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WAVE-BUILT SHELVES ON SOME LOW-ENERGY COASTS

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ABSTRACT

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A nearshore terrace has formed in unconsolidated deposits of the low-energy coast of the Strait of Georgia. Scale-modelling concepts have been used to draw similarities between this small-scale terrace and the continental shelf. The beach grades seaward onto an upward-concave shelf; the outer edge of the shelf is marked by an abrupt increase in gradient on the steep offshore slope. The morphology of the shelf varies systematically with the degree of exposure to wave energy; the width of the shelf and depth of water over the shelf break increase with effective fetch length. Sediments grade seaward across the shelf with a transition from sand to mud at the shelf break. Calculated near-bed velocities under waves, recorded at six sites of differing fetch length within the Strait, show the shelf break has formed in a transitional zone between high and low "wave effectiveness". The profile form, shelf sediments and nearshore dissipation of wave energy suggest that the shelf evolves as an equilibrium form in response to contemporary wave processes. Similar terraces have developed on sheltered lake shores and on the Fiordland coast of New Zealand suggesting a general model of terrace formation at effective fetch lengths up to 50 km. Data from the Great Lakes indicate that the model may be extended up to 100 km, but break down at larger fetch lengths where effective fetch is probably an unreliable indicator of wave conditions. Similarities between the restricted fetch model and the continental terrace suggest there may be a continuum of shelf forms from small lakes through to proto-continental shelves.

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INTRODUCTION

The origins of continental terraces are multiple and complex. Primary structural controls and Pliocene and Pleistocene geological events molded the existing topography while contemporary processes are considered of secondary importance (Southard and Stanley, 1976). As a result, the shelf width and shelf-break depth show little uniformity around the world and the morphology is out of equilibrium with contemporary processes. However, most continental shelves are covered with sediments approaching equilibrium with contemporary processes, either through deposition of modern shoreface

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sediment wedges or through reworking of previously deposited autochthonous (Swift, 1976) or relict sediments (Emery, 1952). The inheritence of complex topography and ubiquitous presence of relict sediments makes the continental terrace an extremely complex and varied system to study, to which it is difficult to apply principles of uniformitarianism (Pilkey et al., 1978).

One approach to understanding complex natural systems has been to use models whereby the natural system can be simplified and the object of study isolated. Lakes and semi-enclosed bodies of water can be used as natural models of the oceans. Many similarities between the two systems have been found. In the coastal zone, limnic beach morphology and dynamic cycles of beach behaviour (Davis et al., 1972) are similar to those on oceanic coasts. Nearshore bar morphologies (Davis and Fox, 1972) and sediment distributions (Mothersill, 1970) are also analogous in both oceanic and limnic environments. Foreshore responses to fluctuations in lake level (Dubois, 1975, 1976; Pickrill, 1978b) are almost identical to those predicted by Bruun (1962) for changes in stillstand of sea level. In deeper water, numerous studies have shown sediments get finer with depth (e.g. Rea et al., 1981) in response to decreasing energy (Sly, 1973; Rossman and Seibel, 1977). Even beyond effective wave base the morphology of fans (Normark and Dickson, 1976), contourites, turbidites and slumps suggests that depositional processes and post-depositional alterations are similar (Rea et al., 1981).

Previous studies suggest that knowledge of lake-margin terrace genesis can help explain the origin of continental terraces (Pickrill, 1978a). In the present paper data from the British Columbia and Washington coasts are used to develop a model of equilibrium terrace formation on fetch-limited shores in response to wind waves. Data from New Zealand and the North American Great Lakes are used to extend this model to shorter and longer fetch lengths. An attempt is made to apply this model to equilibrium terrace formation on the continental margins.

METHODS

Nearshore profiles were constructed at 181 beach locations; 71 from the Strait of Georgia, British Columbia/Washington, 54 from Lakes Manapouri and Te Anau, New Zealand, and 56 from the Fiordland coast of New Zealand. The Strait of Georgia profiles were reconstructed from soundings and field sheets held by the Canadian Hydrographic Service. The New Zealand profiles were surveyed using a quick-set level on the sub-aerial beach and extended offshore with an echo sounder. At selected sites, surface sediments were collected and subjected to standard textural analyses.

STRAIT OF GEORGIA, PHYSICAL SETTING

The sheltered waters of the Strait of Georgia are 250 km long and 40 km wide. Situated between the Vancouver Island Ranges and the coast mountains of mainland Canada the Strait occupies part of the Georgia depression,

the extension of which can be traced south into the Puget Lowland of Washington State (Fig.1). The Strait is connected to the open ocean via the Strait of Juan de Fuca. Pleistocene glaciations have left both the Juan de Fuca and Georgia Straits steep-sided and deep.

On the western shore of the Strait of Georgia the Vancouver Island Range is fronted by the Nanaimo Lowland, a narrow coastal plain extending south into the Gulf and San Juan Islands (Clague and Bornhold, 1980). North of Nanaimo, the lowland is underlain by unconsolidated Quaternary sediments; farther south the sediment cover is thinner and more sedimentary bedrock is exposed. On the northeastern shore, the Strait is bordered by resistant Mesozoic plutonic, sedimentary and volcanic rocks. Farther south the lowlands of the Fraser valley and northern Washington are underlain by thick unconsolidated Pleistocene deposits including fluvial deposits of the Fraser Delta.

Most of the Strait of Georgia shoreline is rock, dropping steeply into deep water. However, where there is a plentiful supply of unconsolidated sediments, beaches have developed and sands and muds accumulated in the nearshore zone. As a result beaches are most common along the Nanaimo, Fraser and Puget lowland shores. Four genetically distinct morphologic environments can be separated.

(1) *Beaches.* Following the post-glacial rise in sea level, much of the unconsolidated coast of the Strait of Georgia has suffered erosion (e.g. Foster, 1976). Cliff retreat of Pleistocene deposits supplies sediments to beaches along the Nanaimo Lowlands and parts of the northern Washington coast. The large tidal range and plentiful sediment supply has produced wide sandy foreshores with rhythmic topography (McCann and Hale, 1981; Hale and McCann, 1982). Forty-two of the 71 beach/nearshore sites studied have formed in this manner.

(2) *Spits and barriers.* Winds and waves are channelled up and down the long axis of the Strait of Georgia. Waves approach much of the shoreline obliquely, setting up littoral drift. On unconsolidated shores, spits have formed in re-entrants wherever a sudden change in the orientation of the shoreline disrupts the flow of sediment; Dungeness Spit, Mapleguard Spit and Saanichton Spit are examples (Fig.1, profiles *9*, *10*, *11*, *12*, *13*, *27* and *33*); Fronting Esquimalt Lagoon, a barrier beach has enclosed a shallow bay (Fig.1, profile *15*). Twelve nearshore profiles were constructed across these depositional landforms.

