the priorities that are assigned to available resources relate primarily to socio-economic, ecological and geological factors in terms of the desirability to restore the shoreline and of the expected damage to the coastal environment by stranded oil.

The following discussion is designed to consider those inputs into the decision-making process that relate to geological aspects of a restoration programme. Although the major considerations are discussed separately, clean-up decisions must be based upon an analysis of each factor within the context of the overall situation. This involves synthesis of all of the geological aspects as well as ecological and socio-economic factors not discussed here.

9.2 SHORELINE SENSITIVITY

The sensitivity of a shoreline section or a coastal environment in this context is the reaction that results from the alteration of normal processes which is caused by stranded oil or by restoration programmes. Stranded oil alters the local ecosystem in all environments but the impact of man and of coastal oil spills is felt most keenly in biologically productive environments (Group I, Table 16). Biologically sensitive shoreline types should be afforded the highest priority for protection and for restoration in order to minimize damage to natural processes. The impact of oil on marshes can vary widely depending on the type, volume and distribution of oil, on the season, and on the clean-up techniques (Westree, 1977). At the other end of the spectrum, rock or cliff shorelines in high-energy environments (Group IV, Table 16) have less sensitive ecosystems and generally would not require cleanup or protection due to high rates of natural dispersion and degradation of the oil. Between these two extremes are a great variety of environments with very different levels of ecological and geological sensitivity.

Ecological sensitivity is readily visible and is much publicized by photographs such as those of oiled birds or oiled marshes. Geological sensitivity is less apparent and less publicized but is of equal importance in terms of the overall

TABLE 16. Shoreline Sensitivity to Oil Spills

↑ Increasing Sensitivity ↑	I	Marshes Lagoons
	II	Sheltered Environments Pocket Beaches
	III	Exposed Beaches Mud Flats Sand Flats
	IV	Exposed Rock or Cliff Environments

dynamics of shoreline environments. Three examples discussed earlier in this report serve to illustrate the importance of geological sensitivity.

(1) The removal of sediments from the upper beach can result in beach retreat, as shown in the example of Indian Cove in Chedabucto Bay (page 269). On beaches that are backed by marshes or lagoons the retreat of the beach can result in burial or inundation of these backshore environments. If the backshore area has been developed for either residential or recreational housing, these properties could be exposed to wave action following beach retreat.

(2) In the same manner that the upper beach acts as a natural dyke to protect backshore areas from inundation, beaches at the base of unresistant or unconsolidated cliffs absorb wave energy and protect the cliffs from erosion. If this protective beach is removed, erosion can result until sufficient sediment is provided to the littoral zone to replace that which was removed. An instance where this type of sediment removal was initiated is shown in Photo 69 (page 245). In this example, remedial action was undertaken before any damage had been incurred.

(3) A less obvious but nevertheless important effect of oil can be the formation of an "asphalt pavement" (Photo 79, page 265). This immobilization of beach sediments clearly interrupts normal littoral processes and sediment redistribution. Formation of an "asphalt pavement" is most common in low-energy environments and during the infrequent periods of high-wave energy levels (storms) the pavement can act as a ramp across which wave energy is transmitted to the upper beach and backshore. In these conditions wave energy is not lost by infiltration into the sediments nor used to redistribute the sediments, and the pavement in this case allows breaking waves or swash to run up the beach and erode or inundate backshore areas.

9.3 DISPERSAL AND WEATHERING

The natural cleaning of oil on a shoreline is dependent on a wide range of factors (Table 17a and b). The emphasis in this report has been on those factors related to inputs of mechanical energy that affect the impact, distribution and persistence of stranded oil. There are innumerable permutations of the various factors involved (Table 17d), however, there is a basic relationship between the persistence (dispersal and weathering) of oil and energy levels at the shoreline. For example, as wave-energy inputs increase more oil is dispersed, a greater surface-to-volume of oil results, more oxygen is available for chemical breakdown and rates of microbial activity increase. The burial of stranded oil, on the other hand, usually reduces rates of degradation and in anaerobic conditions weathering can cease altogether.

As the persistence of oil is important in clean-up decision making, the major factors that control rates of degradation are outlined briefly.

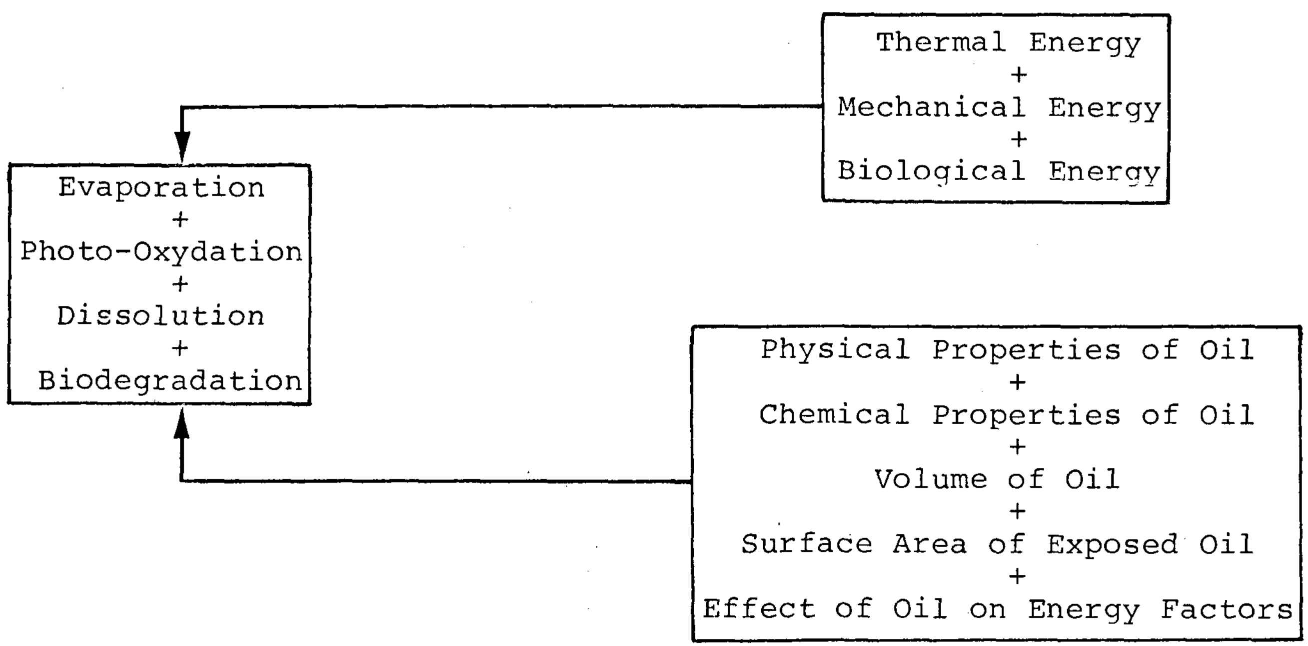
(1) Amounts of <u>evaporation</u> depend on the volume of the volatile components in the oil, but the actual rates of loss of these fractions are related to temperature and wind.

(2) Rates of <u>photo-oxydation</u> depend primarily on the surface-to-volume ratio of the stranded oil and on exposure to sunlight and oxygen.

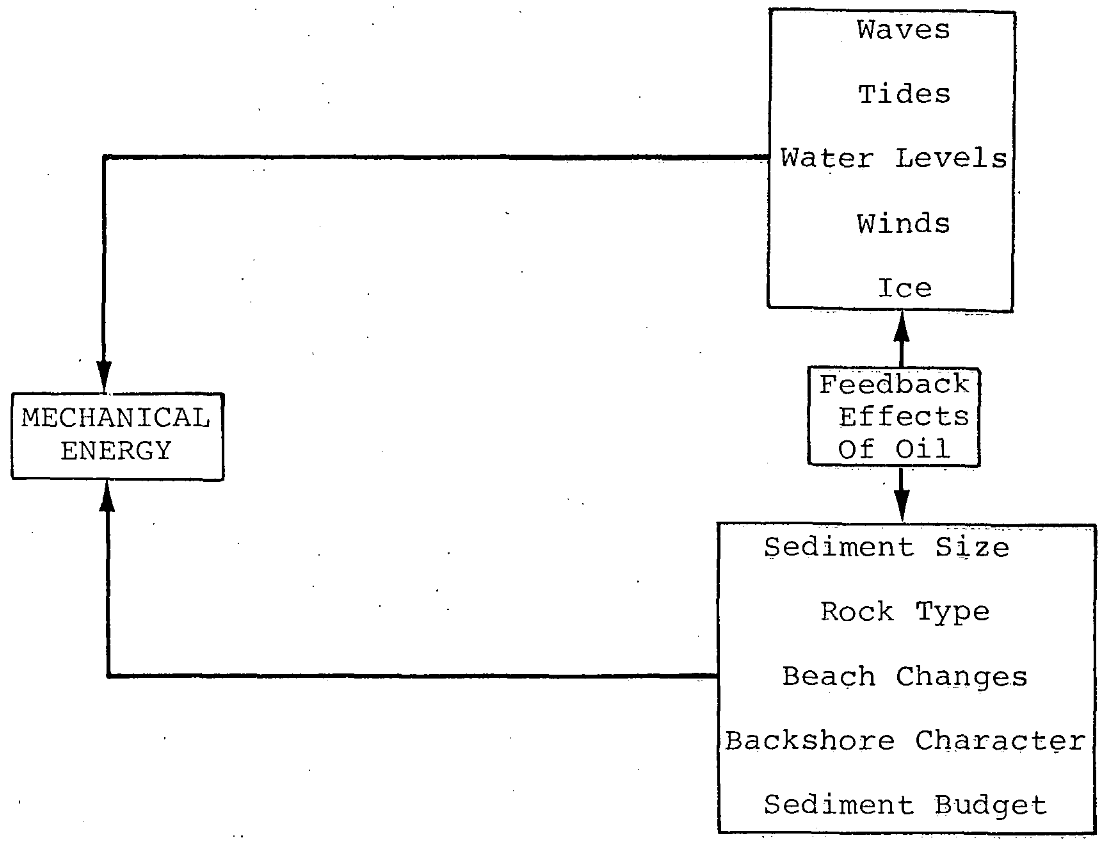
(3) <u>Dissolution</u> of oil requires the presence of water and therefore is only an important factor on oil that is

TABLE 17. Factors That Affect Oil Degradation And Inputs of Mechanical Energy

(a)		(b)
WEATHERING and PERSISTENCE	=	INPUTS OF ENERGY + PROPERTIES OF OIL



(c) LEVELS OF MECHANICAL ENERGY = (d) COASTAL PROCESSES + SHORELINE FACTORS



stranded within the zone of normal wave activity. As mechanical energy levels increase, rates of dissolution and dispersion increase.

(4) Biodegradation takes place predominantly on the surface of oil so that rates of microbial oxydation are dependent primarily on aeration (the surface-to-volume ratio, and the availability of oxygen), agitation and temperature.

The rates of natural, physical dispersion and degradation of stranded oil are an important factor in clean-up decisions. If natural cleaning is rapid no response may be necessary. If oil is stranded above normal levels of wave activity in a high-energy environment the contaminated sediments could be pushed into the intertidal zone. This would result in natural cleaning without sediment removal. In terms of the clean-up programme this action would avoid creation of an unstable beach equilibrium and the cost would be less than a sediment removal and replacement operation.

In principle, as energy levels and rates of natural dispersion and degradation increase so the requirements for a clean-up or restoration programme will decrease.

9.4 SHORELINE PROTECTION METHODS

This section considers available methods of protection and assesses their applicability and effectiveness for some of the major shoreline types. As sheltered coastal environments (Groups I and II, Table 16) are more sensitive to damage by stranded oil, and are usually more difficult to restore, the implementation of an offshore or onshore protection programme can reduce the expected impact of a major spill.

Prevention of oil reaching sensitive environments should be a high priority. This could be achieved by the use of booms to contain the oil offshore or to prevent oil entering inlets, rivers and creeks. This containment would be followed by removal of the oil from the sea surface using skimmers. These can be used in conjunction with sorbents that are broadcast on the slick to reduce spreading and to facilitate collection. The use of dispersants on the sea could also be considered if the movement of a slick into a sensitive or low-energy environment is predicted, particularly if booms and skimmers could not be deployed or would not be effective due to strong currents or to wave activity. Surface collection agents can be used to contain oil and this technique was used in a blowout off the Louisiana coast (Berry, 1972). The agent was spread in the surf zone prior to the oil being deposited on the shoreline and proved effective in preventing the oil from penetrating the sand. If it is predicted that the oil would be stranded on an exposed coast where natural cleaning is rapid, booms or dispersants would not be necessary.

The use and effectiveness of booms, skimmers and dispersants are not covered in this report. The application of dispersants has no geological impact and could, therefore, be recommended for oil dispersal. However, the consideration of biological parameters limits their applicability as the effectiveness of dispersal agents can be offset by damage to flora and fauna. If a decision to use dispersants is approved it must be remembered that this procedure can result in greater penetration of the dispersed oil into shoreline sediments. If the oil is not flushed out of the beach sediments, rates of degradation would be low and the oil would persist until it is exposed by littoral processes.

One of the most important methods of onshore protection will probably be the application of <u>surface treatment agents</u> before oil is stranded on the shoreline. Although this method is in the development and assessment stage, it is important as the agents prevent oil that is washed ashore from adhering to sediment or rock surfaces (Dailey *et al.*, 1975; Stewart, 1975; and Foget *et al.*, 1977). Different natural and synthetic agents are currently being studied to determine methods of application, persistence, effectiveness and climatic limitations.

One readily available agent that could be used is <u>water</u>. Oil tends not to adhere to wet surfaces and if water is sprayed on shorelines, it could prevent or reduce the amounts of oil that would be stranded on the shoreline, providing that ambient temperatures do not evaporate the water. If ambient temperatures are below the freezing point of the water, spraying of the shoreline would produce a film of ice that would prevent oil from contaminating sediment or rock surfaces. This technique would depend also on water temperatures. This technique has not yet been investigated. In all cases the application of a surface treatment agent would act to protect the shoreline, but this operation would have to be followed by removal of the oil using techniques such as sorbents or hoses.

Sorbents can be spread on a shoreline to collect oil and to prevent penetration of oil into beach sediments. The sorbents are most effective when spread on the shoreline before the oil is washed ashore and sorbent pads are usually preferable to loose-fibre sorbents. In tidal environments this is best done at low tide so that the oil and sorbent mix as the water level rises. Following stranding of the oil, the oil-sorbent mixture should be removed as soon as possible so that the oil is not subsequently released.

Tests on the effectiveness of sorbents indicate that synthetic products have a higher sorbtion capacity than natural organic material independent of oil viscosity, and that the sorbtion capacity of inorganic material is low for low vis-

TABLE 18. Criteria Related to Selected Sorbent Materials (from Wardley Smith, 1976)

MATERIAL	AVAILABILITY	TREATMENT NEEDED BEFORE USE	STORAGE PROBLEMS	EASE OF APPLICATION	OIL ABSORBTION	EFFICACY WHEN WET	LEAKS OUT OF OIL BY WATER	EASE OF RECOVERY FROM WATER	EASE OF DISPOSAL (4)
Straw	****	***	***	**	****(1)	*	*	**	***
Untreated sawdust	****	****	*	****	**(2)	*	*	*	**
Treated sawdust	***	*	**	****	**(2)	***	***	*	**
Pine bark	***	*	**	****	***(2)	***	***	*	*
Peat	***	*	**	***	***(2)	***	**	*	***
Ekoperl	**	****	**	****	****(2)	****	****	*	*
Vermiculite	*	****	**	****	*	(3)	—	—	—
Polystyrene pellets	*	***	*	**	*	(3)	—	—	—
Polyurethane foam	**	*	****	**	****(2)	****	***	**	***
Polypropylene fibres	**	***	**	***	****(1)	****	*	****	***

NOTE: Key — more stars, the better

(1) Less effective with thin oils
(2) Less effective with heavy oils
(3) In view of low absorbtion not assessed further
(4) Mainly by burning

cosity oils (Schatzberg and Nagy, 1971; Environment Canada, 1976). In addition, McMinn and Golden (1973) note that in cold climates sorbents are less effective. Table 18 presents data on the use and effectiveness of selected sorbents. The disadvantage of sorbents is that their use is labor-intensive, requiring spreading, mixing, collection and disposal. Various systems have been developed to mechanically spread sorbents on a shoreline (e.g., snowblowers (Logan et al., 1976)) and to collect them from water surfaces (Gumtz and Meloy, 1973; Miller et al., 1973; Shaw and Dorrler, 1977; Brunner et al., 1977). Logan et al., (1976) state that a single snowblower can spread peat moss over a 1 km section of beach in approximately 7.5 hours. If sorbents are washed onto the water with hoses, they can be collected by a variety of mechanical systems.

