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Headland Erosion by Waves

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ABSTRACT

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The process controls associated with the erosion of marine headlands have been debated by May and Tanner (1973) and Komar (1985). Opinions vary as to the evolutionary sequence of headlands. Field measurements at two headland sites in Nova Scotia reveal an apical drift divergence and strong longshore gradients in wave heights, breaking angles and currents dispersing eroded material along the flanks. Although the potential for erosion is maximized at the headlands, it is the shoreline transport system which ultimately controls evolution of the headland, although the narrow needle-like promontories predicted by May and Tanner are, in reality, unlikely to form everywhere due to wave field variability. At both field sites, the downdrift sorting and partitioning of eroded sediment on a textural basis, together with a progressive decrease in the angle of wave approach leads to a reduction in transport potential, and thus a decrease in the rate of erosion.

ADDITIONAL INDEX WORDS: *Headlands, erosion, longshore transport, nearshore wave variability, eastern Canada.*

INTRODUCTION

In 1973, May and Tanner introduced the concept of the coastal cell dividing the shoreline into distinct units, based on the longshore distribution of wave power, P_L. Cell divides occur where $P_L = 0$; such as at headlands. If $P_L = 0$ it indicates that there is no longshore transport potential at this point, and, by implication, that there is no sustained long-term erosion either. Thus a headland, formed of any relatively resistant material, where $P_L = 0$ would survive, while its flanks would erode (Figure 1A) creating a needle-like promontory. KOMAR (1985) has challenged this view from both practical and theoretical standpoints. He maintains that (a) headlands do not erode in the manner indicated by May and Tanner and (b) their cell model is, in any case, incorrect in its interpretation of breaking wave angle. Of particular importance is the rate of change in the breaker angle alongshore ($d\alpha_b/dy$), as it is this variable which is tied-in most closely with the potential for sediment transport. In May and Tanner's model $d\alpha_b/dy$ is zero at the headland, increasing away in both directions. Komar believes this is incorrect, indicating that $d\alpha_b/dy$ will always be non-zero even at a headland. Moreover KOMAR suggests that the maximum erosion of headlands is at the apex, so that they erode as a blunt nose (Figure 1B). CARTER (1988, pp. 203–205) suggested that the gulf between these two opposing views was not as wide as Komar indicated, largely because many headlands act as drift divides, so that at some point on the shore, sediment transport must fall to zero. Given a null drift position between two diverging longshore currents, there must be a matching null erosion position, so that over time a "needle" like headland should develop. However given the usual irregular nature of the incident wave field, such morphology will be rarely encountered. The aim of this paper is to expand these arguments through the use of field data from eastern Canada and to demonstrate that both May and Tanner and Komar 'models' may coexist. This study forms part of a larger project examining shore response to varying rates of sea-level rise (CARTER *et al.*, 1989; FORBES *et al.*, in press).

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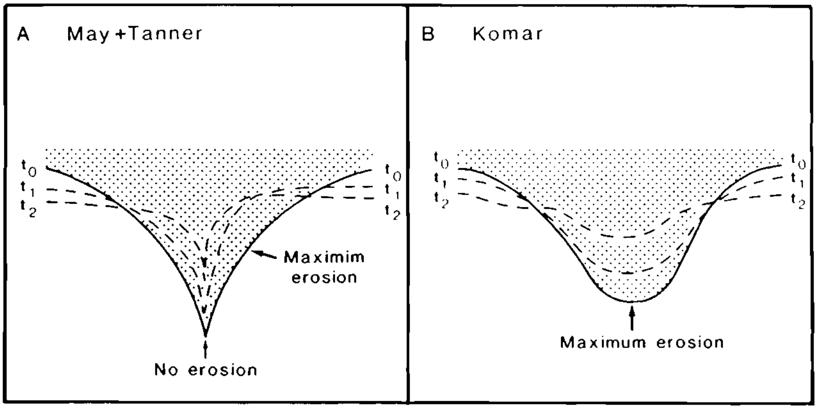


Figure 1. Two opposing views of headland erosion. According to May and Tanner's (1973) model erosion (A) should be maximised at the flanks, leaving a narrow, needle-like promontory as the shoreline retreats. Komar (1985) presents an alternative view (B) in which the maximum erosion is at the headland, and the retreat follows a more subdued pattern, with the headland eventually 'submerging' into a uniform, linear shoreline.