(3) *Deltas.* The deltas of the major rivers make up the longest stretches of depositional coastline. The Fraser River and other small rivers in northern Washington enter the southeast shores of the Strait over extensive flat sandy deltas (Luternauer and Murray, 1973; Luternauer, 1980). Farther north, fiords and lakes dissect the coast mountains and intercept much of the freshwater run-off and deltas are largely confined to the fiords. On Vancouver Island, catchments are small, and so are the associated deltas. Eighteen of the profiles are delta traverses.

(4) *Bars.* Near Comox, a Pleistocene ridge probably connected Denman Island to Vancouver Island; erosion of this ridge has left behind a shallow

sub-tidal bar (Clague, 1976). Although not a true bar four profiles were drawn across this isolated structure.

Nearly all of the profiles traverse Holocene landforms that have evolved in the last 6000 years, during which time relative sea-level changes have been negligible (Clague et al., 1982).

TERRACE MORPHOLOGY

Nearly all of the nearshore profiles have a terrace (Fig.2). The beach slopes decrease seaward across shallow nearshore shelves marked at the outer edges by shelf breaks and steep gradients on the offshore slope.

Shelf morphology. A terrace has formed at 71 of the 76 sites (Table I), and is absent only on parts of the shallow, gently sloping Washington coast and on the steep shores near Powell River. Of the terraced profiles, nearly half have upward-concave shelves (Fig.2, profiles *11*, *17* and *29*); nearly one-third (30%) have linear profiles; 3% have downward-concave shelves, and the remainder have mixed morphologies. Most of the downward-concave and mixed shelves are found on deltas where wide intertidal flats commonly merge with a steepening convex profile in the subtidal zone (Fig.2, profiles *40* and *41*).

Most of the shelves (59%) including all with profiles resulting from deposition (spits, barriers and deltas), have smooth surface morphologies. Irregular morphology is confined to shelves with profiles reflecting an erosional history (beach and bar). On the Comox Bar and on a few beaches, ramped profiles, with higher relief and irregular morphology at the shelf break were

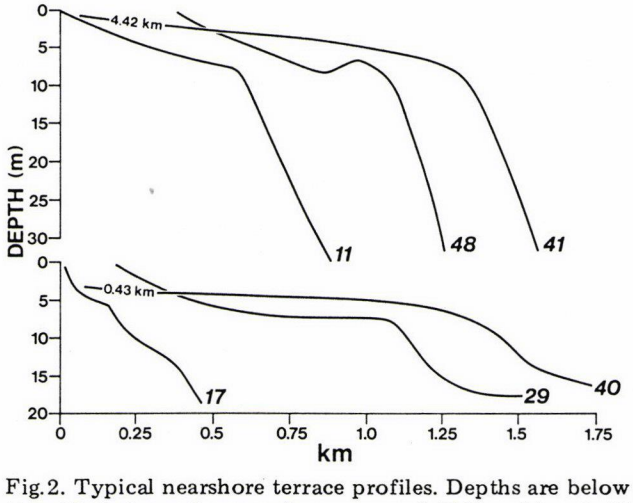


Fig.2. Typical nearshore terrace profiles. Depths are below chart datum (vertical exaggeration 25x). Smooth upward-concave spit (*11*) and beach (*29*) shelves with well defined shelf breaks; *17* = smooth upward-concave beach shelf with poorly defined shelf break; *40*, *41* = mixed deltaic shelves with linear near-flat upper slopes and downward-concave outer slopes. The landward 0.43 and 4.42 km of the profiles have been omitted for ease of illustration; *48* = upward-concave beach shelf with a ramp at the shelf break.

TABLE I

Terrace morphology in the Strait of Georgia

		Shelf morphology									
		Up concave		Linear		Down concave		Mixed		No terrace	Total
		Smooth	Irregular	Smooth	Irregular	Smooth	Irregular	Smooth	Irregular		
Profile type	Bar	0	0	0	4 (4)*	0	0	0	0	0	4 (4)
	Barrier and spit	8	0	4	0	0	0	0	0	0	12
	Beach	20 (1)	4	4	3	2 (1)	0	4 (1)	1 (1)	4	42 (4)
	Delta	2	0	6	0	1	0	8	0	1	18
	Total	30 (1)	4	14	7 (4)	3 (1)	0	12 (1)	1 (1)	5	76

*Number between brackets denotes ramped profiles.

found (Fig.2, profile *48*), suggesting the shelf break may be rocky and have structural origins.

Shelf widths range from a few hundred meters to over 6 km. Most of the spits and barriers are less than 0.75 km wide, the beaches up to 1.5 km, and most of the deltas greater than 1.25 km (Fig.3B). As a result, average shelf slopes are lowest on the deltas and bars (0.4°), but range up to 1.2° on the spits, barriers and beaches (Fig.3C).

Shelf break. On most profiles, the shelf break is a transitional zone, rather than a clearly defined point. In studies of the continental terrace, several different techniques have been used to define the shelf break (e.g. Wear et al., 1974). In this study, the shelf break is defined by extending a straight line parallel to the surface of the outermost shelf profile. The point at which the bottom trace departs from this line is designated, the shelf break (Wear et al., 1974). The shelf break has formed in water depths ranging from 0.8 to 12.5 m beneath chart datum. There is little systematic variation in shelf depth among the various profile types (Fig.3A), but the profiles of depositional features (spits, deltas and barriers) generally have better-defined breaks than the beaches.

Offshore slope. On nearly half the profiles, the steepest terrace slopes are immediately seaward of the shelf break (Fig.2). On most of the profiles (73) the offshore surface is smooth and slopes range between 1 and 22°. Slopes offshore from beaches, spits, bars and barriers cover the full range of angles (Fig.3D), whereas those of deltas generally have lower gradients (<16°).