Protection of upper beach or backshore areas can be achieved by construction of dykes or ditches parallel to the water line near the high-water level. On sand beaches dykes act as a barrier to oil reaching backshore areas and would contain oil on the upper intertidal zone or the upper beach for later removal. In construction of a dyke wet sand pushed up from the intertidal zone makes a more effective barrier to oil, as it is possible to construct a higher dyke than if dry, backshore sand is used. The use of tracked vehicles for this operation is recommended because of the better traction provided by this type of equipment.

Pits or ditches can be dug to act as collectors for oil. When swash and oil run up into the ditch water is drained out through the beach sediments. Oil in the ditches can then be removed with cans, buckets, pumps, or vacuum skimmers. Dykes or ditches would be particularly useful if water levels are high and there is a danger of overwash (see Photo 53, page 197). These methods are less effective on coarse-sediment beaches as the oil would penetrate into the material. Nevertheless a dyke at the high-water mark would collect oil within the pebble-cobble sediments and protect sensitive backshore environments such as marshes or lagoons.

Limiting factors in all methods of onshore protection are:

(a) Prediction of slick movements and where the oil will be washed ashore,

(b) A sufficient time lag to allow completion of protection operations,

(c) Accessibility to areas requiring protection,

(d) Availability of equipment, material and manpower, and,

(e) Environmental conditions.

In the latter case storm-wave conditions on the shoreline would severely hamper and probably prevent implementation of all protection methods. In addition, if dykes or ditches have been constructed these would be rapidly destroyed by wave action.

SUMMARY: Shoreline Protection Methods

(1) Offshore protection (containment and removal or dispersal) is valuable for sensitive or low-energy environments, but not usually necessary for self-cleaning coasts.

(2) *The development of acceptable, non-toxic dispersants and surface treatment agents will probably provide effective and valuable shoreline protection methods in future years.*

(3) *Synthetic agents, water, ice, or sorbents on the shoreline could prevent oil adhering to shoreline surfaces.*

(4) *Dykes and ditches can protect backshore environments, provided that they are not destroyed by wave action.*

(5) *Effective protection requires a knowledge of slick movements, shoreline types, and the availability of equipment, material and manpower.*

9.5 SHORELINE RESTORATION METHODS

After a decision has been made that cleanup is desirable and that the shoreline is to be restored before the oil weathers and ages naturally, a variety of methods are available to carry out this programme. This section considers contemporary methods and techniques and assesses their applicability and effectiveness for different coastal environments and shoreline types.

Dispersion

(i) Chemical dispersion. The use of chemical dispersants is regulated to non- or low-toxic products and prior permission must be obtained for their use in Canada (Ruel et al., 1973;

Environment Canada, 1976a). Dispersants can effectively remove oil from sediment or rock surfaces, but it is advisable to remove as much oil as possible, either mechanically or manually, before a dispersant is applied.

The effectiveness of dispersants increases if they are mixed with the oil. This can be achieved using hoses or by spraying the dispersant on contaminated intertidal zones at low tide, thereby allowing natural wave action to agitate the agent with stranded oil. The oil/dispersant emulsion should be flushed from the shoreline with hoses if it is not removed naturally by the tides (Wardley Smith, 1968).

Apart from toxicity to flora and fauna, two limitations on this method must be considered. The application of dispersant agents frequently leads to emulsification of the oil and this process can retard bacterial degradation rates (Hughes and Stafford, 1976). Secondly the reduction in viscosity of the dispersed oil can result in greater penetration of the oil into the beach sediments (Northeast Region Research and Development Program, 1969).

If acceptable non-toxic biodegradable dispersants are developed these would be a valuable option in the future, particularly for the restoration of rocky shorelines or coarse-sediment beaches in low-energy environments.

(ii) Hydraulic Dispersion. *High-pressure hoses* can be used to wash oil from coarse sediments, rock surfaces or man-made structures. On cobble beaches, however, this action can wash the oil from the beach surface into the sub-surface sediments. On rock shorelines this method can damage flora and fauna, although it has been found in some cases that repopulation following contamination was aided by high-pressure hot-water dispersion (Eidam et al., 1975).

Low-pressure hydraulic dispersion is a biologically preferred method and can be used on all rock surfaces, man-made structures and in marshes (Westree, 1977). The method is not applicable to sand beaches as the water would wash away the sediments and on coarse-sediment beaches it would lead to greater penetration of the oil. As in all dispersion methods the oil should be contained near the shoreline for collection from the water surface. This method is effective and is recommended for rock surfaces, man-made structures and marshes.

Under no circumstances should hydraulic dispersion be used to clean unresistant or unconsolidated cliffs as this could result in undercutting of the cliff or slumping.

(iii) Steam Cleaning. Hot-water or steam cleaning is similar to but more effective than high-pressure hydraulic dispersion and is subject to the same limitations. However, this option is more harmful to flora and fauna as well as being more expensive. The method is recommended only for the cleaning of man-made structures.

(iv) Sandblasting. Although slow, this method removes oil from rock or boulder surfaces and from man-made structures. One advantage of this method is that it removes oil stains from rock surfaces (Der and Ghormley, 1975). It does, however, cause considerable damage to flora and fauna and is, therefore, only recommended for man-made structures. Use of this method is limited by the expense and by the slowness of the operation.

(v) Mixing. On beaches where oil has been removed but light contamination remains, mixing of the surface sediments using mechanical rakes or harrows promotes evaporation and degradation by exposing larger surface areas of the oil to weathering. Similarly on beaches in sheltered environments where sediment removal is not required or is undesirable this method can break up an "asphalt pavement" and increase rates of dispersal and degradation.

Mixing is effective for light-grade oils that evaporate easily on exposure. This is particularly applicable for these types of oil on sandy beaches or where they have penetrated into the beach sediments. In all cases, care must be exercised to avoid burial of the oil as this reduces rates of degradation.

The most effective application of mixing is to use machinery to push contaminated sediments into the zone of wave activity (the lower intertidal zone if it is a tidal environment) and allow normal wave action to abrade and disperse the oil. The waves would not only clean the sediments but would return them to the upper parts of the beach.

Removal

(vi) Mechanical: Sand Beaches. On sand beaches large amounts of oil on the surface of the sediments can be removed effectively and efficiently by the use of mechanical scrapers in combination with elevating graders (Sartor and Foget, 1970). This method is recommended provided that the beach provides adequate traction for this equipment. The most efficient technique for removal of oil on the surface of sand is for the grader with a blade angle of 50° to form windrows that are then removed for disposal by the elevating scraper (Table 14, page 255, and Fig. 50). If graders are not available elevating scrapers can be used alone. If graders are available but scrapers are not, front-end loaders can be used to remove the windrows (Table 14, page 255). If traction is poor or if oil penetration is greater than 2.5 cm, scrapers should be used in place of graders. Where traction is very poor or penetration is greater than 25 cm, front-end loaders may have to be used (Der and Ghormley, 1975).

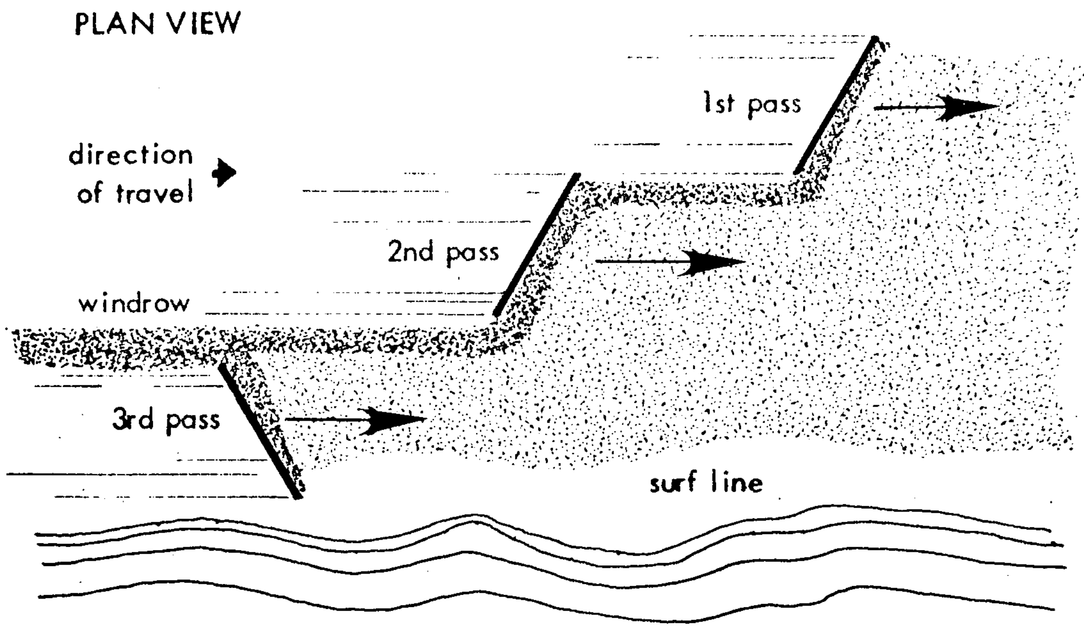


Figure 50. Sequence of windrow formation for removal of surface oil from sand beaches by a motorized grader (from Sartor and Foget, 1970).

These techniques are also useful for removing sediment-oil-sorbent mixtures and are not hampered by small amounts of debris on the shoreline. If beach traction is poor, as is often the case on the upper beach and backshore areas, it may be necessary to reduce tyre pressures or to install flotation tyres.

Overall, front-end loaders are less efficient and effective due to the high rates of spill from the bucket. Amounts of spillage can be reduced if the bucket is only filled to one-quarter capacity (Owens, 1971). In addition, tracked vehicles substantially grind oil into the beach. Further details on the evaluation, operation and use of these types of equipment are given by Sartor and Foget (1970 and 1971). The primary results of these evaluation tests were:

(a) Grader/Scraper. This was found to be the best of the techniques evaluated. Contaminated sediments were pushed into windrows by the grader and then lifted by the scraper. This technique removed the least uncontaminated material but spillage from the scraper required a following pick-up crew. The grader became stuck on coarse sand unless flotation tyres were in use, and the accuracy of the depth of cut decreased if traction was low.

(b) Scraper. Used on its own the scraper had a high spillage and like the grader, it required a flat beach and became stuck easily in coarse sand.

(c) Grader/Front-end Loader. The loader was used to remove the windrows. Its performance in general is outlined below.

(d) Front-end Loader. This machine was the least efficient of those tested as it removed too much uncontaminated material and had a high spillage. The same deficiencies apply to bulldozers and tracked loaders and these were also found to "grind the oil several feet into the sand".

(e) Ramp-Conveyor System. This method was developed to transfer contaminated sediments for disposal and was found to be efficient for very large operations.

The tests and operational procedures discussed in these reports do not include an evaluation of bulldozers, but the problems of spillage and grinding of oil particularly apply to this type of equipment (Owens, 1971). The only time that a bulldozer should be used for cleanup is if other equipment is unavailable or if traction is too low to permit the use of more effective equipment. If a bulldozer is the only available equipment, an angled rather than a straight blade would reduce spillage around the blade edge.

Der and Ghormley (1975) note that the rate at which sediment can be removed (Table 19) is not an indicator of effectiveness on its own and that the ability of graders to remove only a thin layer of oil and contaminated sediments must be taken into account when assessing efficiency.

Several specialized types of equipment have been developed to remove viscous oil or tarry lumps from sand beaches. One approach has been to develop tractor-operated sieving devices that pick up and separate sand from oil, allowing the sand to fall through the screens (Cormack and Jeffrey, 1975; Warren Spring Laboratory, 1973 and 1974). Photographs of

TABLE 19. Cleaning Rates of Various Equipment

Equipment	Approximate Rate hrs/acre
Combination motorized grader & motorized elevating scraper	3
Elevating scraper	3
Combination motorized grader & wheeled front-end loader	6
Combination motorized grader & tracked front-end loader	30
Bulldozer	50

(from Der and Ghormley, 1975)

these two machines are given by Wardley Smith (1976, page 185). The sieve size can be changed to allow for different sizes of sand but this equipment does not work as well if the sand is wet. The evaluations of these two machines indicate that they are effective for tar lump removal. The second method, developed at the Warren Spring Laboratory, is to use a front-mounted rotary brush system to spike the lumps of tar (Wardley Smith, 1968). This equipment is relatively effective on sand beaches and is discussed further below.

Mechanical: Coarse-Sediment Beaches. Mechanical removal is less effective on this type of beach due to the greater penetration depths of the oil and to the low bearing strength of the sediments. Only front-end loaders and bulldozers can operate effectively on this type of beach and even then it is frequently difficult to maintain traction. Wheeled front-end loaders are preferred over tracked vehicles or bulldozers, if traction can be maintained, as rates of grinding are lower for non-tracked equipment (Owens, 1971).

Careful supervision of the operation is required to prevent removal of non-contaminated sediments and to minimize the spillage by insuring that the bucket is not filled to capacity. If oil is restricted to the surface sediments a front-end loader can be used effectively to lift or scrape only the contaminated material from the beach (Photo 80, page 267).

Cleanup of pebble-cobble beaches requires removal of large volumes of material for relatively little oil (page 266). If the oil on the storm ridge has penetrated deeply into the sediments and this is then removed, the material should be replaced to avoid erosion or inundation of backshore areas.

A machine developed at the Warren Springs Laboratory was designed to pick up large tar lumps from coarse-sediment beaches (Wardley Smith, 1976, page 188). This equipment uses 30 loosely-mounted toothed discs to spike the oil that is then removed by scrapers. It was found to be only partially effective on pebble-cobble beaches.

It must be remembered that it is rarely possible to remove all oil from contaminated pebble-cobble beaches. Once the majority of the oil is removed the remaining contaminated sediments can be removed manually or can be pushed to the lower parts of the beach for reworking and abrasion by wave action.

For cleanup and sediment removal on pebble-cobble beaches the use of multi-task buckets that can scrape, dig or grab and remove contaminated material may be more useful than a front-end loader with a simple bucket. In either case, tracked vehicles should not be used in order to avoid grinding in of oil (Owens, 1971).

Mechanical Removal: General Points. In all mechanical removal operations it is critical to remove as little uncontaminated sediment as possible. Where large volumes of sediment are removed, it is advisable in most cases to replace that sediment to prevent adverse alteration of the beach equilibrium.

If oil is to be removed from a beach this should be carried out as soon as possible, before burial can take place, provided that there is no danger of recontamination. If burial is allowed to occur, it would then be necessary to remove large volumes of material, much of which would include clean sediments resting on top of the oil layer (Photo 57, page 202).