STUDY AREA

The Eastern Shore of Nova Scotia (Figure 2) is experiencing a very rapid sea-level rise of between 3 and 4 mm/year (SCOTT *et al.*, 1987). As the sea has risen it has encountered a number of drumlins (Figure 3) which form eroding headlands and provide sediment sources for the development of barriers and associated back-barrier environments (BOYD *et al.*, 1987; CARTER *et al.*, 1989). Geologically speaking, each drowning drumlin has a relatively short

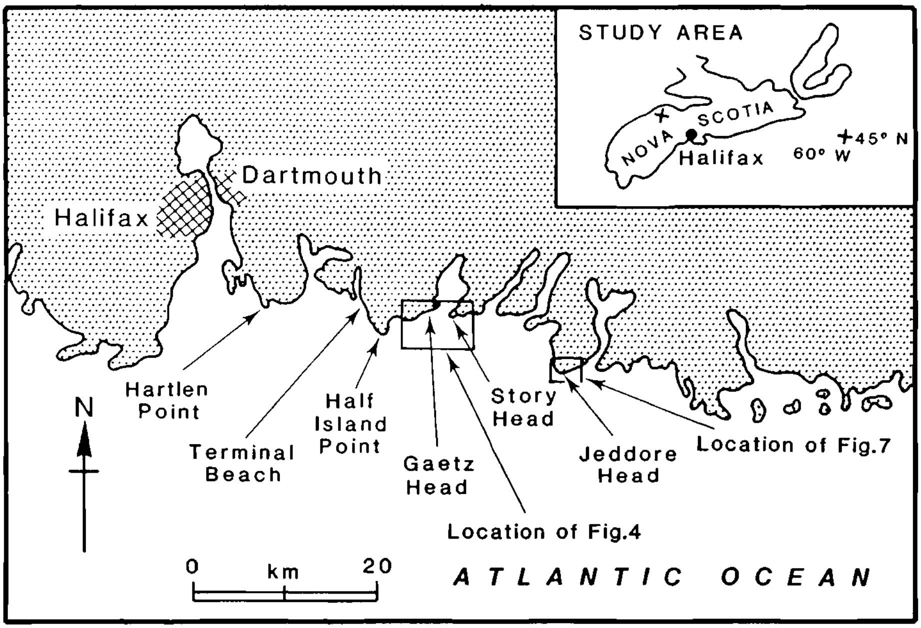


Figure 2. The Eastern Shore of Nova Scotia, illustrating sites mentioned in the text.

Figure 3. Drumlin headlands looking east towards Half Island Point. This is a fully 'emerged' headland with strong longshore process gradients, while the two headlands in the foreground have, as yet, limited influence on the shoreline configuration.

'life' once it is attacked by the sea, perhaps only 1,500 to 2,000 years, depending on size and position relative to the wave field. Cliff erosion rates can be high; WANG and PIPER (1982) and TAYLOR *et al.* (1985) recorded sites where recession exceeded 2 m/year. SONNICHSEN (1984) calculated annual volumetric erosion of cliffs at Half Island Point and Hartlen Point (see Figure 2 for locations) at about 10,000 m^3/km, and CARTER *et al.* (in press) estimated just over 5,100 m^3/year was eroded from Story Head between 1945 and 1982, translated as a cliff retreat rate of c. 0.7 m/year.

The drumlin coast experiences a moderately high-energy wave regime, although there is a distinct seasonality, with relatively low-energy conditions dominating in summer. Most wave activity results from west to east tracking cyclones moving north or south of, but rarely over, the study area. Locally generated seas are superimposed on longer swells moving northeast along the North American seaboard. Annual modal deepwater heights are in the order of 1.5 to 2.0 m, with modal wave periods between 8 and 10 sec. The coast is mesotidal, with a spring range of just over 2 m at Halifax.

METHODS

In order to examine variations in wave processes around headlands, direct measurements of waves and currents were made at 16 sites at two locations, Story Head and Gaetz Head (Figure 4). At every site, one person waded through the surf zone to record at least 30 breaking wave heights (H_b) using a hand-held wave staff. Wave periods (T) and breaking wave angles (α_b) were also measured at each site. Surface directions and velocities of longshore currents were tracked by timing sodium flouroscein dye movements alongshore. All sites were occupied within a single low tide period. In addition