RELATIONSHIPS WITHIN THE TERRACE MORPHOLOGY

Correlation and linear regression between morphological elements of the terrace suggest there are systematic variations in terrace form. The shelf

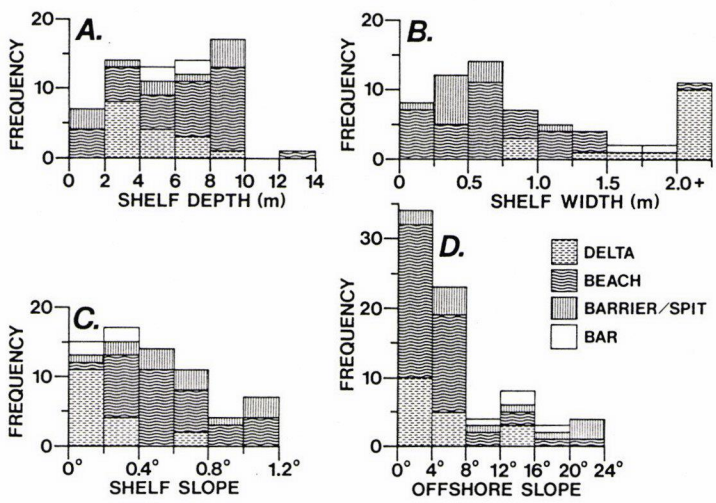


Fig.3. Nearshore terrace characteristics, Strait of Georgia.

width and depth are positively correlated with the best fit curve showing that shelf width increases logarithmically with the depth of water over the shelf break (Fig.4). Considering the predominance of upward-concave shelf morphologies, a logarithmic rather than linear relationship is probably to be expected. With increasing shelf width the shelf gradient decreases (Fig.4). The offshore slope is not correlated to any of the other terrace facets. These relationships suggest that a spectrum of terrace morphologies has been produced ranging from narrow, shallow, steep shelves to wide, deep, low-angle shelves.

RELATIONSHIPS BETWEEN TERRACE MORPHOLOGY AND WAVE ENERGY

In restricted bodies of water wave generation is limited by the fetch, wind speed and duration. At short fetch lengths (<50 km), only short wind durations are required for fully arisen seas to develop (Table II) and the wave climate can be accurately hindcast from the fetch and wind conditions. If wind conditions are assumed constant over an area then fetch can be used as an index of wave energy which almost increases linearly with effective fetch (U.S. Army Coastal Engineering Research Centre, 1977, p.3.29) for any given wind speed (Fig.5).

The depth of water at the shelf break increases linearly with effective fetch length whereas the width of the shelf increases logarithmically (Fig.6). Shelf slopes, however, are relatively uniform and bear no relationship to fetch

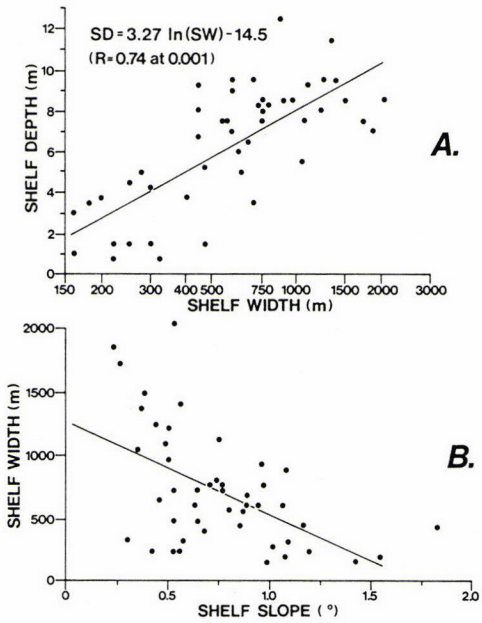


Fig.4. (A) Shelf depth plotted as a function of shelf width, Strait of Georgia; (B) shelf width plotted as a function of shelf slope.

TABLE II

Minimum wind durations (h) to develop a fully arisen sea

Effective fetch (km)	Wind speed (km h^{-1})						
	20	30	40	50	60	70	80
5	2.4						
10	2.4	1.8	1.6	1.3	1.2	1.1	1.0
20	3.7	2.9	2.5	2.2	1.9	1.8	1.7
30	5.8	4.3	3.8	3.3	2.9	2.8	2.6
50	7.9	5.9	5.0	4.5	4.0	3.8	3.4
100	14.0	10.7	9.0	7.9	7.3	6.6	6.0
200	27.0	20.0	16.0	14.0	12.7	11.8	11.0
300	38.0	28.0	23.0	20.0	18.0	16.0	15.0
500	58.0	40.0	32.0	28.0	25.0	23.0	21.0
1000	115.0	73.0	60.0	51.0	45.0	40.0	37.0

From U.S. Army Coastal Engineering Research Centre, 1977, fig.3.15.

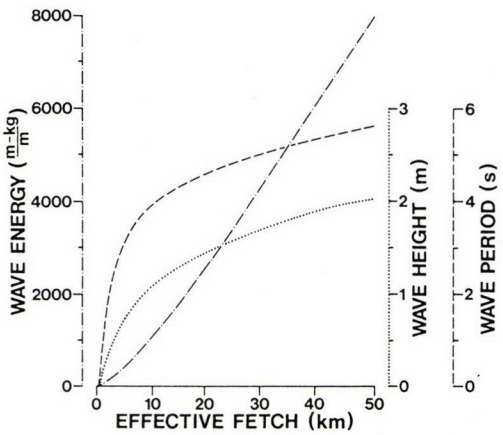


Fig.5. Predicted deep-water wave height and period for 50 km h^{-1} winds of unlimited duration (U.S. Army Coastal Engineering Research Centre, 1977, fig.3.15) and calculated wave energy per wave length (where $E = \rho g H^2 L/8$).

conditions. These correlations suggest the terrace increases in size, but maintains a constant slope with increasing fetch length and wave energy.

Points that plot below the depth/fetch curve and width/fetch curve are derived from terraces that are shallower and narrower than predicted. At least five sites fall into this category: four off Esquimalt harbour (14, 15, 16, 17) and one off Point Grey (44). At both sites the terrace is not well developed (Fig.2); to fit the predicted trend the shelf must be widened and the shelf break depth increased, either through progradation at the shelf break or by landward retreat of the shoreline. At both sites the shoreline is being eroded. At Esquimalt, erosion rates are estimated at 15—30 cm yr^{-1}

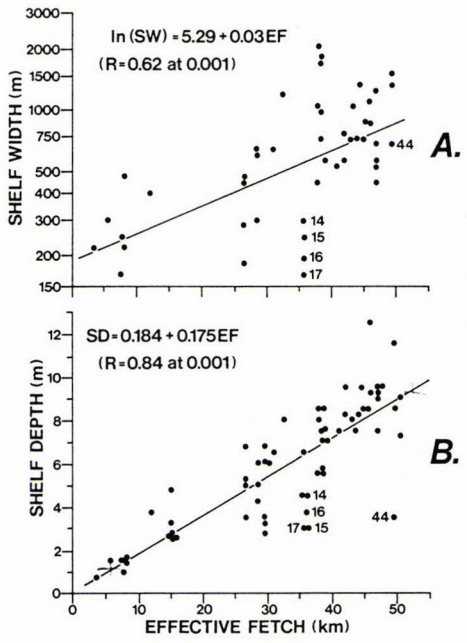


Fig.6. (A) Shelf width plotted as a function of effective fetch (as defined by U.S. Army Coastal Engineering Research Centre, 1977, p.3.29) for the Strait of Georgia; (B) shelf width plotted as a function of effective fetch.