Stockpiling of sediments on backshore areas should be avoided to prevent mixing of clean and contaminated sediments. The use of bulldozers to simply push oiled sediments into backshore areas for later removal is not recommended. In the tests performed by Sartor and Foget (1970) a ramp and conveyor belt system was used to transfer material directly from the elevating scrapers into trucks. If larger-scale cleanup is required this system can be efficient and can reduce clean-up costs. In addition, on sand beaches a screening system can be incorporated to separate oil-soaked debris and sorbents from the sediment.

In locations where low bearing strengths do not permit access even of tracked vehicles, draglines could be used to remove contaminated sediments. In the Casco Bay spill in Maine this equipment was used on a sand beach, due to local problems of accessibility, and the draglines removed beach sediment to an average depth of 20 cm (Foget, 1972).

(vii) Manual. For small amounts of oil or in areas inaccessible to or unsuitable for machinery, manual removal of oil can be effective. This method can be used on every shoreline type, but is not applicable for unresistant or unconsolidated cliffs, and is often used in combination with other restoration methods. For example, when machinery is used on a sand beach some manual removal may be necessary to clean up small amounts of oil spilled by the equipment.

A variety of procedures can be used including rakes, forks, shovels, buckets, cans, pumps or vacuum skimmers. In addition, contaminated intertidal or marsh vegetation can be cropped manually with scythes or sickles. Westree (1977) cautions that in marsh environments personnel should be careful not to trample oil into the sediments during restoration, as this can damage the root systems of plants such as *Spartina* or can spread oil from contaminated to clean areas.

Manual removal of oil is labor intensive and can, therefore, be expensive. This method has been an integral part of clean-up programmes in the past and has been found to be effective in restoring contaminated shorelines.

(viii) Sorbents. A variety of materials are available to be mixed with and to absorb oil (Table 18, page 338). Although the commercially-developed products have been developed primarily for use in recovering oil from water surfaces they can also be used on shorelines.

Inorganic sorbents are usually fine-grained materials that are either mined or manufactured, so that their availability is often limited. They are useful for low viscosity oils and are difficult to collect but can be reused if the oil is incinerated. Natural organic materials are usually the most readily available and are the least expensive sorbents. In particular straw and peat moss have been widely used. This type is most effective on weathered crude or heavy fuel oils (Wardley Smith, 1976). Synthetic polymeric materials have been developed that are very effective. These come in granular form, as mats of fibres or as chemicals that can be mixed at the site.

Evaluation of different sorbents by Schatzberg and Nagy (1971) found that in general synthetic organic products were more effective than natural organic materials or inorganic materials (Table 20). The products with the highest capacities were found to be the polymeric foams, either shredded or as cubes. In general, as the viscosity of oil decreases the effectiveness of the sorbent also decreases. McMinn and Golden (1973) found that sorbents were less effective when tested in an arctic environment, because as much energy was required to mix the oil and sorbent as would have been required to clean up the unabsorbed oil. During the "Arrow" spill considerable amounts of peat moss were used and these had a maximum sorbtion capacity of 17 gms oil/gm peat moss (Task Force, Operation Oil, 1970). The peat moss was spread manually and with modified snow blowers and was harvested from sand beaches with

TABLE 20. Maximum Oil Sorption Capacity for Selected Materials

(grams oil/gram sorbent)

	BUNKER C	HEAVY CRUDE	LIGHT CRUDE	NO. 2 FUEL
Sawdust	3.0	3.7	3.6	2.8
Vermiculite	4.3	3.8	3.3	3.6
Wheat Straw	5.8	6.4	2.4	1.8
Wood Cellulose Fibre	18.6	17.3	11.4	9.0
Polyethylene Fibres Sheet, Matted	18.6	17.6	11.9	10.6
Volcanic Ash	21.2	18.1	7.2	5.0
Polyurethane Foam (a) Polyether, Shredded	72.7	74.8	60.0	48.7
(b) Polyether, 1/2" Cubed	72.7	71.7	66.1	64.9

(from Schatzberg and Nagy, 1971)

rakes. The collection technique proved an effective method of mixing the oil with the peat moss.

Collection can be difficult from coarse-sediment beaches, rock surfaces or marshes but it is possible to use low-pressure hoses to move the oil/sorbent onto water surfaces for collection. This would be effective for oil on rock surfaces and in marshes.

Equipment has been developed to clean and reuse synthetic sorbents, including a relatively portable regenerator that is mounted on the back of a pickup truck (Shaw and Dorrler, 1977).

(ix) Burning. This method is seldom successful for oil removal (Der and Ghormley, 1975). Frequently ignition and wicking agents are required to initiate and maintain combustion. In addition to residues produced by the partial burning of the oil, these agents themselves produce residues. Oil can be burnt more successfully if it is contained on an ice surface, in this case the residues are relatively easy to remove. Oil burnt on snow melts pits and this makes the removal of residues difficult (McMinn and Golden, 1973).

Oil in marshes can be successfully burnt in autumn or winter months, as long as the root systems of the vegetation are not damaged. Controlled burning is frequently used in marsh management and can have beneficial effects.

Except for marshes, burning is not a practical or efficient method of removal as (1) undesirable heavy residues remain that then have to be removed, (2) the smoke from burning can be an undesirable form of pollution, and (3) on beaches, viscosity decreases and the oil penetrates into the sediments.

(x) *In Situ* Cleaning of Sediments. This method involves a variety of techniques that have been developed that involve removal of contaminated sediments from the beach, removal of the oil from the sediments, and then replacement of the clean sediments. The various techniques include combustion, froth flotation, or washing. Although a variety of designs have been developed and some of the equipment has been field-tested, no one technique has yet proved to be cheap, portable and efficient. Although some of the techniques are effective the main disadvantages of existing equipment are high cost, bulky equipment and rates of cleaning that are relatively slow. The majority of the techniques developed have been for sand-size sediments and are, therefore, limited in their application to Canada's coastal zones.

Sand can be separated from oil by deposition of the contaminated sediments in sumps dug in backshore areas. This allows the sand to sink to the bottom whereas the oil floats and can be removed with pumps.

9.6 DISCUSSION

Shoreline restoration programmes at the present time depend heavily on unsophisticated manual and mechanical methods using readily available equipment. Clean-up operations in which these methods have been implemented have proven to be effective (e.g., the Santa Barbara and "NEPCO 140" spills). As a result of learning experiences from spills and simulated field evaluations, the present methods have been developed to a point where major new innovations are unlikely and expected improvements in the immediate future are only refinements of the existing techniques.

Possible long-term improvements in restoration methods will be in the development of surface treatment agents and of acceptable non-toxic dispersants, as well as improvements in offshore protection methods. In particular, surface treatment agents could prove to be of great value as a method of shoreline protection and biodegradable, non-toxic dispersants would be a valuable tool for removal of stranded oil.

The design and construction of elaborate equipment for specific tasks is suitable for high-risk environments, such as ports, but these machines are generally not very mobile and it is difficult to envisage that they could be generally employed at spill sites distant from populated areas. Although present methods and techniques can be effective when properly utilized, clean-up operations are nevertheless time-consuming and usually difficult and expensive.

In the implementation of a restoration programme two important points must be borne in mind: (1) to prevent more damage than is caused by the oil alone, and (2) to prevent recontamination of restored shorelines (Photo 103). Damage can be caused by sediment removal, destruction of backshore vegetation,

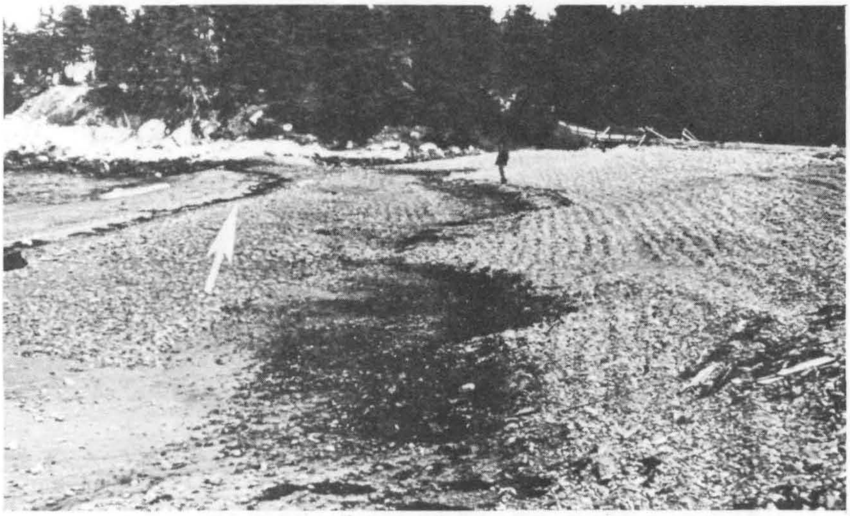


Photo 103. Pebble-cobble beach at Indian Cove, N.S., May 1970, recontaminated by oil released from adjacent rock shorelines during a spring tide. This photograph was taken at low tide on the day following completion of the clean-up operation. The oil was deposited at the spring high-tide mark, the arrow marks the normal high-tide level.

and disturbance of littoral flora and fauna. As a general principle, restoration should take place working from clean areas towards contaminated areas so that oil is not spread over uncontaminated sediments by personnel and machinery. It is rarely possible to clean just one section of a shoreline without danger of recontamination from alongshore. In Chedabucto Bay recontamination was still occurring two years after the spill as undegraded oil became mobile in warm weather (Thomas, 1973).

Two aspects of the response to a spill are important to an effective clean-up programme. The first is the ability to predict which sections of shoreline will be contaminated. This is necessary in order to protect those types of shorelines where the oil could seriously damage the environment or where clean-up techniques are least effective or most difficult. Secondly it is important to be able to predict the expected impact of the oil in order to efficiently mobilize and deploy available restoration resources.

The methods used to restore a contaminated shoreline depend on the amount and type of oil, the location and the nature of the contamination, and expected rates of natural dispersion and weathering. In particular, the selection of removal equipment for oiled beaches depends on the penetration depth of the oil and the bearing strength of the sediments.

Although no action is recommended in most cases, Table 21 presents the major restoration methods and their applicability and effectiveness for the major shoreline types.

TABLE 21. Shoreline Restoration Methods

	CHEMICAL DISPERSANTS	HYDRAULIC HIGH-PRESSURE	HYDRAULIC LOW-PRESSURE	STEAM CLEANING	SANDBLASTING	MIXING	MECHANICAL REMOVAL	MANUAL REMOVAL	SORBENTS	BURNING	CROPPING
Rock Surfaces	+	+	√	+	+	-	-	√	+	-	+
Man-Made Structures	+	√	√	√	√	-	-	√	+	-	-
Unresistant or Unconsolidated Cliffs	-	x	x	x	x	-	x	x	x	-	-
Coarse Sediment Beaches	+	+	+	x	x	+	+	√	+	x	-
Sand Beaches	+	x	x	x	x	+	√	√	√	x	-
Intertidal Coarse Sediments	+	+	+	+	x	+	+	√	+	x	-
Intertidal Sand	+	x	x	x	x	x	+	+	+	x	-
Intertidal Mud	+	x	x	x	x	x	x	+	+	x	-
Marshes	x	x	√	x	x	-	x	√	+	+	+

√ Recommended x NOT Recommended

\+ Applicable and possibly useful - Not Applicable

No significant breakthroughs in restoration methods or techniques can be anticipated in the immediate future. Where a response to a major coastal spill is necessary existing methods and techniques, if properly executed, can be effective in restoring contaminated shorelines without incurring further damage to the environment.

PART 10 - CONCLUSIONS

1. Most of Canada's coastline is relatively unexplored in terms of an inventory of the shoreline character or of an understanding of local littoral processes. Apart from a few exceptions, the majority of the detailed scientific studies in the last 20 years have focussed on the lower Great Lakes, the southern Gulf of St. Lawrence and the Mackenzie and Fraser deltas.

2. Although there is a wide range of geologic, oceanographic, climatic and biologic environments, the coasts of Canada are predominantly low-wave energy environments with rock shorelines or coarse-sediment beaches. In terms of the process environment, ice is a major factor in the littoral zone for approximately 90% of the total coastline.

3. The development of shoreline restoration methods has reached the point where relatively unsophisticated techniques using available equipment can be effectively applied to meet the objectives of clean-up operations. The implementation of these methods is nevertheless usually difficult and time-consuming.

4. Shoreline protection should have a primary importance for

areas sensitive to damage from stranded oil and for environments that are difficult to restore. The technology for offshore protection (booms, skimmers, sorbents, etc.) is relatively well-developed and is effective except in adverse environmental situations.

5. Future improvements in shoreline protection methods will probably be in the development of acceptable non-toxic dispersants for offshore protection and of surface treatment agents for onshore protection.

6. In areas where socio-economic or aesthetic factors are not critical, natural dispersion and degradation of stranded oil may be acceptable for shoreline restoration rather than a clean-up operation. The rates of self-cleaning of a shoreline are related primarily to the characteristics of the stranded oil and to littoral zone energy levels, in particular levels of wave energy.

7. The primary purposes of this report have been: (a) to collate and review information on the character of the coasts of Canada and the processes that operate in the different coastal environments, (b) to consider how and why oil impacts on the shoreline, and (c) to relate information on shoreline dynamics to clean-up operations. This approach

can provide the basis for the development of local and regional contingency plans as well as for on-site decisions during a restoration programme.

BIBLIOGRAPHY OF

THE COASTS OF CANADA

Allen, W.T.R., 1964, Break-up and freeze-up dates in Canada; Can. Dept. of Transport, Meteorological Branch, CIR 4116, 201 p.

Beals, C.S. (ed.), 1968, Science, History and Hudson Bay; Dept. Energy, Mines and Resources, Ottawa, 2 volumes.

Bird, J.B., 1967, The Physiography of Arctic Canada; The Johns Hopkins Press, Baltimore, 336 p.

Canada, Department of Transport, 1968, Climatic normals, v. 5, Winds; Meteorological Branch, Toronto, 95 p.

CHS (Canadian Hydrographic Service), 1968, Pilot of Arctic Canada; volumes II and III, Fisheries and Marine Service, Environment Canada, Ottawa.

_______________, 1970, Pilot of Arctic Canada; volume I, Fisheries and Marine Service, Environment Canada, Ottawa.

_______________, 1973, Sailing Directions, Gulf and River St. Lawrence; Fisheries and Marine Service, Environment Canada, Ottawa.

_______________, 1974a, Sailing Directions, British Columbia Coast; 2 volumes, Fisheries and Marine Service, Environment Canada, Ottawa.

_______________, 1974b, Sailing Directions, Labrador and Hudson Bay; Fisheries and Marine Service, Environment Canada, Ottawa.

_______________, 1974c, Sailing Directions, Newfoundland; Fisheries and Marine Service, Environment Canada, Ottawa.

_______________, 1974d, Sailing Directions, Nova Scotia (S.E. Coast) and Bay of Fundy; Fisheries and Marine Service, Environment Canada, Ottawa.

_______________, 1976, Sailing Directions, Great Lakes; 2 volumes, Fisheries and Marine Service, Environment Canada, Ottawa.

_______________, 1977, Tide and Current Tables; 6 volumes, Fisheries and Marine Service, Environment Canada, Ottawa.

Clemens, R.H., 1976, Selected environmental criteria for the design of artificial structures on the southeast shore of Lake Erie; Univ. South Carolina, Dept. of Geology, Tech. Rept. CRD No. 8, 95 p.

Cooper, E.J., McColl, R.E., and Smith, F., 1971, Measurements of Canada's coastline; Canadian Hydrographic Service, unpub. ms., 34 p.

Cry, G.W., 1965, Tropical cyclones of the North Atlantic ocean; U.S. Dept. of Commerce, Weather Bureau, Tech. Paper No. 55, 148 p.