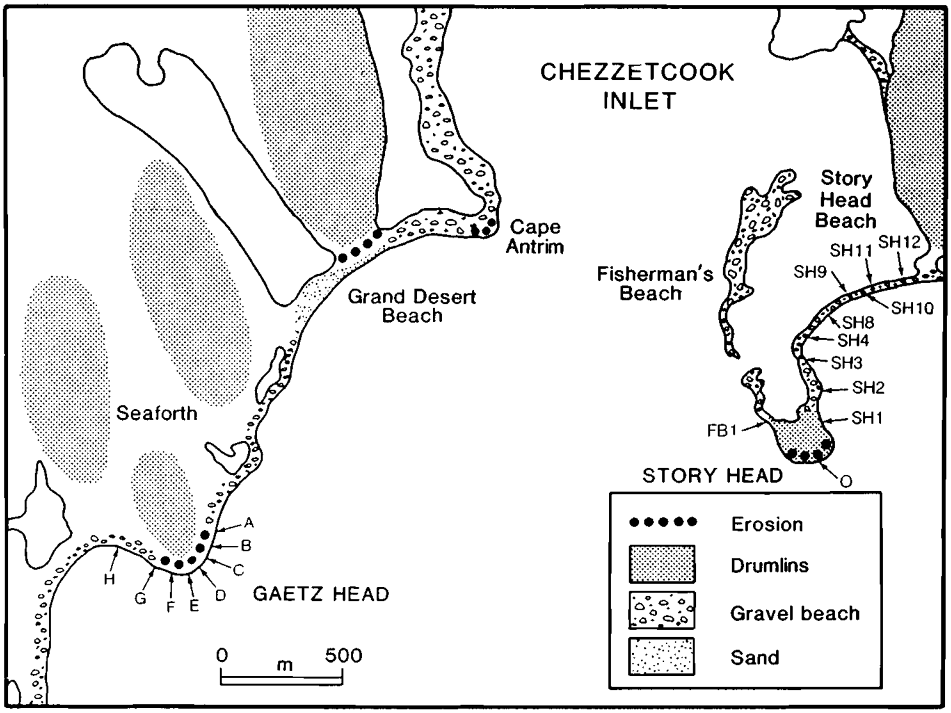


Figure 4. Locations of sampling points at Story Head and Gaetz Head.

shore profiles were surveyed and a record of sediment character was made.

As well as field measurements, a number of air photographs were examined, as these are ideal for revealing breaker angle, the variable at the crux of this debate.

RESULTS

Process Measurements Around Headlands

There are quite clear gradients in breaking wave heights alongshore at both Gaetz Head and Story Head (Figure 4, Table 1), with the median at the headlands (sites E and SH0) being 2 to 3 times greater than wave heights on the flanks. In both cases wave height 'peaks' are the headlands (Figure 5). As the wave height relationship to breaking depth is approximately invariant (*e.g.* VAN DORN, 1978), this ratio is largely responsible for the rapid increases in surf zone width evident from Table 1. Longshore variations in wave period at Gaetz Head showed only limited, non-systematic changes, although at Story Head the higher frequency waves at the time of observation displayed a certain variation between the headland and the flanking beaches. This may be associated with the appearance of secondary waves in the nearshore spectrum generated as crests pass over the complex drowned topography.

The angle of breaker approach (α_b) shows a consistent pattern at both Gaetz Head and Story Head. At the headlands the waves approach the shore orthogonally, with the angle increasing towards the flanks. This produces a drift reversal (see Figure 5) which is located at both headlands by the somewhat unsatisfactory but pragmatic method of interpolating between measuring sites. Downdrift from the headland, α_b increases to a maximum, and then decreases again as the shoreline curvature becomes more swash aligned (Figure 6A-D). The rate of change in the approach angle ($d\alpha_b/dy$) shows that maxima occur away from the actual headland (Figure 5C). A somewhat similar basic pattern can be discerned at Jeddore Head (Figure

Table 1. *Wave data from Gaetz Head and Story Head.*

Gaetz Head: 20 August 1988

	Wave height cm			Angle of Wave Approach[1]	Wave Period	Shore	Longshore Current Velocity*	Beach Slope[2] Degrees,	Surf Zone Width
Site	Md	LQ	UQ	degrees	sec	Material	m/sec	minutes	m
A	26	21	34	73	11.8	gravel/sand	−0.12	6.30	6
B	28	23	34	96	11.7	cobble/boulder	−0.09	7.20	10
C	34	23	44	125	13.1	cobble/boulder	0.27	6.20	32
D	39	30	57	111	12.3	boulder	0.15	5.50	28
E	53	42	61	97	13.8	boulder	0.27	3.30	40+
F	31	24	40	81	12.6	cobble/boulder	0.33	2.10	40+
G	14	12	20	67	14.9	gravel	−0.18	2.00	40+
H	15	13	18	89	11.7	sand/gravel	−0.01	4.40	2