(Foster, 1976) whereas at Point Grey, shoreline erosion is a major problem and has been intensively studied (e.g. Lum, 1975). There is less scatter of points above the depth/fetch curve, suggesting that few shelves have developed to depths much greater than predicted by the relationships. The shelves of progradational spits and deltas tend to plot close to the shelf depth/fetch curve, suggesting a balance between sediment supply and wave energy. However, the spits are generally below the width/fetch curve, producing steeper slopes, whereas the broad intertidal flats on the deltas produce extremely wide shelves, isolating them as a separate group.

Implicit in this discussion is the suggestion that the terrace evolves to a specific width and depth that can be predicted from either the effective fetch length or wave energy. Few shelves have developed larger terraces than predicted, implying there is an upper limit to terrace size, whereas eroding shorelines backing terraces that are smaller than predicted implies they are immature. These relationships suggest the terrace evolves to an optimum size that is probably in equilibrium with formative wave processes.

WAVE-ENERGY DISSIPATION ON THE TERRACE

In the preceding discussion of terrace morphology, the development of an equilibrium profile has been inferred from systematic variations in morphology with wave energy (as inferred from the fetch). Implicit in this model is the

suggestion that the profile shape develops in response to the dissipation of wave energy across the nearshore zone, transporting sediment and grading the profile into an equilibrium form.

The ability of waves to set sediment in motion on the sea floor is a function of the near-bed orbital velocities and the frequency with which they occur. Following the magnitude and frequency concepts of Wolman and Miller (1960), McCave (1971) derived a wave effectiveness parameter Up^3P where Up is the peak particle speed near the bed and P is the percentage of time at which Up is exceeded. Up^3P is proportional to the amount of work done per unit area of bed by waves of that particular P and Up. A graph of Up^3P against Up^2 (proportional to bed shear stress) for each depth shows a maximum at which waves are most effective in performing geomorphic work. By plotting these maximum values of Up^3P against depth, McCave (1971) was able to identify three zones of wave effectiveness. In shallow water, there is a zone of high wave effectiveness, a zone of low wave effectiveness in deep water and a transitional zone between the two.

Within the Strait of Georgia, Waverider Accelerometer Buoys (Marine Environmental Data Service, 1974, 1976, 1977a, b, 1978a, b) have been deployed at six sites exposed to effective fetch lengths ranging from 12 to 50 km (Fig.1). From bivariate plots of wave height against wave period (Fig.7A), percentage exceedance curves of near-bed velocities for specific water depths were compiled using linear wave theory to derive Up (Fig.7B):

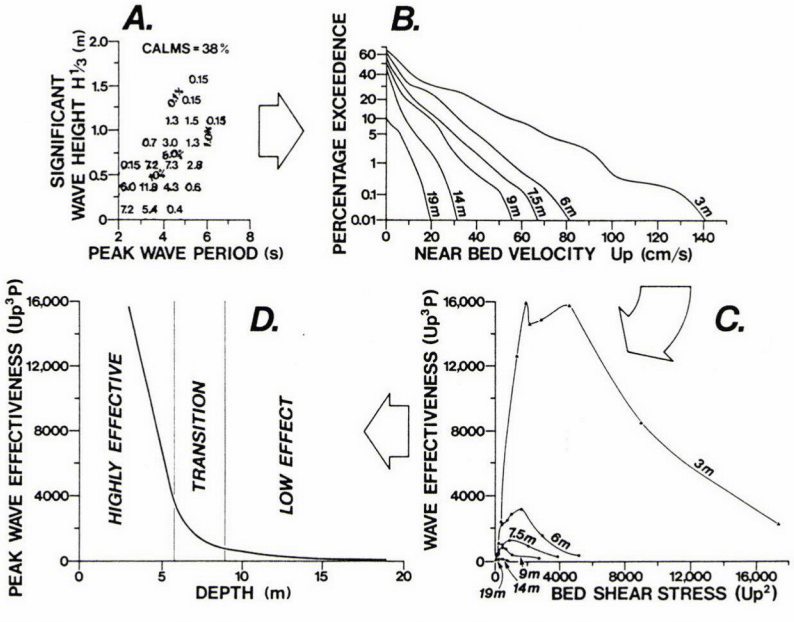


Fig.7. An example of the steps in the derivation of peak wave effectiveness, French Creek. (A) Plot of significant wave height against peak wave period; (B) Percentage exceedance curves of near-bed velocities for water depths of 3, 6, 7.5, 9, 14 and 19 m; (C) The distribution of wave effectiveness at the bed versus bed shear stress; (D) Peak wave effectiveness (from each curve in C) plotted as a function of depth.

$$Up = \frac{\Pi H}{T \sinh (2\Pi h)/L}$$

where H, T and h are wave height, wave period and water depth. In deep water ($h/L \geqslant 0.25$) wave length is independent of water depth:

$L_\infty = gT^2/2\Pi$

in shallow water ($h/L \leqslant 0.25$):

$L_S = T(gh)^{1/2}$

in intermediate water ($h/L = 0.05$—0.25):

$L_I = L_\infty [\tanh (2\Pi\ h/L_\infty)]^{1/2}$

From the percentage exceedance curves of Up graphs of wave effectiveness (Up^3P) versus bed shear stress (Up^2) were drawn (Fig.7C) and peak Up^3P plotted against depth (Fig.7D). All six Waverider stations show similar shaped curves (Fig.8). Wave effectiveness decreases rapidly with depth and then declines asymptotically to the abscissa. The curves have a similar shape to those derived by McCave (1971) for the Irish and North Seas and can be broken down into the same three zones of high, intermediate, and low wave effectiveness. Assuming two straight line segments and a transition region between the two (Fig.7D).

The main difference between sites is the depth of water at the boundaries between zones (Fig.8). The water depth at the wave effectiveness boundaries increases as a function of fetch length (Fig.9). When the depth-to-shelf break data are plotted on the same axes, nearly all of the depths fall within the zone of transitional wave effectiveness; the best-fit regression line passes through the centre and nearly parallels the wave effectiveness boundaries. The shelf is in the zone of high wave effectiveness. As water depth increases

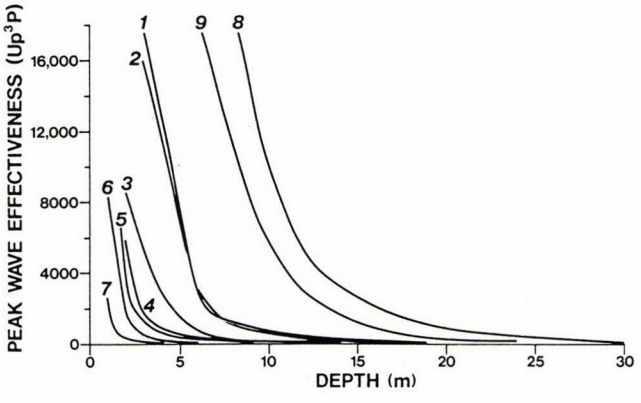


Fig.8. Peak wave effectiveness plotted as a function of depth. Numbers *1*—*6* refer to wave-rider stations in Fig.1; Station *7* = Lake Manapouri, New Zealand; *8* = Toronto, Lake Ontario; *9* = Battle Island, Lake Superior.