Davies, J.L., 1972, Geographical Variation in Coastal Development; Oliver and Boyd, Edinburgh, 204 p.

Dionne, J-C., 1968, Morphologie et sédimentologie glacielles, côte sud du Saint-Laurent; Zeits. für Geomorphologie, Sp. Pub. No. 7, p. 56-84.

Dohler, G., 1969, Tides in Canadian Waters; Canadian Hydrographic Service, Marine Sciences Branch, Ottawa, 14 p.

Dolan, R., Hayden, B., Hornberger, G., Zieman, J., and Vincent, M., 1972, Classification of the coastal environments of the world, Part 1, The Americas; Dept. of Environmental Sciences, Univ. of Virginia, Tech. Rept. No. 1, 163 p.

Douglas, R.J.W. (ed.), 1970, Geology and Economic Minerals of Canada; Geol. Surv. Can., Econ. Geol. Rept. No. 1, 5th edition, 838 p.

Dubois, J-M., 1973, Essai de classification de la zone côtière et d'identification d'unités physiographiques sur la côte nord du Saint-Laurent; Canada, Min. Travaux Publics, Montréal, Etude des Rives du St-Laurent, 71 p. & appendices.

Environment Canada, 1973, Climatic normals, v. 1, Temperature; Atmospheric Environment Service, Downsview, Ontario, 186 p.

__________________, 1975, Monthly and yearly mean water levels, v. 1, Inland; Marine Environmental Data Service, Ottawa, 145 p.

Geological Survey of Canada, 1967, Geology of Canada; Dept. Energy, Mines and Resources, Ottawa, 17 p.

Holland, S.S., 1976, Landforms of British Columbia; British Columbia Dept. of Mines & Petroleum Resources Bull. 48, 138 p.

Hough, J.L., 1968, Great Lakes; in R.W. Fairbridge (ed.), Encyclopaedia of Geomorphology, Reinhold, N.Y., p. 499-506.

Neu, H.A., 1971, Wave climate of the Canadian Atlantic coast and continental shelf-1970; AOL Rept. 1971-10, Bedford Institute, Dartmouth, Nova Scotia, 172 p.

__________, 1972, Extreme wave height distribution along the Canadian Atlantic coast; Ocean Industry, 7, p. 45-49.

Owens, E.H., 1974, A framework for the definition of coastal environments in the southern Gulf of St. Lawrence; in B.R. Pelletier (ed.), Offshore Geology of Eastern Canada, vol. 1, Geol. Surv. Can. Paper 74-30, p. 47-76.

__________, 1975, Barrier beaches and sediment transport in the southern Gulf of St. Lawrence, Canada; Proc. 14th Internat'l Coastal Engin. Conf., Copenhagen, June 1974, Amer. Society Civil Engineers, N.Y., vol. 2, p. 1177-1193.

__________, 1977a, Coastal environments, oil spills, and clean-up programmes in the Bay of Fundy; Environment Canada, Environmental Protection Service (in press), 175 p.

__________, 1977b, Process and morphology characteristics of two barrier beaches in the Magdalen Islands, Gulf of St. Lawrence, Canada; Proc. 15th Internat'l Coastal Engin. Conf., Honolulu, July 1976, Amer. Society Civil Engineers, N.Y., (in press).

__________, and Bowen, A.J., (in press), Coastal environments of the Maritime Provinces; Maritime Sediments.

__________, and McCann, S.B., (in preparation), The coastal geomorphology of the Magdalen Islands.

Pincus, H.J. (ed.), 1962, Great Lakes Basin; Amer. Assoc. Advancement of Science, Pub. No. 71, Washington, D.C., 308 p.

Ploeg, J., 1971, Wave climate study, Great Lakes and Gulf of St. Lawrence, vol. 1; Nat. Res. Council Canada, Mech. Engin. Rept. MH-107A, 160 p.

Ragotzkie, R.A., 1974, The Great Lakes Rediscovered; American Scientist 62(4), p. 454-464.

Reader's Digest, 1976, Scenic Wonders of Canada; Montreal, 384 p.

Taylor, R.B., 1973, Coastal Environments and Processes in the Canadian Arctic Archipelago; unpub. M.Sc. thesis, McMaster University, 210 p.

U.S. Naval Oceanographic Office, 1965, Sailing Directions for Labrador and Hudson Bay; Hydrographic Office Pub. No. 15.

BIBLIOGRAPHY OF

COASTAL ENVIRONMENTS OF THE PACIFIC COAST

Canada, Department of Transport, 1968, Climatic normals, v. 5, Winds; Meteorological Branch, Toronto, 95 p.

CHS (Canadian Hydrographic Service), 1974, Sailing Directions, British Columbia Coast; 2 volumes, Fisheries and Marine Service, Environment Canada, Ottawa.

____________________________________, 1977, Tide and current tables; volumes 5 and 6, Fisheries and Marine Service, Environment Canada, Ottawa.

Clague, J.J., 1975, Late Quaternary sea level fluctuations, Pacific coast of Canada and adjacent areas; Geol. Surv. Can. Paper 75-1C, p. 17-21.

____________, 1976, Pleistocene sediments in the northern Strait of Georgia, B.C.; Geol. Surv. Can. Paper 76-1B, p. 157-160.

Cooper, E.J., McColl, R.E., and Smith, F., 1971, Measurements of Canada's coastline; Canadian Hydrographic Service, unpub. ms., 34 p.

Douglas, R.J.W. (ed.), 1970, Geology and Economic Minerals of Canada; Geol. Surv. Can., Econ. Geol. Rept. No. 1, 5th edition, 838 p.

Giovando, L.F., 1975, Oil-pipeline marine terminals at Port Angeles and Rosario Strait: Some suggested oil-spill consequences; Pacific Envir. Institute, unpub. ms., 40 p.

Glass, D.J. (ed.), 1972, Geology of Vancouver Area, British Columbia; Guidebook for Field Excursions A05-C05; Internat'l Geol. Congress, Montreal, 47 p.

Holland, S.S., 1976, Landforms of British Columbia; British Columbia Dept. of Mines & Petroleum Resources Bull. 48, 138 p.

Kellerhals, P., and Murray, J.W., 1969, Tidal flats at Boundary Bay, Fraser River Delta, British Columbia; Can. Petroleum Geologists Bull. 17, p. 67-91.

Kozloff, E.N., 1973, Seashore Life of Puget Sound, the Strait of Georgia and the San Juan Archipelago; Univ. of Wash. Press, Seattle, 282 p.

Lang, A.H., and Muller, J.E., 1975, The Geology of the Long Beach Segment Pacific Rim National Park; Geol. Surv. Can. Misc. Rept. 24, 56 p.

Luternauer, J.C., 1976a, Fraser Delta sedimentation, Vancouver, British Columbia; Geol. Surv. Can. Paper 76-1A, p. 213-219.

_______________, 1976b, Skeena Delta sedimentation, British Columbia; Geol. Surv. Can. Paper 76-1A, p. 239-242.

_______________, and Murray, J.W., 1973, Sedimentation of the western delta front of the Fraser River, British Columbia; Can. Jour. Earth Sci., v. 10, no. 11, p. 1642-1663.

Mathews, W.H., and Shepard, F.P., 1962, Sedimentation of the Fraser River Delta, British Columbia; Amer. Assoc. Petroleum Geologists Bull., v. 46, p. 1416-1443.

Medley, E., and Luternauer, J.C., 1976, Use of aerial photographs to map sediment distribution and to identify historical changes on a tidal flat; Geol. Surv. Can. Paper 76-1C, p. 293-304.

Paish and Associates, 1972, The west coastal oil threat in perspective - an assessment of the natural resource, social and economic impacts of marine oil transport in southwest British Columbia coastal waters; Report to Environment Canada, April, 188 p.

Ricketts, E.F., and Calvin, J., 1968, Between Pacific Tides; Stanford Univ. Press, 614 p.

Sutherland Brown, A., 1968, Geology of the Queen Charlotte Islands, British Columbia; Dept. of Mines & Petroleum Resources Bull. 54.

BIBLIOGRAPHY OF

COASTAL ENVIRONMENTS OF THE ARCTIC COASTS

Allen, W.T.R., 1964, Break-up and freeze-up dates in Canada; Can. Dept. Transport, Meteorological Branch, CIR 4116, 201 p.

Beals, C.S. (ed.), 1968, Science, History and Hudson Bay; Dept. Energy, Mines and Resources, Ottawa, 2 volumes.

Bird, J.B., 1967, The Physiography of Arctic Canada; The Johns Hopkins Press, Baltimore, 336 p.

Blake, W., 1975, Radiocarbon age determination and post-glacial emergence at Cape Storm, southern Ellesmere Island, Arctic Canada; Geogr. Annaler, v. 57, series A, p. 1-71.

_________, 1976, Sea and land relationships during the last 15,000 years in the Queen Elizabeth Islands, Arctic Archipelago; Geol. Surv. Can. Paper 76-1B, p. 201-207.

CHS (Canadian Hydrographic Service), 1968, Pilot of Arctic Canada; vols. II and III, Fisheries and Marine Service, Environment Canada, Ottawa.

_________, 1970, Pilot of Arctic Canada; vol. I, FIsheries and Marine Service, Environment Canada, Ottawa.

_________, 1974, Labrador and Hudson Bay: Sailing Directions; Fisheries and Marine Service, Environment Canada, Ottawa.

_________, 1977, Tide and Current Tables; Volume 4, Fisheries and Marine Service, Environment Canada, Ottawa.

Collin, A.E., 1962, Oceanography of Lancaster Sound; Ph.D. Thesis, McGill University.

Craig, B.G., and Fyles, J.G., 1960, Pleistocene geology of Arctic Canada; Geol. Surv. Can. Paper 60-10, 21 p.

Douglas, R.J.W. (ed.), 1970, Geology and Economic Minerals of Canada; Geol. Surv. Can., Econ. Geol. Rept. No. 1, 5th edition, 838 p.

Dunbar, M., and Greenaway, K.R., 1956, Arctic Canada from the air; Can. Defense Res. Bd., Ottawa, 541 p.

Forbes, D.L., 1975, Sedimentary processes and sediments, Babbage River Delta, Yukon Coast; Geol. Surv. Can. Paper 75-1B, p. 157-160.

___________, 1976, Sedimentary processes and sediments, Babbage River Delta, Yukon Coast: A progress report; Geol. Surv. Can. Paper 76-1C, p. 165-168.

Fortier, Y.O., et al., 1963, Geology of the north-central part of the Arctic Archipelago, Northwest Territories (Operation Franklin); Geol. Surv. Can. Memoir 320, 671 p.

Haseton, G.M., 1970, Marine beach investigations in the Richmond Gulf area, eastern Hudson Bay, Quebec; Geol. Surv. Can. Paper 70-1A, p. 174-175.

Jackson, G.D., 1960, Belcher Islands, N.W.T.; Geol. Surv. Can. Paper 60-20.

King, C.A.M., 1969, Some arctic coastal features around Foxe Basin and in east Baffin Island; Geografiska Annaler, Series A, 51(4), p. 207-218.

Lewis, C.P., 1975, Sediments and sedimentary processes, Yukon-Beaufort Sea coast; Geol. Surv. Can. Paper 75-1B, p. 165-170.

___________, and Forbes, D.L., 1974, Sediments and sedimentary processes, Yukon-Beaufort Sea coast; Environmental-Social Committee, Northern Pipelines Task Force on Northern Oil Development, Rept. No. 74-29, 40 p.

Logan, W.J., Thornton, D.E., and Ross, S.L., 1976, Oil spill countermeasures for the southern Beaufort Sea; Environment Canada (Victoria, B.C.), Beaufort Sea Project Tech. Rept. 31, 2 volumes, 326 p.

Mackay, J.R., 1963, The Mackenzie delta area, N.W.T.; Dept. of Mines & Tech. Surveys, Ottawa, Geographical Branch, Memoir No. 8, 202 p.

McCann, S.B., and Taylor, R.B., 1975, Beach freeze-up sequence at Radstock Bay, Devon Island, Arctic Canada; Arctic and Alpine Research 7(4), p. 379-386.

McDonald, B.C., and Lewis, C.P., 1973, Geomorphic and sedimentologic processes of rivers and coasts, Yukon Coastal Plain; Environmental-Social Committee, Northern Pipelines Take Force on Northern Oil Development, Rept. No. 73-39, 245 p.

McLaren, P., 1974, Coastal erosion-sedimentation, southeast Melville and Western Byam Martin Islands, District of Franklin; Geol. Surv. Can. Paper 74-1A, p. 267-268.

Owens, E.H., 1969, The arctic beach environment, southwest Devon Island, N.W.T.; M.Sc. Thesis, McMaster University, 152 p.

___________, and McCann, S.B., 1970, The role of ice in the arctic beach environment, with special reference to Cape Ricketts, southwest Devon Island, N.W.T., Canada; Amer. Jour. Sci. 268(5), p.397-414.

Rampton, V.N., and Bouchard, M., 1975, Surficial geology of Tuytoyaktuk, District of Mackenzie; Geol. Surv. Can. Paper 74-53, 17 p.

Shilts, W.W., and Boydell, A.N., 1974, Terrain mapping of the Churchill-Chesterfield Inlet corridor, District of Keewatin; Geol. Surv. Can. Paper 74-1A, p. 253-256.

Stephen, W.J., 1976, A reconnaissance study of the coastal processes on Banks Island, District of Franklin; Geol. Surv. Can. Paper 76-1A, p. 271-272.

Taylor, A., 1956, Physical geography of the Queen Elizabeth Islands; Amer. Geogr. Soc., N.Y.

Taylor, R.B., 1973, Coastal environments and processes in the Canadian Arctic Archipelago; unpub. M.Sc. thesis, McMaster University, 210 p.

___________, 1974, A coastal investigation of northern Somerset Island, District of Franklin; Geol. Surv. Can. Paper 74-1A, p. 269-272.

___________, 1975, Coastal investigations of northern Somerset Island and Barrow Strait, District of Franklin; Geol. Surv. Can. Paper 75-1A, p. 501-504.

___________, 1976, Nearshore observations along the east coast of Melville Island, District of Franklin; Geol. Surv. Can. Paper 76-1B, p. 43-58.

Taylor, R.B., and McCann, S.B., 1976, The effects of sea and nearshore ice on coastal processes in the Canadian Arctic Archipelago; Rev. Géogr. Montréal 30(1-2), p. 123-132.

Thorsteinsson, R., 1974, Carboniferous and Permian stratigraphy of Axel Heiberg Island and western Ellesmere Island, Canadian Arctic Archipelago; Geol. Surv. Can. Bull. 224, 115 p.

Tozer, E.T., and Thorsteinsson, R., 1964, Western Queen Elizabeth Islands, Arctic Archipelago; Geol. Surv. Can. Memoir 332.

U.S. Naval Oceanographic Office, 1965, Sailing Directions for Labrador and Hudson Bay; Hydrographic Office Pub. No. 15.

Webb, K., 1976, What made the Hudson Bay arc?; Can. Geographical Jour., 92(3), p. 20-25.

BIBLIOGRAPHY OF

COASTAL ENVIRONMENTS OF THE ATLANTIC COAST

Armon, J., 1975, The dynamics of a barrier island chain, Prince Edward Island, Canada; Unpub. Ph.D. Thesis, McMaster Univ., 546 p.

Bowen, A.J., Edmond, D.P., Piper, D.J.W., and Welsh, D.A., 1975, The maintenance of beaches; technical report, Inst. of Environmental Studies, Dalhousie Univ., Halifax, 582 p.

Bryant, E.A., 1972, The barrier islands of Kouchibouguac Bay, New Brunswick; Unpub. M.Sc. thesis, McMaster Univ., 277 p.