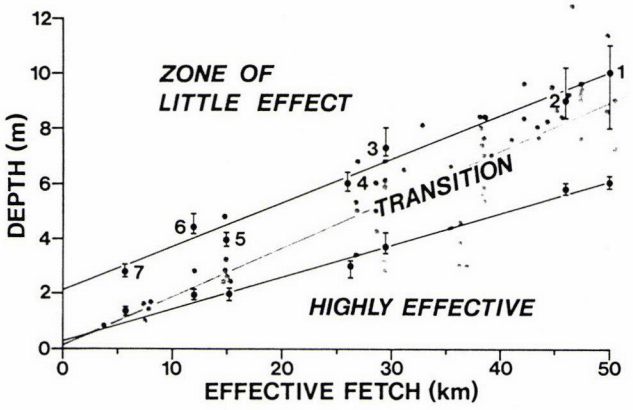


Fig.9. Depth to the high/transitional and transitional/low wave effectiveness boundaries. Error bars mark the maximum likely range in determining the boundaries. Shelf depths (from the profiles) and the best fit regression line are also plotted as a function of fetch.

across the shelf wave effectiveness decreases; at the shelf break water depths are coincident with the transition to low wave effectiveness. Beyond the shelf break, wave effectiveness is low. Therefore, the wave data suggest that the shelf evolved as an equilibrium form out to a "wave base" which can be defined by the wave effectiveness parameter. Profiles with shelf break depths in the zone of high wave effectiveness at Point Grey (44) and Esquimalt (14—17) have previously been shown to be too shallow and narrow for an equilibrium profile to develop and the shoreline is retreating in an attempt to establish equilibrium. The wave effectiveness data reinforce this hypothesis.

Across most of the shelves, relatively high-velocity, low-frequency events are most effective at the sea floor, increasing in velocity shoreward (Table III). At shelf break depths, i.e. the transitional effectiveness zone, velocities of 20—80 cm s^{-1} occurring less than 10% of the time are most effective. These velocities are produced by high-energy storm waves.

So far, the discussion of terrace formation has been based on depth to chart datum which provides a reasonable estimate of minimum water depths at the shelf break during times of mean low water. However, throughout much of the Strait of Georgia, the tidal range is 5 m or greater. This range results in large diurnal and longer period fluctuations in near-bed velocities across the terrace. The velocity range is greatest at shorter fetch lengths where wave heights and periods are smaller and orbital velocities decrease more rapidly with depth. For instance at Lund (effective fetch 12 km) near-bed velocities at shelf break depths may be decreased by a factor of 2 to 10 (Fig.10A) (wave effectiveness by 8 to 1000). By contrast, at French Creek (Fig.10B) (effective fetch 46 km) velocities are only reduced by a factor of 1.5 to 4 (wave effectiveness by 3 to 64). The net result of the water level fluctuations is a shore-normal translation of the wave effectiveness curve through the tide cycle. On typical shelf slopes (0.2—2.0°) the curve may be displaced by 150—1400 m during large tides. For example at French Creek

TABLE III

Wave conditions at peak wave effectiveness

	Water depth (m)								
	1.0	2.0	3.0	4.5	6.0	7.5	9.0	14.0	19.0
Sturgeon Bank									
Up (cm s^{-1})			120.0		65.0		*45.0	60.0	
Up^2			14,400.0		4225.0		2025.0	3600.0	
Up^3P			17,280.0		2746.0		911.0	216.0	
P (%)			0.01		0.01		0.01	0.001	
French Creek									
Up (cm s^{-1})			43.0		40.0	29.0	*20.0	23.0	12.0
Up^2			1849.0		1600.0	841.0	400.0	530.0	144.0
Up^3P			15,901.0		6400.0	1220.0	800.0	122.0	17.0
P (%)			0.2		0.1	0.05	0.1	0.01	0.01
White Rock									
Up (cm s^{-1})			80.0	60.0	*24.0	30.0	25.0	27.0	
Up^2			6400.0	3600.0	576.0	900.0	625.0	729.0	
Up^3P			5120.0	2160.0	691.0	270.0	156.0	20.0	
P (%)			0.01	0.01	0.05	0.01	0.01	0.001	
West Vancouver									
Up (cm s^{-1})		83.0	24.0	24.0	31.0		21.0		
Up^2		6890.0	576.0	576.0	961.0		441.0		
Up^3P		5718.0	1382.0	691.0	297.0		93.0		
P (%)		0.01	0.1	0.05	0.01		0.01		
Powell River									
Up (cm s^{-1})	55.0	31.0	38.0	25.0	18.0				
Up^2	3028.0	961.0	1444.0	625.0	324.0				
Up^3P	8318.0	1489.0	548.0	157.0	58.0				
P (%)	0.05	0.05	0.01	0.01	0.01				
Lund									
Up (cm s^{-1})	106.0	33.0	51.0	36.0	28.0				
Up^2	11,236.0	1089.0	2601.0	1296.0	784.0				
Up^3P	11,910.0	3593.0	1326.0	466.0	220.0				
P (%)	0.01	0.1	0.01	0.01	0.01				

*Approximate shelf depth.

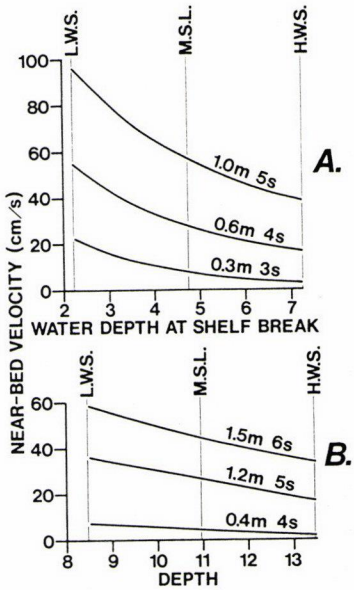


Fig.10. Tidal-cycle fluctuation in near-bed velocity at the shelf break for three combinations of wave height and period representing high, moderate and low-energy conditions. (A) Lund (EF = 12 km); (B) French Creek (EF = 46 km).

where the shelf break is at 9 m, the zone of high wave effectiveness is displaced nearly 500 m landward from the outer shelf (6 m) to shallow subtidal depths (1 m), while the shelf break moves from the transitional zone into the zone of little effect (Fig.11A). At shorter fetch lengths, tidal translation has an even greater influence. At Cordova Bay (EF 12 km) during low water, most of the shelf is in the transitional zone. Despite only a 3.8 m tidal range, almost the entire shelf is in the low-effectiveness zone at high water and the highly effective zone is confined to the intertidal beach (Fig.11B). Therefore, the combination of low wave energies and a large tidal range produces strong tidal translation of wave effectiveness across the shelf. This translation suggests that at short fetch lengths almost the entire shelf has evolved in response to high energy storm waves during low tidal stages. At longer fetch lengths the outer shelf probably evolved in response to similar conditions, whereas the inner shelf may be reworked by storm waves at all stages of the tide.

The dominant role of tides in terrace formation is in controlling the depth of water over the terrace. Tidal currents are insufficient to induce sediment transport in the intertidal zone, except in major runnels (Hale and McCann, 1982) and where tidal streams are concentrated.

TERRACE SEDIMENTS

Most of the shelves have a smooth surface morphology and are mantled with unconsolidated sediments. Two extensive studies of nearshore sediments,

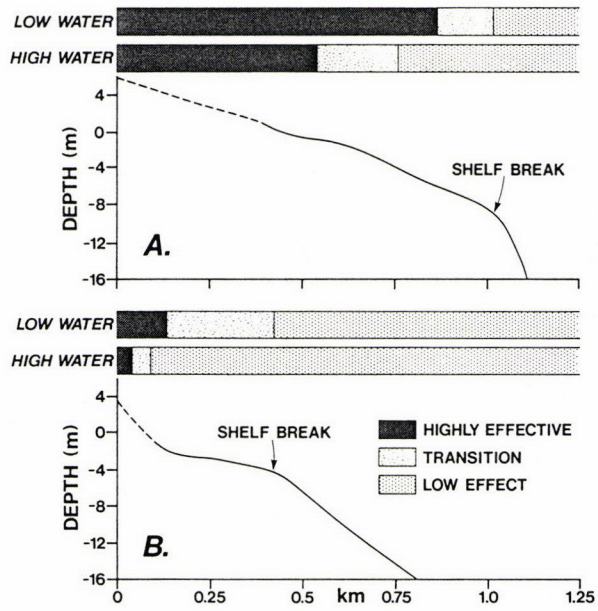


Fig.11. Tidal translation of peak wave effectiveness zones across the terrace. (A) High-energy terrace at French Creek (47; EF = 46 km) with a tidal range of 5.0 m. (B) low-energy terrace at Cordova Bay (24, EF = 12 km) with a tidal range of 3.8 m (wave data from Lund).

Comox Bar in the northern Strait of Georgia (Clague, 1976) and the Fraser Delta in the south (Luternauer and Murray, 1973), illustrate typical terrace sediment distributions. Despite the two sites having completely different origins [i.e. the Comox Bar has erosional origins (Clague, 1976) while the Fraser delta has undergone extensive progradation], the two have similar patterns of surface-sediment distribution.

Surface sediments on Comox Bar are sand and gravel and are thought to be lag concentrates from Pleistocene sediments which probably once formed a continuous sub-aerial ridge between Denman Island and Vancouver Island. At the shelf break, there is a sharp change from well-sorted sand to silty sand grading downslope to sandy silt and mud (Fig.12).

The front of the Fraser delta is 48 km long, with most of the sediment (85%) entering through the Main Channel of the Fraser River which bisects the delta into two intertidal areas: Sturgeon Bank in the north and Roberts Bank in the south (Luternauer and Murray, 1973; Luternauer, 1980). On Sturgeon Bank and northern Roberts Bank, sediments are mainly well-sorted medium to fine sands (Fig.13). Seaward of the shelf-break there is an abrupt decrease in grain size; the shelf break is coincident with the change from sand to muddy sand which grades downslope into mud. Repeated bathymetric surveys show that this section of the delta front is stable or prograding. By contrast, southern Roberts Bank is retreating and mass wasting redistributes sandy shelf sediments into deep water.

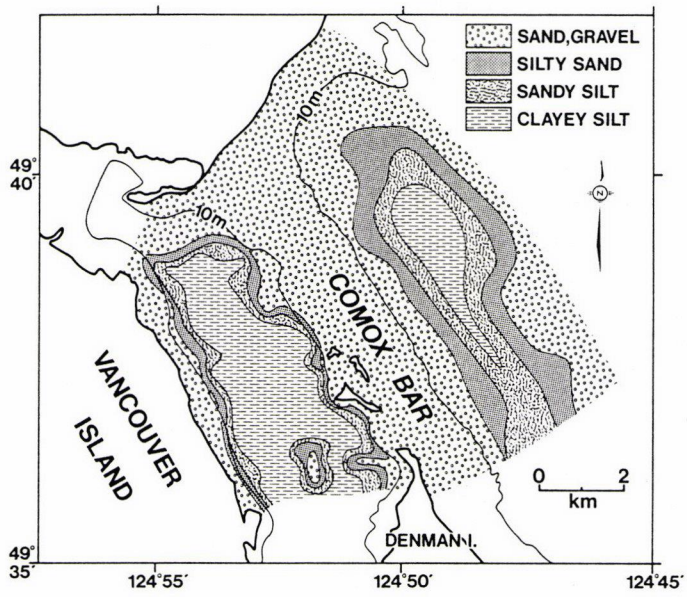


Fig. 12. Distribution of surficial sediments, Comox Bar (from Clague, 1976).

In the preceding discussion, it was shown that the terrace developed an equilibrium form in response to wave processes with the shelf break forming at the transitional boundary between high and low wave effectiveness. The transition from sand to mud at the shelf break suggests a change in the processes of sediment transport with sandy sediments being reworked by wave activity on the shelf and muddy sediments settling out in the quieter deeper waters of the offshore slope. The transitional boundary between the high and low wave effectiveness zones marks the boundary between active sediment reworking (preventing the deposition of fines), and predominant sediment deposition.

APPLICATION OF THE MODEL AT SHORT FETCH LENGTHS: NEW ZEALAND

While the model of equilibrium terrace formation has been developed specifically for the Strait of Georgia, it has general applicability to many restricted fetch environments.