__________, and McCann. S.B., 1972, A note on wind and wave conditions in the southern Gulf of St. Lawrence; Maritime Sediments, v. 8(3), p. 101-103.

____________________, 1973, Long and short term changes in the barrier islands of Kouchibouguac Bay, southern Gulf of St. Lawrence; Can. Jour. Earth Sci., vo. 10, p. 1582-1590.

Cameron, H.L., 1965, The shifting sands of Sable Island; Geogr. Rev., 55(4), p. 463-476.

CHS (Canadian Hydrographic Service), 1973, Sailing Directions: Gulf and River St. Lawrence; Fisheries and Marine Service, Environment Canada, Ottawa.

________________________, 1974a, Sailing Directions: Labrador and Hudson Bay; Fisheries and Marine Service, Environment Canada, Ottawa.

________________________, 1974b, Sailing Directions: Newfoundland; Fisheries and Marine Service, Environment Canada, Ottawa.

________________________, 1974c, Sailing Directions: Nova Scotia (S.E. Coast) and Bay of Fundy, Fisheries and Marine Service, Environment Canada, Ottawa.

________________________, 1977, Tide and Current Tables; volumes 1, 2, and 3, Fisheries and Marine Service, Environment Canada, Ottawa.

Dalrymple, R.W., Knight, R.J., and Middleton, G.V., 1975, Intertidal sand bars in Cobequid Bay (Bay of Fundy); in L.E. Cronin (ed.), Estuarine Research, vol. 2, Academic Press, N.Y., p. 293-307.

Davidson-Arnott, R.G.D., and Greenwood, B., 1976, Facies relationships on a barred coast, Kouchibouguac Bay, New Brunswick; in R.A. Davis , Jr. and R.L. Ethington (eds.), Beach and Nearshore Sedimentation, Soc. Econ. Paleontologists and Mineralogists Spec. Publ. No. 24, p. 149-168.

Dionne, J-C., 1968, Schorre morphology on the south shore of the St. Lawrence estuary; Amer. Jour. Sci., 266(5), p. 380-388.

____________, 1972, Aspects morpho-sédimentologiques du glacier, en particulier des côtes du Saint-Laurent; Thèse, Univ. de Paris, 412 p. (Also, Québec, Lab. Rech. Forestières Rapp. Infor. QF-X-9, 324 p.

Dohler, G., 1969, Tides in Canadian Waters; Canadian Hydrographic Service, Marine Sciences Branch, Ottawa, 14 p.

Dolan, R., Hayden, B., Hornberger, G., Zieman, J., and Vincent, M., 1972, Classification of the coastal environments of the world, Part 1, The Americas; Dept. of Environmental Sciences, Univ. of Virginia, Tech. Rept. No. 1, 163 p.

Dubois, J-M., 1973, Essai de classification de la zone côtière et d'identification d'unités physiographiques sur la côte nord du Saint-Laurent; Canada, Min. Travaux Publics, Montréal, Etude des Rives du St-Laurent, 71 p. and appendices.

Geological Survey of Canada, 1967, Geology Map, Island of Newfoundland; Surveys and Mapping Branch, Map 1231A.

Greenwood, B., and Davidson-Arnott, R.G.D., 1975, Marine bars and nearshore sedimentary processes, Kouchibouguac Bay, New Brunswick; in J. Hails and A. Carr (eds.), Nearshore Sediment Dynamics and Sedimentation, Wiley & Sons, N.Y., p. 123-150.

James, N.P., and Stanley, D.J., 1967, Sediment transport on Sable Island, Nova Scotia; Smithsonian Misc. Coll., 152(7), Publ. 4723, 33 p.

______________________________, 1968, Sable Island Bank off Nova Scotia: Sediment dispersal and recent history; Amer. Assoc. Petr. Geol. Bull. 52(11), p. 2208-2230.

Johnson, D.W., 1925, The New England Acadian Shoreline; Wiley & Sons, N.Y., 608 p. (Facsimile Ed.: Hafner, N.Y., 1967).

Klein, G. deV., 1970, Depositional and dispersal dynamics of intertidal sand bars; J. Sed. Petrol., 40, p. 1095-1127.

Knight, R.J., and Dalrymple, R.W., 1976, Winter conditions in a macro-tidal environment, Cobequid Bay, Nova Scotia; Rev. Geogr. Montr., 30(1-2), p. 65-85.

Matheson, K.M., 1967, The meteorological effect on ice in the Gulf of St. Lawrence; McGill Univ., Marine Sci. Center, Unpub. Rept. No. 3, 110 p.

McCann, S.B., 1972, Reconnaissance survey of Hog Island, Prince Edward Island; Maritime Sediments, v. 8, p. 107-113.

____________, and Bryant, E.A., 1973, Beach changes and wave conditions, New Brunswick; Proc. 13th Internat'l Coastal Engin. Conf., Vancouver, Am. Soc. Civil Engin., N.Y., p. 1293-1304.

Owens, E.H., 1971, A reconnaissance of the coastline of Chedabucto Bay, Nova Scotia; Mar. Sci. Paper No. 4, Dept. of Environment, Ottawa, 24 p and map.

____________, 1974, A framework for the definition of coastal environments in the southern Gulf of St. Lawrence; in B.R. Pelletier (ed.), Offshore Geology of Eastern Canada, Geol. Surv. Can. Paper 74-30, vol. 1, p. 47-76.

____________, 1975, Barrier beaches and sediment transport in the southern Gulf of St. Lawrence, Canada; Proc. 14th Internat'l Coastal Engin. Conf., Copenhagen, June 1974, Am. Soc. Civil Engin., N.Y., v. 2, p. 1177-1193.

____________, 1976, The effects of ice on the littoral zone, Richibucto Head, eastern New Brunswick; Rev. Geogr. Montr., 30(1-2), p. 95-104.

____________, 1977a, Process and morphology characteristics of two barrier beaches in the Magdalen Islands, Gulf of St. Lawrence, Canada; Proc. 15th Internat'l Coastal Engin. Conf., Honolulu, July 1976, Am. Soc. Civil Engin., N.Y., (in press).

____________, 1977b, Coastal environments, oil spills and clean-up programmes in the Bay of Fundy; Environment Canada, Environmental Protection Service, (in press), 175 p.

Owens, E.H., and Bowen, A.J., (in press), Coastal environments of the Maritime Provinces; Maritime Sediments.

__________, and Rashid, M.A., 1976, Coastal environments and oil spill residues in Chedabucto Bay, Nova Scotia; Can. Jour. Earth Sci., 13(7), p. 908-928.

Ploeg, J., 1971, Wave climate study, Great Lakes and Gulf of St. Lawrence; Vol. 1, Nat. Res. Council Canada, Mech. Engin. Rept. MH-107A, 160 p.

Stephenson, T.A., and Stephenson, A., 1954, Life between the tide-marks in North America, Part III - Nova Scotia and Prince Edward Island; Jour. Ecol., v. 42, p. 14-70.

Swift, D.J.P., Pelletier, B.R., Lyall, A.K., and Miller, J.A., 1973, Quaternary sedimentation in the Bay of Fundy; in P.J. Hood (ed.), Earth Science Symposium on Offshore Eastern Canada, Geol. Surv. Can. Paper 71-23, p. 113-151.

U.S. Naval Oceanographic Office, 1958, Sailing Directions for Newfoundland; Hydrographic Office Publication No. 14.

______________________________, 1965, Sailing Directions for Labrador and Hudson Bay; Hydrographic Office Publication No. 15.

Welsted, J.E., 1974, Morphological maps of the Fundy coast; Maritime Sediments 10(2), p. 46-51.

Zimlicki, L.M. and Welsh, D.A., 1975, Literature Survey for the Terrain Management of Sable Island; Canadian Wildlife Service, Sackville, N.B., Rept. for Contract #WE74-75-119, 85 p.

Addendum

Munroe, H.D., 1977, Unpub. M.Sc. Thesis in preparation, University of South Carolina.

BIBLIOGRAPHY OF

COASTAL ENVIRONMENTS OF THE GREAT LAKES

Bird, S.J.G., and Armstrong, J.L., 1970, Scarborough Bluffs - A recessional Study; Proc. 13th Conf. on Great Lakes Research, p. 187-197.

Boulden, R.S. (ed.), 1975, Canada - Ontario Great Lakes Shore Damage Survey; Tech. Rept., Environment Canada and Ontario Min. of Nat. Resources, 97 p.

Brebner, A., and LeMéhauté, B., 1961, Wind and waves at Cobourg, Lake Ontario; Queens Univ. Civil Engin. Dept. Rept. No. 19, 44 p.

Chapman, L.J., and Putman, D.F., 1966, The Physiography of Southern Ontario; Univ. of Toronto Press, Toronto, 2nd edition, 386 p.

Clemens, R.H., 1976, Selected environmental criteria for the design of artificial structures on the southeast shore of Lake Erie; Univ. South Carolina, Dept. of Geology, Tech. Rept. CRD No. 8, 95 p.

Coakley, J.P., 1970, Natural and artificial tracer experiments in Lake Ontario; Proc. 13th Conf. on Great Lakes Research, p. 198-209.

______________, 1972, Nearshore sediment studies in western Lake Erie; Proc. 15th Conf. on Great Lakes Research, p. 330-343.

______________, 1976, The formation and evolution of Point Pelee, western Lake Erie; Can. Jour. Earth Sci., 13(1), p. 136-144.

______________, and Cho, H.K., 1972, Shore erosion in western Lake Erie; Proc. 15th Conf. on Great Lakes Research, p. 344-360.

______________________________, 1973, Beach stability investigations at Van Wagners Beach, western Lake Ontario; Proc. 16th Conf. on Great Lakes Research, p. 357-376.

______________, Haras, W., and Freeman, N., 1973, The effect of storm surge on beach erosion, Point Pelee; Proc. 16th Conf. on Great Lakes Research, p. 377-389.

Cole, A.L., 1971, Hindcast waves for the western Great Lakes; Proc. 14th Conf. on Great Lakes Research, p. 412-421.

Donnelly, P., and Brebner, A., 1961, A field investigation of littoral drift in the Port-Hope/Cobourg area of Lake Ontario; Queens Univ. Civil Engin. Dept. Rept. No. 16, 43 p.

Environment Canada and Ontario Min. of Nat. Resources, 1973, Canada - Ontario Great Lakes Shore Damage Survey - Coastal Zone Atlas; 637 p.

Fricsbergs, K.S., 1970, Erosion control in the Toronto area; Proc. 13th Conf. on Great Lakes Research, p. 751-755.

Gelinas, P.J., and Quigley, R.M., 1973, The influence of geology on erosion rates along the north shore of Lake Erie; Proc. 16th Conf. on Great Lakes Research, p. 421-430.

Hough, J.L., 1958, Geology of the Great Lakes; Univ. of Illinois Press, 313 p.

___________, 1968, Great Lakes; in R.W. Fairbridge (ed.), Encyclopaedia of Geomorphology, Reinhold, N.Y., p. 499-506.

Lathem, K.W., 1975, Formation and stability of Rondeau Spit, Lake Erie; Proc. 2nd Can. Hydrotechnical Conf., Burlington, Ontario.

Lewis, C.F.M., 1970, Recent uplift of Manitoulin Island, Ontario, Can. Jour. Earth Sci. 7(2), pt. 2, p. 665-675.

Marshall, E.W., 1967, Lake Superior ice characteristics; Proc. 10th Conf. on Great Lakes Research, p. 214-220.

Martini, L.P., 1975, Sedimentology of a lacustrine barrier system at Wasaga Beach, Ontario, Canada; Sedimentary Geology, 14, p. 169-190.

Matyas, E.C., White, O.C., and LeLievre, B., 1974, A study of shoreline erosion in western Lake Ontario; Geol. Surv. Can. Paper 74-1B, p. 204-205.

Pezzetta, J.M., 1973, The St. Clair river delta: sedimentary characteristics and depositional environments; Jour. Sed. Pet. 43(1), p. 168-187.

Pincus, H.J. (ed.), 1962, Great Lakes Basin; Amer. Assoc. Advancement of Science, Pub. No. 71, Washington, D.C., 308 p.

Ploeg, J., 1971, Wave climate study, Great Lakes and Gulf of St. Lawrence; Nat. Res. Council Canada, Mech. Engin. Rept. MH-107A, 160 p.

Quigley, R.M., and Tutt, D.B., 1968, Stability - Lake Erie north shore bluffs; Proc. 11th Conf. on Great Lakes Research, p. 230-238.

Quigley, R.M., Palmer, J.H.L., Rowland, A., and Bere, D., 1974, Groyne stabilization of slope movements and toe erosion, Lake Huron near Bayfield, Ontario; Proc. 17th Conf. on Great Lakes Research, p. 193-206.

_______________, Gelinas, P.J., Bou, W.T., and Parker, R.W.,1976, Cyclic erosion-instability relationships, Lake Erie North shore bluffs; Preprints 29th Canadian Geotech. Conf., Vancouver, p. 1-34.

Ragotzkie, R.A., 1974, The Great Lakes Rediscovered; American Scientist 62(4), p. 454-464.

Richards, T.L., and Phillips, D.W., 1970, Synthesized winds and wave heights for the Great Lakes; Can. Dept. Transport, Meteorological Branch, Climatological Studies, No. 17, 53 p.

Rukavina, N.A., 1969, Nearshore sediment survey of western Lake Ontario - methods and preliminary results; Proc. 12th Conf. on Great Lakes Research, p. 317-324.

_______________, 1970, Lake Ontario nearshore sediments, Whitby to Wellington, Ontario; Proc. 13th Conf. on Great Lakes Research, p. 266-273.

_______________, 1974, Seasonal and progressive changes in the nearshore sediments of western Lake Ontario; Mém. Instit. Géol. Bassin Aquitaine, 7, p. 119-123.

_______________, 1976, C.C.I.W. Hydraulics Research Division, Coastal Research Activities; Proc. Workshop on Great Lakes Coastal Erosion and Sedimentation (N.A. Rukavina, ed.), Can. Centre for Inland Waters, Burlington, Ontario, p. 11-14.

_______________, 1976, Nearshore sediments of Lakes Erie and Ontario; Geoscience Canada 3(3), p. 185-190.

_______________, and St. Jacques, D.A., 1971, Lake Erie nearshore sediments - Fort Erie to Mohawk Point, Ontario; Proc. 14th Conf. on Great Lakes Research, p. 387-393.

_______________________________________, 1972, Lake Ontario nearshore sediments - Wellington to Main Duck Island, Ontario; Proc. 15th Conf. on Great Lakes Research, p. 394-400.

St. Jacques, D.A., and Rukavina, N.A., 1973, Lake Erie nearshore sediments - Mohawk Point to Port Burwell, Ontario; Proc. 16th Conf. on Great Lakes Research, p. 454-467.

St. Jacques, D.A., and Rukavina, N.A., 1976, Lake Erie nearshore sediments - Port Burwell to Point Pelee, Ontario; C.C.I.W. Unpub. Rept., 48 p.

Tsang, G., 1975, Ice conditions and the proposed containment and removal of spill oil on St. Clair and Detroit Rivers; Environment Canada, Inland Waters Directorate, Ottawa, Sci. Series No. 56, 25 p.

Wood, H.A., 1960, Wave transport of beach materials on Long Point, Lake Erie; Can. Geographer 16, p. 27-35.

BIBLIOGRAPHY OF

LITTORAL PROCESSES, COASTAL GEOMORPHOLOGY AND OIL SPILLS

Ages, A., 1971, Oil reconnaissance in the Magdalen Islands - 1970; AOL Report 1971-8, Bedford Institute, Dartmouth, Nova Scotia, 22 p.

Baker, J.M., 1971, Effects of cleaning; in E.B. Cowell, (ed.), Ecological Effects of Oil Pollution on Littoral Communities, Applied Science Publishers, U.K., p. 52-61.

Bakker, W.T., 1968, A mathematical theory about sand waves and its application on the Dutch Wadden Isle of Vlieland; Shore and Beach 36, p. 4-14.

Bascom, W., 1964, Waves and Beaches; Anchor Books, N.Y., 267 p.

Berry, W.L., and Wolfe, J.W., 1975, Clean Gulf Associates unveils a new generation of oil spill cleanup equipment; Proc. of Conf. on Prevention and Control of Oil Pollution, American Petroleum Institute, Washington, D.C., p. 323-327.

Betancourt, O.J. and McLean, A.Y., 1973, Changes in chemical composition and physical properties of a heavy residual oil weathering under natural conditions; Jour. Inst. Petroleum, 59(569), p. 223-230.

Bird, E.C.F., 1968, Coasts; M.I.T. Press, Cambridge, Mass., 246 p.

Bowen, E.J., Emond, D.P., Piper, D.J.W., and Welsh, D.A., 1975, The maintenance of beaches; Technical Report, Inst. of Environmental Studies, Dalhousie University, Halifax, 582 p.

Bruun, P., 1955, Migrating sand waves and sand humps, with special reference to investigations carried out on the Danish North Sea coast; Proc. 5th Conf. on Coastal Engineering, p. 269-295.

CHS (Canadian Hydrographic Service), 1970, Pilot of Arctic Canada; volume I, Fisheries and Marine Service, Environment Canada, Ottawa.

____________________, 1977a, Canadian Tide and Current Tables; volume 4, Fisheries and Marine Service, Environment Canada, Ottawa.

CHS (Canadian Hydrographic Service), 1977b, Canadian Tide and Current Tables; volumes 5 and 6, Fisheries and Marine Service, Environment Canada, Ottawa.

Cowell, E.B. (ed.), 1971, The Ecological Effects of Oil Pollution on Littoral Communities; Applied Science Publishers, U.K.

____________, 1971, Some effects of oil pollution in Milford Haven, United Kingdom; Proc. Joint Conf. on Prevention and Control of Oil Spills, American Petroleum Institute, Washington, D.C., p. 429-436.

Dalrymple, R.W., Knight, R.J., and Middleton, G.V., 1975, Intertidal sand bars in Cobequid Bay (Bay of Fundy); in L.E. Cronin (ed.), Estuarine Research, v. 2, Academic Press, N.Y., p. 293-307.

Davies, J.L., 1964, A morphogenic approach to world shorelines; Zeit. fur Geomorphologie, 8, Mortensen Sonderheft, p. 127-142.

____________, 1972, Geographical Variation in Coastal Development; Oliver and Boyd, Edinburgh, 204 p.

Davis, R.A., Jr., and Fox, W.T., 1971, Beach and nearshore dynamics in eastern Lake Michigan; Tech. Rept. No. 4, ONR Contract 388-092, 145 p.

Der, J.J., and Ghormley, E.L., 1974, Oil contaminated beach cleanup; Rept. AD-778-329, National Tech. Information Service, Springfield, Virginia, 38 p.

______________________________, 1975, Oil contaminated beach cleanup; Proc. of Conf. on Prevention and Control of Oil Pollution, American Petroleum Institute, Washington, D.C., p. 431-436.

Der, J.J., and Graham, J., 1973, Quantitative evaluation of mechanical oil spill cleanup devices; Proc. Joint Conf. on Prevention and Control of Oil Spills, American Petroleum Institute, Washington, D.C., p. 627-634.

Dolan, R., 1971, Coastal landforms; crescentic and rhythmic; Geol. Soc. Amer. Bull., v. 82, p. 177-180.

Drapeau, G., 1973, Natural cleaning of oil polluted seashores; Proc. 13th Internat'l Coastal Engin. Conf., Vancouver, Am. Soc. Civil Engin., N.Y., p. 2557-2575.

Eidam, C.L., Fitzpatrick, W.V., and Conlon, J.F., 1975, The Casco Bay oil spill: problems of cleanup and disposal; Proc. of Conf. on Prevention and Control of Oil Pollution, American Petroleum Institute, Washington, D.C., p. 217-221.

Floodgate, M.C., 1972, Microbial degradation of oil; Mar. Poll. Bull. 3, p. 41-43.

Foget, C.R., Thornton, S., and Castle, R., 1977, Evaluation of selected surface treatment agents for the protection of shorelines from oil spills; Proc. of Oil Spill Conf., American Petroleum Institute, Washington, D.C., p. 237-241.

Galvin, C.J., 1968, Breaker type classification on three laboratory beaches; Jour. Geophysical Research, v. 73(12), p. 3651-3659.

____________, and Hayes, M.O., 1969, Winter beach profiles and wave climate; (abs) in Abstracts with Programs, Annual Mtg., Geol. Soc. Amer., Atlantic City, N.J., November 1969, p. 74-75.

Glaeser, J.L., 1971, Oil pollution problems in the Arctic; Proc. Joint Conf. on Prevention and Control of Oil Spills, American Petroleum Institute, Washington, D.C., p. 479-484.

Guard, H.E., and Cobet, A.B., 1973, The fate of Bunker fuel in beach sand; Proc. Joint Conf. on Prevention and Control of Oil Spills, American Petroleum Institute, Washington, D.C., p. 827-834.

Gunnerson, C.G., and George, P., 1976, The "Metula" oil spill; U.S. Dept. of Commerce, NOAA Special Rept., Boulder, Colorado, 37 p. (U.S. Gov't Printing Office 1976-678-768).

Hann, R.W., 1975, Follow-up field survey of the oil pollution from the tanker "Metula"; Unpub. Rept., Civil Engin. Dept., Texas A&M University, College Station, 57 p.

Hanson, J.R., and Kochis, D.M., 1975, Oakland estuary oil spill cleanup: a review of a major oil spill cleanup in a trash-laden estuary emphasizing small boat harbour cleanup; Proc. Conf. on Prevention and Control of Oil Pollution, American Petroleum Institute, Washington, D.C., p. 233-240.

Hayes, M.O., 1975, Morphology of sand accumulation in estuaries; in L.E. Cronin (ed.), Estuarine Research, v. 2, Academic Press, N.Y., p. 3-22.

__________, and Boothroyd, J.C., 1969, Storms as modifying agents in the coastal environments; in Coastal Research Group; Coastal Environments, Northeastern Massachusetts and New Hampshire: S.E.P.M. Field Trip Guidebook; Contrib. No. 1, Dept. of Geology, University of Massachusetts, Amherst, p. 245-265.

Ingle, J.C., Jr., 1966, The movement of beach sand; Developments in Sedimentology, No. 5, Elsevier, N.Y., 221 p.

Johnston, R., 1970, The decomposition of crude oil residues in sand columns; Jour. Mar. Biol. Assoc. U.K. 50, p. 925-937.

Komar, P.D., 1976, Beach Processes and Sedimentation; Prentice-Hall, N.J., 429 p.

Logan, W.J., Thornton, D.E., and Ross, S.L., 1976, Oil spill countermeasures for the southern Beaufort Sea; Environment Canada (Victoria, B.C.), Beaufort Sea Project Tech. Rept. 31, 2 volumes, 326 p.

Mackay, G.D.M., McLean, A.Y., Betancourt, O.J., and Johnson, B.D., 1973, The formation of water-in-oil emulsions subsequent to an oil spill; Jour. Instit. of Petroleum 59 (568), p. 164-172.

McCann, S.B., 1973, Beach processes in an arctic environment; in D.R. Coates (ed.), Coastal Geomorphology, Binghamton, State Univ. of N.Y., p. 141-155.

__________, and Owens, E.H., 1969, The size and shape of sediments in three arctic beaches, southwest Devon Island, N.W.T., Canada; Arctic and Alpine Res., v. 1(4), p. 267-278.

McMinn, T.J., and Golden, P., 1973, Behavioural characteristics and cleanup techniques of North Slope crude oil in an arctic winter environment; Proc. Joint Conf. on Prevention and Control of Oil Spills, American Petroleum Institute, Washington, D.C., p. 263-275.

Otto, L., 1973, Environmental factors in operations to combat oil spills; World Meteorological Organization, Marine Science Affairs, Geneva, Rept. No. 9, 25 p.

Owens, E.H., 1971, The restoration of beaches contaminated by oil in Chedabucto Bay, Nova Scotia; Dept. Energy, Mines & Resources, Ottawa, Marine Sciences Manuscript Rept. No. 19, 75 p.

__________, 1973, The cleaning of gravel beaches polluted by oil; Proc. 13th Internat'l Coastal Engin. Conf., Vancouver, Am. Soc. Civil Engin., N.Y., p. 2549-2556.

__________, 1976, The effects of ice on the littoral zone, Richibucto Head, eastern New Brunswick; Rev. Géogr. Montréal, v. 30(1-2), p. 95-104.

__________, 1977a, Coastal environments, oil spills, and clean-up programmes in the Bay of Fundy; Environmental Protection Service, Environment Canada, Ottawa, 175 p. (in press).

__________, 1977b, Contingency planning for the impact of oil spills in different coastal environments of eastern Canada; Proc. of Oil Spill Conf., American Petroleum Institute, Washington, D.C., p. 115-122.

__________, (in press), Ice Foot; in R.W. Fairbridge and M.L. Schwartz (eds.), Encyclopaedia of Beaches and Coastal Environments; Dowden, Hutchinson and Ross, Stroudsburg, Pa.

__________, and Bowen, A.J., (in press), Coastal environments of the Maritime Provinces; Maritime Sediments.

__________, and Drapeau, G., 1973, Changes in beach profiles at Chedabucto Bay, N.S., following large-scale removal of sediments; Can. Jour. Earth Sciences v. 10(8), p. 1226-1232.

__________, and Frobel, D.H., 1977, Ridge and runnel systems in the Magdalen Islands, Quebec; Jour. Sed. Petrology, v. 47(1), p. 191-198.

__________, and Harper, J.R., (in preparation), Frost-table depths in the littoral zone near Peard Bay, Alaska.

Owens, E.H., and McCann, S.B., 1970, The role of ice in the arctic beach environment with special reference to Cape Ricketts, southwest Devon Island, N.W.T., Canada; American Jour. of Science, v. 268(5), p. 397-414.

__________, and Rashid, M.A., 1976, Coastal environments and oil spill residues in Chedabucto Bay, Nova Scotia; Can. Jour. Earth Sciences, v. 13(7), p. 908-928.

Rashid, M.A., 1974, Degradation of Bunker C oil under different coastal environments of Chedabucto Bay, Nova Scotia; Estuarine and Coastal Marine Science, v. 2, p. 137-144.

Sartor, J.D., and Foget, C.R., 1971, Evaluation of selected earthmoving equipment for the restoration of oil-contaminated beaches; Proc. Joint Conf. on Prevention and Control of Oil Spills, American Petroleum Institute, Washington, D.C., p. 505-522.

Sittig, M., 1974, Oil spill prevention and removal handbook; Noyes Data Corp, Park Ridge, N.J., 465 p.

Task Force - Operation Oil, 1970, Cleanup of the "Arrow" oil spill in Chedabucto Bay; volume II, Ministry of Transport, Ottawa, 104 p.

Taylor, R.B., and McCann, S.B., 1974, Depth of "frost table" on beaches in the Canadian Arctic Archipelago; Jour. Glaciology, v. 13, p. 321-322.

______________________________, 1975, The effects of sea and nearshore ice on coastal processes in the Canadian Arctic Archipelago; Rev. Géogr. Montréal, v. 30(1-2), p. 123-132.

Von Borstel, B.B., 1974, The physical behaviour of oil in sandy beaches, McNabs Island, Nova Scotia; M.Sc. Thesis, Dalhousie University, Halifax.

Wardley Smith, J., 1968, Recommended methods for dealing with oil pollution; Rept. No. LR 79(EIS), Warren Spring Laboratories, Stevenage, U.K., 22 p.

________________ (ed.), 1976, The Control of Oil Pollution; Graham and Trotman, London, 251 p.

Westree, B., 1977, Biological criteria for the selection of clean-up techniques in salt marshes; Proc. of Oil Spill Conf., American Petroleum Institute, Washington, D.C., p. 231-235.

BIBLIOGRAPHY OF

COASTAL ENVIRONMENTS OF CANADA AND OIL SPILLS

Ages, A., 1971, Oil reconnaissance in the Magdalen Islands-1970; Atlantic Oceanographic Lab, Bedford Institute, Dartmouth, N.S., AOL Rept. 1971-8, 22 p.

________, 1972, The "Vanlene" accident, March 1972; Environment Canada, Marine Sciences Branch (Victoria, B.C.), Pacific Marine Sciences Report No. 72-4, 17 p.

Atlas, R.M., 1974, Fate and effects of oil pollutants in extremely cold marine environments; unpub. rept. to U.S. Dept. of Navy, Office Naval Res., ADIA-003554, University of Louisville, 36 p.

________, and Bartha, R., 1972, Biodegradation of petroleum in sea water at low temperatures; Can. Jour. Microbiology 18, p. 1851-1855.

Barber, F.G., 1970, Oil spills in ice: some clean-up options; Arctic, v. 23, p. 285-286.

________, 1971, An oiled arctic shore; Arctic, v. 24(3), p. 229.

________, 1973, Containment of oil by sea ice - some qualitative aspects; Proc. Joint Conf. on Prevention and Control of Oil Spills, American Petroleum Institute, Washington, D.C., p. 133-137.

Betancourt, O.J., 1973, Effect of natural weathering on the shore-bound oil after the Chedabucto Bay spill; in D. Mackay and W. Harrison (eds.), Oil in the Canadian Environment, Conf. Proc., May 1973, Inst. of Environ. Sci. and Engin., Univ. of Toronto, p. 87-89.

Department of Environment, 1971, The environmental consequences of the proposed oil transport between Valdez and Cherry Point Refinery; Water Management Service, 32 p.

Drapeau, G., 1973, Natural cleaning of oil polluted seashores; Proc. 13th Internat'l Coastal Engin. Conf., Vancouver, Am. Soc. Civil Engin., N.Y., p. 2557-2575.

Drapeau, G., Harrison, W., Bien, W., and Leinonen, P., 1975, Oil slick fate in a region of strong tidal currents; Proc. 14th Internat'l Coastal Engin. Conf., Copenhagen, Am. Soc. Civil Engin., N.Y., vol. iii, p. 2245-2259.

Environment Canada, 1976, Spill Technology Newsletter; Environmental Protection Service, Ottawa, published bi-monthly.

__________________, 1976, Countermeasures for oil and chemical spills in the Burrard Inlet area; Burrard Inlet Technical Working Group on Environmental Emergencies; Environment Canada, Environmental Protection Service, Vancouver, B.C., 287 p.

Foley, J.P., and Tressidder, S.J., 1977, The St. Lawrence River oil spill of June 23, 1976 - are you ever truly ready?; Proc. Oil Spill Conf., American Petroleum Institute, Washington, D.C., p. 81-85.

Giovando, L.F., 1975, Oil-pipeline marine terminals at Port Angeles or Rosario Strait: some suggested oil-spill consequences; Unpub. ms., Environment Canada (Vancouver), Pacific Environment Institute, 40 p.

______________, (undated), The coastal waters of British Columbia, some general aspects of their physical oceanography; Unpub. ms., Environment Canada (Vancouver), Pacific Environment Institute.

Glaeser, J.L., 1971, Oil pollution problems in the Arctic; Proc. Joint Conf. on Prevention and Control of Oil Spills, American Petroleum Institute, Washington, D.C., p. 479-484.

Green, D.R., Bawden, C., Cretney, W.J. and Wong, C.S., 1974, The Alert Bay oil spill: A one-year study of the recovery of a contaminated bay; Environment Canada, Marine Sciences Directorate, Pacific Marine Science Report No. 74-9, unpub. ms., 42 p.