Nearshore surveys of 110 profiles around the shores of Lakes Manapouri and Te Anau and the fiord coast of southern New Zealand have shown that a terrace forms off all shores mantled with unconsolidated material and exposed to a range of fetch lengths between 0.3 and 11.0 km (Pickrill, 1978a, 1980). In the Strait of Georgia, the tidal range may exceed 5 m whereas on the New Zealand fiord coast the tidal range is only 2 m and lake levels fluctuate 4.8 m on Manapouri and 3.9 m on Te Anau in response to variable inflows. However, if exceptionally high flood levels are excluded (which inundate the backshore) the water-level range is approximately 2 m on both lakes. Despite

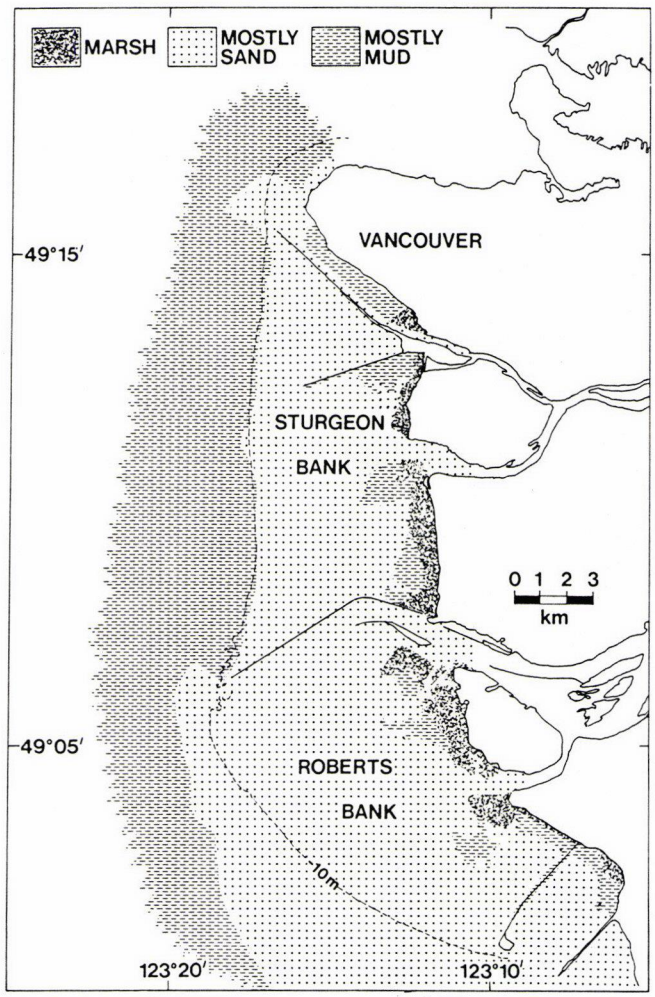


Fig.13. Distribution of surficial sediments, Fraser Delta (from Luternauer, 1980).

a much smaller range of fetch lengths in New Zealand (11 km) similar relationships exist among the terrace-slope facets (Pickrill, 1978a, 1980) and between these and the effective fetch (Fig.14). The bivariate plot of shelf width against depth shows that the New Zealand shelves are narrower and steeper than those in the Strait of Georgia probably because of the much smaller water level range. The shelf width and depth to the shelf break both increase with fetch.

Unfortunately, wave data are available from only one site on the shores of Lake Manapouri where there is a fetch of 5.3 km. However, the plot of peak wave effectiveness (Fig.8) against depth can be divided into the same three zones of high, transitional and low wave effectiveness (Pickrill, 1978a). The boundaries between the zones fall at approximately the same depths as

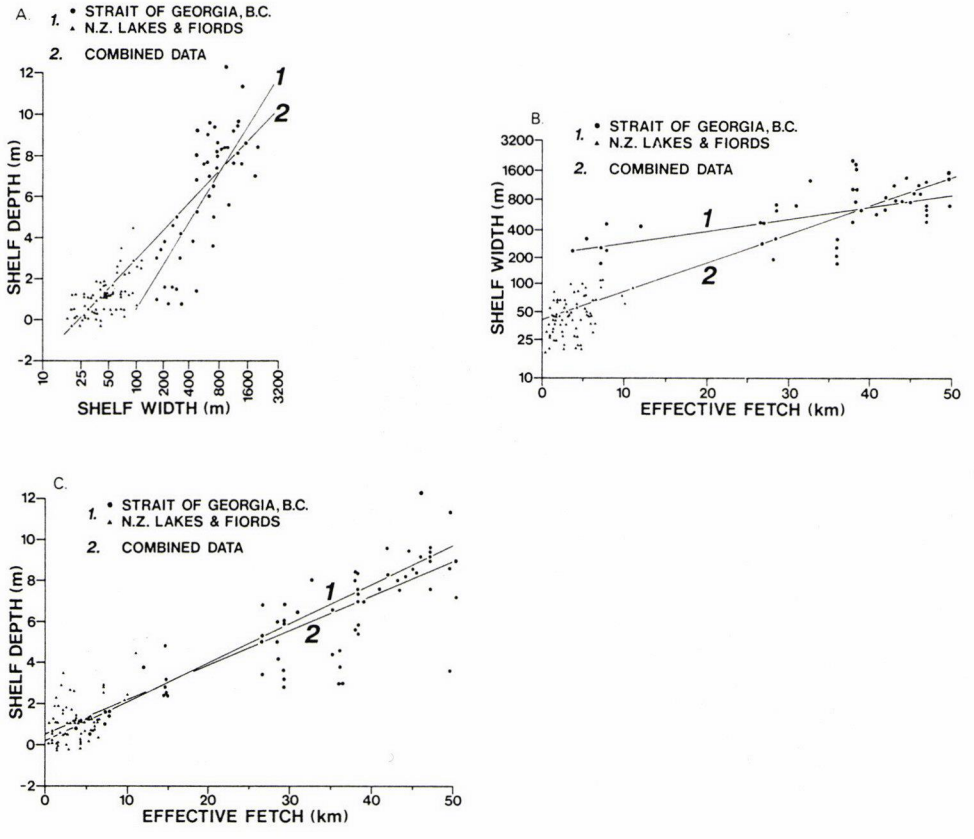


Fig.14. Bivariate plots of terrace characteristics from the Strait of Georgia, Lakes Manapouri and Te Anau New Zealand and the New Zealand fiords. (A) Shelf width and depth to the shelf break, where for the combined data, $SD = 2.50 \log e^{x} SW - 6.92$, and $R = 0.89$; (B) shelf width and effective fetch where for the combined data $\log e^{x} SW = 3.70 + 0.07$, EF and $R = 0.90$; (C) shelf depth and effective fetch where for the combined data $SD = 0.47 + 0.17$, EF and $R = 0.93$.

predicted by the Strait of Georgia wave effectiveness data (Fig.9). As in the Strait of Georgia, the shelf break has formed in response to low-frequency, high-energy waves concident with low water levels when wave effectiveness at the shelf break is highest. In all four environments, terrace sediments have similar distributions with the shelf break marking the transition from wave-worked shelf sands to slope muds deposited out of suspension.