Herlinveaux, R.H., 1972, Preliminary report on the oil spill from the grounded freighter "Vanlene", March 1972; Environment Canada, Marine Sciences Directorate, Pacific Marine Science Report No. 72-11, 21 p.

Herlinveaux, R.H., (undated), The impact of oil spillage from tankers moving from Alaska southward along the British Columbia coast: Part I, Review of significant environmental factors; Unpub. ms., Environment Canada, Marine Sciences Directorate, Pacific Region (Victoria).

Hoult, D.P., Wolfe, S., O'Dea, S., and Patureau, J.P., 1975, Oil in the Arctic; U.S. Dept. of Transportation, U.S. Coast Guard Rept. No. CG-D-96-75, 218 p.

Hufford, G.L., Lissauer, I.M., and Thompson, D.B., 1977, Storm related oil spill movement on the Beaufort Sea Shelf; Proc. of Oil Spill Conf., American Petroleum Institute, Washington, D.C., p. 455-460.

Hum, S., 1977, The development and use of resource sensitivity maps for oil spill countermeasures; Proc. of Oil Spill Conf., American Petroleum Institute, Washington, D.C., p. 105-110.

Logan, W.J., Thornton, D.E., and Ross, S.L., 1976, Oil spill countermeasures for the southern Beaufort Sea; Environment Canada (Victoria, B.C.), Beaufort Sea Project Tech. Rept. 31, 2 volumes, 326 p.

MacGregor, C., and McLean, A.Y., 1977, Fate of crude oil spilled in a simulated arctic environment; Proc. of Oil Spill Conf., American Petroleum Institute, Washington, D.C., p. 461-463.

Mackay, D., and Harrison, W. (eds.), 1973, Oil and the Canadian Environment: Conf. Proc., May 1973, Inst. of Environ. Sci. and Engin., Univ. of Toronto, 142 p.

McLean, A.Y., and Betancourt, O.J., 1973, Physical and chemical changes in spilled oil weathering under natural conditions; Offshore Technology Conf., Dallas, Paper No. OTC 1748, I-250 to I-255.

____________, and Odedra, D.A., 1974, The properties of Sable Island crude oil in relation to its behaviour in the event of a spill at sea; Offshore Technology Conf., Dallas, Preprint No. OTC1981, p. 449-460.

McMinn, T.J., and Golden, P., 1973, Behavioural characteristics and cleanup techniques of North Slope crude oil in an arctic winter environment; Proc. Joint Conf. on Prevention and Control of Oil Spills, American Petroleum Institute, Washington, D.C., p. 263-275.

Milne, A.R., 1976, Canadian environmental studies of the southern Beaufort Sea; in D.W. Hood and D.C. Burrell (eds.), Assessment of the Arctic Marine Environment, Occasional Publ. No. 4, Inst. of Marine Sci., Univ. of Alaska, Fairbanks, p. 87-94.

__________, and Smiley, B.D., 1976, Offshore drilling for oil in the Beaufort Sea: A preliminary environmental assessment; Environment Canada (Victoria, B.C.), Beaufort Sea Project Tech. Rept. 39.

O'Rourke, C., 1976, Oil spill cleanup in the Beaufort Sea; Environment Canada (Ottawa), Spill Technology Newsletter, v. 1(6), p. 12-35.

Owens, E.H., 1971, The restoration of beaches contaminated by oil in Chedabucto Bay, N.S.; Dept. Energy, Mines and Resources, Ottawa, Marine Sciences Manuscript Rept. No. 19, 75 p.

__________, 1977a, Coastal environments, oil spills, and clean-up programmes in the Bay of Fundy; Environmental Protection Service, Environment Canada, Ottawa, 175 p., (in press).

__________, 1977b, Contingency planning for the impact of oil spills in different coastal environments of eastern Canada; Proc. of Oil Spill Conf., American Petroleum Institute, Washington, D.C., p. 115-122.

__________, and Drapeau, G., 1973, Changes in beach profiles at Chedabucto Bay, N.S., following large-scale removal of sediments. Can. Jour. Earth Sciences v. 10(8), p. 1226-1232.

__________, and Harper, J.R., (in preparation), Frost-table depths in the littoral zone near Peard Bay, Alaska.

__________, and Rashid, M.A., 1976, Coastal environments and oil spill residues in Chedabucto Bay, Nova Scotia; Can. Jour. Earth Sciences v. 13(7), p. 908-928.

__________, and Wiseman, Wm. J., Jr., 1976, Ice-foot features and sediment redistribution in the littoral environment; (abst.) Abstracts with Programs, Geol. Soc. America, Annual Mtg., Denver, p. 1038.

Ramseier, R.O., Gantcheff, G.S., and Colby, L., 1973, Oil spill at Deception Bay, Hudson Strait; Inland Waters Directorate, Water Resources Branch, Ottawa, Scientific Series No. 29, 60 p.

Rashid, M.A., 1974, Degradation of Bunker C oil under different coastal environments of Chedabucto Bay, Nova Scotia; Estuarine and Coastal Marine Science, v. 2, p. 137-144.

Ricker, K.E., 1974, Effects of the Burrard Inlet oil spill on various geologic environments; Geol. Surv. Can. Paper 74-1B, p. 205-207.

Scarratt, D.J., Sprague, J.B., Wilder, D.G., Zitko, V., and Anderson, J.M., 1970, Some biological and chemical investigations of a major winter oil spill on the Canadian east coast; ICES Fish. Improv. Comm. Rept. 14, 8 p.

______________, and Zitko, V., 1972, Bunker C oil in sediments and benthic animals from shallow depths in Chedabucto Bay, Nova Scotia; Jour. Fish. Res. Bd., Canada, 29, p. 1347-1350.

Sittig, M., 1974, Oil spill prevention and removal handbook; Noyes Data Corp, Park Ridge, N.J., 465 p.

Task Force - Operation Oil, 1970, Cleanup of the "Arrow" oil spill in Chedabucto Bay; 3 volumes, Ministry of Transport, Ottawa.

Thomas, M.L.H., 1973, Effects of Bunker C oil on intertidal and lagoonal biota in Chedabucto Bay, N.S.; Jour. Fish. Res. Bd., Canada, 30, p. 83-90.

Thomson, K.P.B., and McColl, W.D., 1972, A remote sensing survey of the Chedabucto Bay oil spill; Centre for Inland Waters, Burlington, Scientific Series No. 26, 15 p.

Thornton, D.E., Ross, S.L., Logan, W.J., and Ross, C.W., 1977, Arctic offshore oil spill countermeasures with emphasis on oil and gas blowout in the southern Beaufort Sea; Proc. of Oil Spill Conf., American Petroleum Institute, Washington, D.C., p. 313-319.

Tsang, G., 1975, Ice conditions and the proposed containment and removal of oil on St. Clair and Detroit Rivers; Environment Canada, Inland Waters Directorate, CCIW, Burlington, Scientific Series No. 56, 25 p.

Vance, G.P., 1971, Control of arctic oil spills; Ocean Industry, Jan., p. 14-17.

Vanderkooy, N., Robertson, A., and Beckett, C.J., 1976, Evaluation of oil spill barriers and deployment techniques for the St. Clair-Detroit River system; Environment Canada, Environmental Protection Service, Technology Dev. Rept. EPS-4-EC-76-4, 97 p.

Vandermeulen, J.H., 1975, 1970 "Arrow" Bunker C oil in 1974: Re-entry of stranded oil from a low-energy beach into the marine environment; Unpub. ms., Department of Environment 20 p.

__________________, Keizer, P.D., and Penrose, W.R., 1972, Persistence of non-alkane components of Bunker C oil in beach sediments of Chedabucto Bay, and lack of their metabolism by molluscs; Proc. of Oil Spill Conf., American Petroleum Institute, Washington, D.C., p. 469-473.

Vagners, J., and Mar, P., 1972, Oil on Puget Sound; Univ. of Washington Press, Seattle, 629 p.

Wong, C.S., 1973, Ocean chemistry programs to study the distribution and fate of marine hydrocarbons in northeast Pacific Ocean; in D. Mackay and W. Harrison (eds.), Oil in the Canadian Environment, Conf. Proc., May 1973, Inst. of Environ. Sci. and Engin., Univ. of Toronto, p. 130-132.

BIBLIOGRAPHY OF

THE RESTORATION OF CONTAMINATED SHORELINES

Acres Consulting Services, Ltd., 1976, Review of spray-on grouting sealants for petroleum product storage areas and dykes in the north; Environment Canada, Environmental Protection Service, Ottawa, Economic and Tech. Review Dept. EPS-3-EC-76-12, 27 p.

Baker, J.M., 1971, Effects of Cleaning; in E.B. Cowell (ed.), Ecological Effects of Oil Pollution on Littoral Communities, Applied Science Publishers, U.K., p. 52-61.

Berry, W.L., 1972, Pollution control aspects of the Bay Marchand Fire; Jour. of Petroleum Technology, March, p. 241-249.

__________, and Wolfe, J.W., 1975, Clean Gulf Associates unveils a new generation of oil spill cleanup equipment; Proc. of Conf. on Prevention and Control of Oil Pollution, American Petroleum Institute, Washington, D.C., p. 323-327.

Brunner, D.E., Der, J.J., and Hall, D., 1977, An offshore mechanized sorbent oil recovery system using vessels of opportunity; Proc. of Oil Spill Conf., American Petroleum Institute, Washington, D.C., p. 251-254.

Cormack, D., and Jeffery, P.G., 1975, An oil pollution control officer training course; Proc. of Conf. on Prevention and Control of Oil Pollution, American Petroleum Institute, Washington, D.C., p. 69-72.

Dailey, J.J., Cassidy, P.E., and Yager, B.J., 1975, Beach protection by a degradable, sprayed film; Proc. of Conf. on Prevention and Control of Oil Pollution, American Petroleum Institute, Washington, D.C., p. 415-423.

Der, J.J., and Ghormley, E.L., 1975, Oil contaminated beach cleanup; Proc. of Conf. on Prevention and Control of Oil Pollution, American Petroleum Institute, Washington, D.C., p. 431-436.
(also Rept. AD-778-329, National Tech. Information Service, 38 p.)

Der, J.J., and Graham, J., 1973, Quantitative evaluation of mechanical oil spill cleanup devices; Proc. Joint Conf. on Prevention and Control of Oil Spills, American Petroleum Institute, Washington, D.C., p. 627-634.

Environment Canada, 1976a, Environment Canada Standard List of Oil Spill Dispersants; Environmental Emergency Branch, Ottawa.

_________________, 1976b, Selection criteria and laboratory evaluation of oil spill sorbents; Environmental Emergency Branch, Ottawa, Technology Dev. Rept. No. EPS-4-EC-76-5.

Eryuzla, N.E., and Hausser, R., 1977, Use of floating deflectors for oil spill control in fast flowing waters; Proc. of Oil Spill Conf., American Petroleum Institute, Washington, D.C,, p. 335-340.

Foget, C.R., 1972, The cleanup of oil contaminated sand from West Beach, Long Island, Casco Bay, Portland, Maine; URS Research Company Report.

___________, Thornton, S., and Castle, R.W., 1977, Evaluation of selected surface treatment agents for the protection of shorelines from oil spills; Proc. of Oil Spill Conf., American Petroleum Institute, Washington, D.C., p. 237-241.

Foley, J.P., and Tresidder, S.J., 1977, The St. Lawrence River oil spill of June 23, 1976 - are you ever truly ready?; Proc. of Oil Spill Conf., American Petroleum Institute, Washington, D.C., p. 81-85.

Freiberger, A., and Byers, J.M., 1971, Burning agents for oil spill cleanup; Proc. Joint Conf. on Prevention and Control of Oil Spills, American Petroleum Institute, Washington, D.C., p. 245-251.

Gumtz, G.D., and Meloy, T.P., 1971, Froth flotation cleanup of oil-contaminated beaches; Proc. Joint Conf. on Prevention and Control of Oil Spills, American Petroleum Institute, Washington, D.C., p. 523-531.

Hughes, D.E., and Stafford, S., 1976, Bacterial degradation of crude oil; in J. Wardley-Smith (ed.), The Control of Oil Pollution, Graham and Trotman, London, P. 39-46.

Logan, W.J., Thornton, D.E., and Ross, S.L., 1976, Oil spill countermeasures for the southern Beaufort Sea; Environment Canada (Victoria, B.C.), Beaufort Sea Project Tech. Rept. 31, 2 volumes, 326 p.

McMinn, T.J., and Golden, P., 1973, Behavioural characteristics and cleanup techniques of North Slope crude oil in an arctic winter environment. Proc. Joint Conf. on Prevention and Control of Oil Spills, American Petroleum Institute, Washington, D.C., p. 263-275.

Mikolaj, P.G., and Curran, E.J., 1971, A hot water fluidization process for cleaning oil-contaminated beach sand; Proc. Joint. Conf. on Prevention and Control of Oil Spills, American Petroleum Institute, Washington, D.C., p. 533-539.

Miller, E.R., et al., 1973, Development and preliminary design of a sorbent recovery system; Proc. Joint Conf. on Prevention and Control of Oil Pollution, American Petroleum Institute, Washington, D.C., p. 291-308.

Northeast Region Research & Development Program, 1969, Cleaning oil contaminated beaches; U.S. Dept. of Interior, FWPCA, Water Poll. Control Res. Series DAST-27, 22 p.

Owens, E.H., 1971, The restoration of beaches contaminated by oil in Chedabucto Bay, Nova Scotia; Dept. Energy, Mines & Resources, Ottawa, Marine Sciences Manuscript Rept. No. 19, 75 p.

__________, 1973, The cleaning of gravel beaches polluted by oil; Proc. 13th Internat'l Coastal Engin. Conf., Vancouver, Am. Soc. Civil Engin., N.Y., p. 2549-2556.

__________, 1977a, Coastal environments, oil spills, and clean-up programmes in the Bay of Fundy; Environmental Protection Service, Environment Canada, Ottawa, 175 p. (in press).

__________, 1977b, Contingency planning for the impact of oil spills in different coastal environments of eastern Canada; Proc. of Oil Spill Conf., American Petroleum Institute, Washington, D.C., p. 115-122.

Ruel, M., Ross. S.L., Nagy, E., and Sprague, J.B., 1973, Guidelines on the use and acceptability of oil spill dispersants; Environmental Emergency Branch, Environment Canada, Ottawa, Rept. EPS-1-EE-73-1, 54 p.

Sartor, J.D., and Foget, C.R., 1970, Preliminary operations planning manual for the restoration of oil-contaminated beaches; Water Pollution Control Res. Series 5080 EOS 3/70, U.S. Dept. of Interior, 54 p.

______________________________, 1971, Evaluation of selected earth moving equipment for the restoration of oil-contaminated beaches; Proc. Joint. Conf. on Prevention and Control of Oil Spills, American Petroleum Institute, Washington, D.C., p. 505-522.

Schatzberg, P., and Nagy, K.V., 1971, Sorbents for oil spill removal; Proc. Joint Conf. on Prevention and Control of Oil Spills, American Petroleum Institute, Washington, D.C., p. 221-233.

Shaw, S.H., and Dorrler, J.S., 1977, A distributed reusable-sorbent oil recovery system; Proc. of Oil Spill Conf., American Petroleum Institute, Washington, D.C., p. 247-250.

Solsberg, L.B., 1977, A field evaluation of oil spill recovery devices; Proc. of Oil Spill Conf., American Petroleum Institute, Washington, D.C., p. 303-307.

Stewart, W.S., 1975, Microbiological and natural product systems for the protection of coastal shorelines from oil spills and oil contamination; Proc. Conf. on Prevention and Control of Oil Pollution, American Petroleum Institute, Washington, D.C., p. 425-430.

Thomas, M.L.H., 1973, Effects of Bunker C oil on intertidal and lagoonal biota in Chedabucto Bay, N.S.; Jour. Fish. Res. Bd., Canada, 30, p. 83-90.

Wardley Smith, J., 1968, Recommended methods for dealing with oil pollution; Rept. No. LR 79(EIS), Warren Spring Laboratories, Stevenage, U.K., 22 p.

__________________ (ed.), 1976, The Control of Oil Pollution; Graham and Trotman, London, 251 p.

Warren Spring Laboratory, 1973, Beach cleaning equipment, Massey Fergusen Brighton (Australia) beach cleaner; Rept. LR 185(OP).

_________________________, 1974, Beach cleaning equipment, The Beemer beach cleaner, model 603; Rept. LR 198(OP).

Westree, B., 1977, Biological criteria for the selection of clean-up techniques in salt marshes; Proc. of Oil Spill Conf., American Petroleum Institute, Washington, D.C., p. 231-235.

Whitehead, H., 1976, An A-Z of Offshore Oil and Gas; Gulf Publishing Co., Houston, 339 p.

APPENDIX

DEFINITION OF TERMS

ANGLE OF REPOSE: The maximum angle at which unconsolidated sediments form a stable slope. The maximum slope for dry, coarse sand is 34°. The angle increases as *sediment size* increases (e.g., pebbles or cobbles) or if the sand is wet.

API GRAVITY RANGE: A reference scale for the density of *oil*, as the number increases the *oil* is less dense (see Table 22, page 404) (API=American Petroleum Institute).

ASPHALT: Refers to the *heavy fractions* of *oil* that have a high boiling point (see Table 22, page 404).

BACKSHORE: That part of a *beach* above the *high-water mark* that extends landward to the limit of *storm-wave* activity (see Fig. 51).

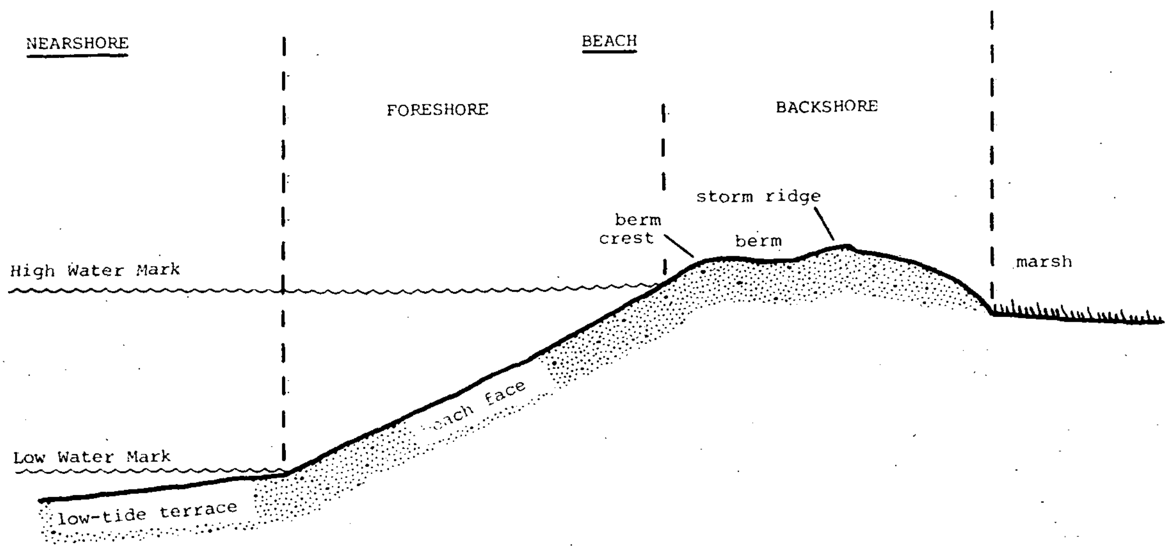


Figure 51. Sketch of beach profile with terminology.

BACKWASH: The movement of water down the *beach-face* slope after a wave has broken and has surged up the *beach face* (see *swash*).

BASALT: A resistant *volcanic rock* that occurs either as a *lava* flow or as an *intrusive rock*.

BEACH: An environment of unconsolidated sediments in the coastal zone, between the *low-water mark* and the landward limit of storm-wave activity (see Fig. 51). The upper limit is usually marked by vegetation, dunes or a cliff.

BEACH DRIFT: See Longshore Drift.

BEACHFACE: Upper part of the *foreshore*, between the *low-* and *high-water marks* that is exposed to *swash* action (see Fig. 31, page 175). Usually the beachface has the steepest slopes (up to 40°) in the beach zone (see Fig. 51).

BERM: A zone above the *beachface* that is nearly horizontal and is above the limit of normal wave action (see Fig. 51).

BERM CREST: The seaward limit of the *berm* (see Fig. 51).

BORE: The landward movement of a wave after collapse of the breaker, but before *swash*. Bores occur in the surf zone (Fig. 31, page 175).

CRUDE OIL: Naturally-occurring undistilled or unrefined *oil* (see Table 22).

TABLE 22. Classification and components of crude oil (from Whitehead, 1976)

Boiling Point Range °C	−200 · −10 · 0 · 30 · 150 · 200 · 250 · 350 · 380 · 520 · 1000+
General Classification	← Gases → ← Light Fraction → ← Middle Fraction → ← Heavy Fraction → ← Residue →
Main Components	← Gases → (*dry* – *wet*); ← Gasolines → (*light* – *heavy*); ← Fuel Oils →; ← Asphaltenes →; ← Gas Oils →; ← LPG →; ← Kerosines →; Naphthas; ← Lubricating Oils →
Hydrocarbon Range	← C_4 and lower → ← Pentane Plus → ← Liquid → ← Solid →; C_1 · C_4 · C_5 · C_8 · C_{14} · C_{16} · C_{60}
US Bureau of Mines Correlation Index	Paraffinic-Paraffinic · Paraffinic-Naphthenic · Naphthenic-Paraffinic · Naphthenic-Naphthenic
Base Classification	Paraffinic (Light) · Mixed (Aromatic) · Naphthenic (Heavy) · Asphaltic
Typical API Gravity Range	38° 47° · 37° 30° · 25° – 15°
Specific Gravity	0.835 0.800 · 0.840 0.876 · 0.900 0.970

Note: The classifications shown in this table are intended to be representative, and no precise demarcations are implied.

CUESTA: A landform that results from tilting of *sedimentary rocks*. Usually with a steep face on one side and a gentle slope on the other side of a hill.

DIURNAL TIDES: A tidal cycle with one high and one low tide each day.

EMULSION: A mixture of two fluids that do not usually mix, in this report this term refers either to a water-in-oil or an oil-in-water mixture.

ESTUARY: The lower reach of a river that is affected by tides or where fresh and seawater mix.

FETCH: The area of open water over which waves are generated by wind (Fig. 32, p. 176).

FJORD: A long, narrow, U-shaped, coastal inlet that has been enlarged by glacial erosion along a former river valley (Photo 20, page 72).

FORESHORE: That part of the shore zone between the *high-* and *low-water marks* (Fig. 51).

FROST TABLE: The upper limit of ice in a *beach*. The depth to the frost table coincides with the depth of the active *beach* in which sediments can be reworked by *littoral* processes.

HEAVY FRACTION: Hydrocarbon compounds that have a very high boiling point (>350°C) (see Table 22).

HIGH-WATER MARK: The higher limit of the tidal water level.

HIGH-WATER MARK (cont'd): *Mean high-water mark* or the mean high-tide mark is the higher limit averaged over a time period. *Spring high-water mark* or spring high-tide mark is the higher limit of *spring tides*. *Neap high-water mark* is the higher limit of *neap tides*.

ICE FOOT: A feature that is formed by the accumulation of ice that results from freezing of wave spray and *swash* in the *littoral zone* (Photos 62 and 63, pages 220 and 221).

ICE SHEET: A large, flat mass of ice that covers an extensive area (e.g., Greenland or Antarctica).

IGNEOUS ROCKS: Rocks that are formed by the cooling of *lava* or molten material in the earth. *Intrusive rocks* are one type of igneous rock.

INTERTIDAL ZONE: See Foreshore.

INTRUSIVE ROCKS: Rocks formed as molten material solidified before reaching the earth's surface. They are *igneous rocks*.

LAVA: Molten material that solidifies on the earth's surface; derived from volcanoes or from cracks in the earth's surface.

LIGHT FRACTION: Hydrocarbon compounds with a boiling point below 150°C (see Table 22, page 404).

LITTORAL ZONE: Synonymous with *foreshore*, used more as an adjective.

LITTORAL DRIFT: The movement of sediment alongshore in the *littoral zone* (Fig. 39, page 194).

LONGSHORE SEDIMENT TRANSPORT: The mechanism by which material is moved parallel to the coast by wave- or tide-induced *littoral* processes.

LOW-TIDE TERRACE: The flat or gently-sloping lower part of the *foreshore* at the base of the *beach-face* slope (see Fig. 51). All or part of the low-tide terrace may be exposed at low tide.

LOW-WATER MARK: The lower limit of the tidal water level. *Mean low-water mark* or the mean low-tide mark is the lower limit averaged over a time period. *Spring low-water mark* or spring low-tide mark is the lower limit of *spring tides*. *Neap low-water mark* is the lower limit of *neap tides*.

LPG: Liquified petroleum gas (see Table 22, page 404).

MARSH: (salt-marsh) A flat, vegetated area at or above the *high-water mark* that is flooded by *spring tides* or during *storm surges*.

MEAN HIGH-WATER MARK: See High-Water Mark.

MEAN LOW-WATER MARK: See Low-Water Mark.

MEGARIPPLES: Ripples of sand or *mud* that have crests spaced between 50 cm and 5 m apart (see *Sand Wave*).

METAMORPHIC ROCKS: *Igneous* or *sedimentary* rocks that have undergone physical changes due to chemical alteration or to heat and pressure.

METASEDIMENTARY ROCKS: *Sedimentary rocks* that have undergone *metamorphic* changes.

MORAINE: A deposit of unconsolidated sediments derived from erosion and deposition by glaciers or *ice sheets.*

MUD: A *sediment size* that is smaller than sand: composed of a mixture of silts and clays.

MUSKEG: A bog or swamp found in sub-arctic forest regions of Canada.

NEAP HIGH-WATER MARK: See High-Water Mark.

NEAP LOW-WATER MARK: See Low-Water Mark.

NEAP TIDES. Tides that occur when the gravitational pull of the sun is at right angles to, and therefore opposes, the pull of the moon. *Tidal range* is reduced during neap tides. These tides occur twice each month, during the first and last quarter of the moon (e.g., Fig. 19, page 79).

NEARSHORE ZONE: That part of the shoreline seaward of the *low-water mark* that is within the zone of wave-generated processes.

OIL: A liquid mineral compound of hydrocarbons, with minor amounts of other substances that is insoluble with and lighter than water. The physical and chemical properties

OIL: (Cont'd) of naturally-occurring (*crude*) oils vary considerably (see Table 22, page 404).

OUTWASH: The process by which rivers or streams, associated with the melting of glaciers or *ice sheets*, deposit sediments on the adjacent land areas.

PERMAFROST: Permanently frozen ground in which the upper parts may thaw seasonally. If the frozen ground is interrupted by unfrozen sections the permafrost is described as "discontinuous".

PLEISTOCENE: A time period dating from 10,000 to 2 M years ago that was characterized by expansion and contraction of *ice sheets* and glaciers.

POLAR FRONT: The unstable boundary zone between cold, dense arctic air and warmer, lighter air to the south.

POUR POINT: The lowest temperature at which an *oil* will flow (in *crudes* these can vary between -26°C and +50°C).

RAISED BEACH: A *beach* deposit that is now above the *littoral zone* due to changes in the land level or sea level. These are common in areas that were depressed due to the weight of ice during the *Pleistocene* and that have now rebounded.

RIA: A type of coast characterized by long, narrow bays separated by resistant headlands. The trends of the bays and headlands are perpendicular to the coastal trend.

RIDGE AND RUNNEL: A migratory feature in the *littoral* and *nearshore* zones that forms and moves landward onto a *beach* following wave erosion. This mechanism returns sand eroded from the *beach* that was deposited in the *nearshore* zone. The runnel is a trough formed between the ridge and the *beachface* (see Fig. 37, page 190).

SAND WAVES: Regular spaced wave-like sand forms that have a crest-to-crest spacing greater than 5 m (see Photo 41, page 141).

SEA WAVES: Term used to refer to waves within the generating area as opposed to *swell* waves that have left the generating area (Fig. 32, page 176).

SEDIMENT SIZE: Units are defined by the mean diameter of the particles:

boulder	256 mm
cobble	64-256 mm
pebble	4-64 mm
coarse sand	0.5-4 mm
medium sand	0.25-0.5 mm
fine sand	0.06-0.25 mm
silt	0.06 mm

(See also *Mud*)

SEDIMENTARY ROCKS: Rocks formed by the deposition of sediments in layers, by wind, river, ice or marine processes.

SEICHE: A change in the level of the water surface that may or may not be oscillatory. Often formed by winds piling water up against the shore in lakes (See Fig. 12, page 44).

SEMI-DIURNAL TIDES: A tidal cycle with two high and two low tides each day (see Fig. 43, page 209).

SIGNIFICANT WAVE HEIGHT: The average height of the highest one-third of the waves.

SPECIFIC GRAVITY: (Table 22) Synonymous with density.

SPRING HIGH-WATER MARK: See High-Water Mark.

SPRING LOW-WATER MARK: See Low-Water Mark.

SPRING TIDES: Tides that occur when the gravitational pull of the sun is in the same direction, and therefore reinforces, that of the moon. High tides are higher and low tides are lower than usual. Spring tides occur twice a month at the new and full moon (e.g., Fig. 19, page 79). The highest spring tides occur twice a year at the spring and autumn equinoxes, when the sun is overhead at the equator.

STORM RIDGE: A ridge formed in the *backshore* above the *high-water mark* by wave action during storms. The ridge is changed only by subsequent storm waves (see Fig. 51).

STORM SURGE: During storms the water level can be raised above the normal *high-water mark* as water is piled against the coast by onshore winds.

STORM-WAVE ENVIRONMENT: An environment that is characterized by frequent short periods of high wave-energy levels that result from local wave generation by winds during storms.

STRANDFLAT: A wide platform, that may be above or below sea

STRANDFLAT: (Cont'd) level, in coastal areas. It is formed by marine erosion, ice erosion or weathering.

SWASH: The rush of water up a *beachface* that follows breaking of the wave.

SWELL: Wind-generated waves that have left the generating area (*fetch*) (Fig. 32, page 176). Usually the waves are long-period, very regular and lower in height than waves within the *fetch* area.

SWELL-WAVE ENVIRONMENT: An environment dominated by swell waves rather than by locally-generated storm waves.

TALUS: The sediments that accumulate at the foot of a cliff. The material is derived from weathering of the cliff face and the steep talus slope often rests at the maximum *angle of repose*.

TIDAL RANGE: The difference in elevation between *high* and *low water marks*.

VISCOSITY: The property of a fluid that tends to resist relative motion or flow within the fluid.

VOLCANIC ROCKS: Rocks that have formed by volcanic action, they may be *intrusive rocks* or *lavas*.

WAVE-CUT NOTCH: A notch at the base of a coastal cliff eroded at or near the *high-water mark* by waves.

WINDS (DOMINANT): Those winds which over a time period (usually a year) have the highest velocities. The direction

WINDS (DOMINANT): (Cont'd) of the dominant winds may differ from that of the *prevailing winds*.

WINDS (PREVAILING): Those winds which occur with the highest frequency.