The similarity of terrace structure, shore-normal dissipation of wave effectiveness, and sediment distribution between the New Zealand fiords and lakes and the Strait of Georgia and the presence of a terrace in many other steep-sided New Zealand and Canadian lakes (Pickrill, pers. observation; C.H. Pharo, pers. commun., 1982) suggest that the terrace is a common feature which develops as an equilibrium size-graded shelf in response to the wave climate.

APPLICATION OF THE MODEL AT LONG FETCH LENGTHS: THE GREAT LAKES OF NORTH AMERICA

The terrace model is applicable at fetch lengths up to 50 km. Data from the Great Lakes are used to test the applicability of the model at longer fetch lengths. Off Toronto in western Lake Ontario, Accelerometer Waverider Buoy records are available for a 13-month period in 1972—1973 (Marine Environmental Data Service, 1973b). Effective fetch length is 114 km and the wave effectiveness curve breaks down into the three zones of high, transitional and low, with boundaries in 12 and 20 m of water (Fig.15). The boundaries lie very close to the extrapolated best fit boundaries from the Strait of Georgia and New Zealand wave effectiveness data.

Much of the nearshore zone in western Lake Ontario is bedrock with a veneer of till. The tills are usually covered with complex surficial deposits comprising coarse lag gravels and sand (Thomas et al., 1972). In places extensive sand deposits have accumulated in the nearshore zone. On the southwest shore of the lake (at similar effective fetch lengths to Toronto), the surficial sands grade lakeward with oscillatory wave ripples down to 10.2 m and the sand/mud boundary at about 15 m (Sutton et al., 1970).

The complex Recent history of lake levels makes it difficult to differentiate between relict nearshore morphology and morphology evolving in response to modern processes. In places, a nearshore terrace has developed with a break point in 11—15 m of water. However, any interpretation of nearshore morphology must be treated with caution. Despite these limitations, the wave effectiveness and textural boundary data suggest that in Lake Ontario the shelf model can probably be extended up to fetch lengths of 114 km.

In northern Lake Superior, Battle Island is exposed to effective fetch lengths of 240 km. From six months of Waverider records (Marine Environmental Data Service, 1973a), the inflexion points on the peak wave effectiveness curves are in 10 and 18 m of water, depths approximately half of those predicted by the wave effectiveness/effective fetch model (Fig.15). Unfortunately, there are no sediment data to see if the textural boundary falls within the zone of transitional effectiveness.

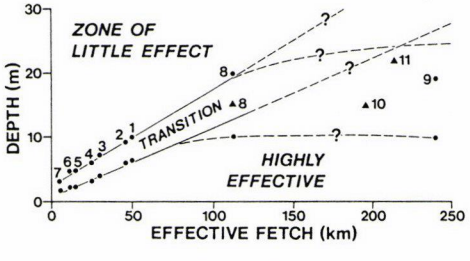


Fig.15. Depth to the wave effectiveness (•) and sand/mud boundary (▲) plotted as a function of fetch in New Zealand lakes and fiords, the straits of Georgia and the Great Lakes. Station numbers are identified in Figs.1 and 8; Station *10* = Lake Michigan; *11* = Lake Huron.

In southern Lake Huron (EF 214 km) and southern Lake Michigan (EF 193 km) the textural boundaries lie at 22 and 15 m, respectively (Hough, 1935), several meters shallower than predicted by the linear trends (Fig.15). The wave effectiveness and sediment data suggest the model breaks down at fetch lengths of approximately 100 to 200 km and greater.

The break down of the linear model is to be expected. The linear relationship between wave energy and fetch length illustrated in Fig.5 (for constant wind speed and unlimited duration) is applicable to fetch lengths up to approximately 500 km. At short fetch lengths (<50 km), where fully developed seas are quickly developed, (Table II) these assumptions are reasonable and relationships between fetch and shelf break depth, peak wave effectiveness and sediment textural boundaries can probably be represented best by linear functions. At longer fetch lengths such as in the larger Great Lakes, wind durations required to produce fully arisen seas may exceed 24 h (Table II) and fully arisen seas are rarely generated (Sly, 1973). As a result, shelf depth, wave effectiveness and depth to the textural boundary are less than predicted by the linear relationships developed at shorter fetch lengths.

APPLICATION OF THE MODEL TO THE CONTINENTAL SHELF

On the continental margins where fetch is unrestricted, shelf width and shelf break depth show little uniformity around the world. The topography of the continental shelf has evolved in response to processes operating over several million years, incorporating many transgressions and regressions, whereas the terrace model developed in this paper represents the morphology produced during just one period of relatively stable sea level. As a result the continental shelf is wider and deeper than might be expected from the model. Despite this both have a similar topography. Both shelves have a "concave-up" profile with the steepest slopes at the shore face (Swift, 1969). In both, there is sometimes a sharp break in slope at the outer edge of the shelf with the steepest (continental/offshore) slopes immediately seaward of the break.

On the continental shelf the sediment distribution is complex with modern and autochthonous sediments producing a diversity of patterns. However, modern sediments normally form a nearshore seaward-fining wedge of sand, giving way to the modern mud blanket in deeper water. In the Celtic Sea, McCave (1971) has shown the change from sand to mud marks the transitional/low wave effectiveness boundary, suggesting there is a continuum of shelf sedimentation processes from fetch lengths of a few kilometers out to the unrestricted fetch conditions of the oceans.

On low-energy terraces the shelf break, wave effectiveness boundary and textural boundary are coincident. On the continental terrace, the wave effectiveness and textural boundaries may also be coincident but the shelf break depth is inherited from earlier events. If the model is valid then on a proto-continental terrace formed during a period of steady sea level the shelf break should form at the wave effectiveness boundary and mark the textural boundary between wave-worked sand and quiet-water mud deposition with the

shelf width and depth increasing with the energy in the wave climate. Furthermore the model suggests the proto-shelf break should form at "wave-base" in relatively deep water in response to infrequent transport by high energy waves, as suggested by Moore and Curray (1964) rather than at "surf base" as proposed by Dietz and Menard (1951) and Dietz (1963).

In 1919, Johnson proposed the first comprehensive model of continental shelf sedimentation. He saw the shelf as a two-fold structure: an inner wave-cut platform and an outer progradational wave-built terrace with material eroded from the inner zone deposited on a prograding shelf out to wave base. Shore-normal sorting produced a seaward textural gradient and an equilibrium profile in both texture and grade. While subsequent research has shown this to be a gross oversimplification, the terrace model developed here for limited fetch environments bears a remarkable similarity to the Johnson model.

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