Story Head: 28 August 1988

	Wave Height cm			Angle of Wave Approach	Wave[3] Period	Shore	Longshore Current Velocity*	Beach Slope Degrees,	Surf Zone Width
Site	Md	LQ	UQ	degrees	sec	Material	m/sec	minutes	m
SH1	22	14	26	86	3.5	Cobble/gravel	−0.09	n.d.	n.d.
SH8	26	18	33	88	6.5	Gravel/sand	−0.013	4 50	10.5
SH4	26	21	35	95	5.5	Sand	0.27	5 20	n.d.
SH3	12	9	15	97	4.7	Gravel/cobble	0.18	2 10	3
SH2	23	18.5	29	130	4.0	Gravel/cobble	0.28	7 40	n.d.
SH1	23.5	20	32	93	5.8	Gravel/cobble/boulder	0.15	2 50	n.d.
SH0	62	52	71	83	8.1	Large boulder	−0.06	n.d.	40+
FB1	48	32	56	64	6.4	Large boulder	−0.23	n.d.	40+

*Minus to the west n.d. not determined

Md = Median, LQ = lower quartile, UQ = upper quartile

[1] 90° directly onshore, < 90° from the observer's left, > 90° from the observer's right.

[2] Beach slope proved difficult to measure at Gaetz Head due to its highly irregular form, with boulders up to 1 m in length throughout the swash zone. Values given are averages across measured profiles.

[3] Variations in wave period are probably associated with the elimination or obscuring of smaller waves at the higher energy sites.

7) from air photographs. Figure 7, taken directly from a vertical print, shows waves approaching the headland itself at almost right angles, but becoming more oblique along the flank, before approaching at right angles once again at Oyster Pond Beach. Jeddore Head highlights a common phenomenon with these wave approach patterns, notably that the angle increases and decreases several times within a short distance on the headland flank (see inset on Figure 7). Vertical photographs of Story Head reveal an even more complex pattern (Figure 8), especially along the western flank (Fishermans' Beach) where the wave angle opens and closes several times over the length of spit.

Longshore currents are generated by both oblique wave thrust and/or lateral changes in wave height (KOMAR, 1976). Although in places wave angles approach the value of optimum thrust (45°), longshore currents rarely exceed 0.3 m/sec (Figure 5D). Longshore currents at both sites showed a marked divergence at the headland apex, as predicted by the MAY and TANNER (1973) model. At Gaetz Head the longshore current pattern was resolved into two distinct cells (Figure 5D), with the current accelerating to a maximum on the headland flanks and then decelerating to zero on the bay beaches. A similar current cell pattern was apparent on Story Head Beach, but incomplete measurements do not allow its full delineation.

The longshore partitioning of wave energy or power is clearly of fundamental importance to both the erosion and dispersal of headland material. Total wave power (P_N) was calculated from the formula

$$P_N = 0.0625\, \rho\, g\, H_b\, C_b\, n \qquad Jm_{-2}sec$$

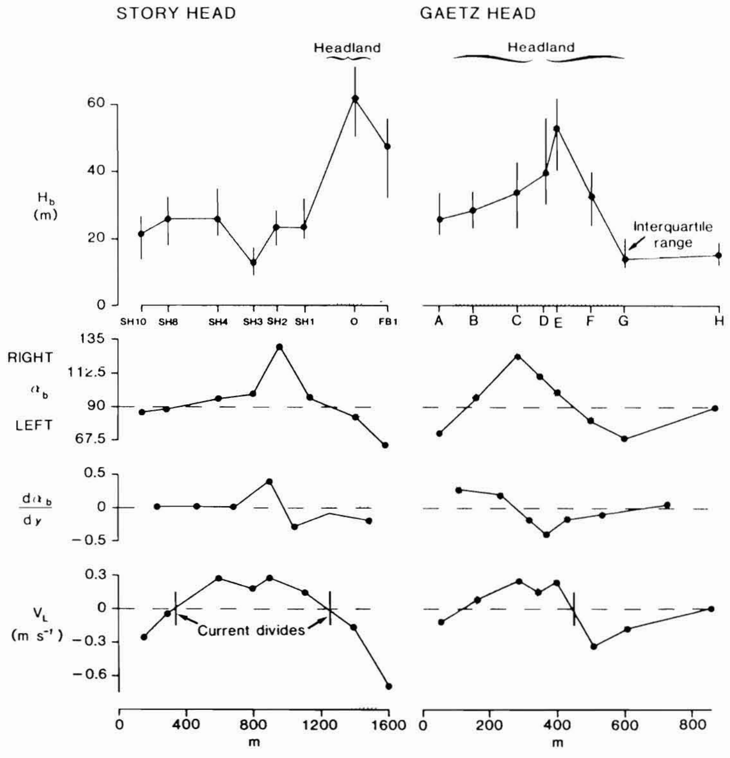


Figure 5. Measured longshore variations in breaking wave height, angle of breaker approach and longshore current at Story Head and Gaetz Head.

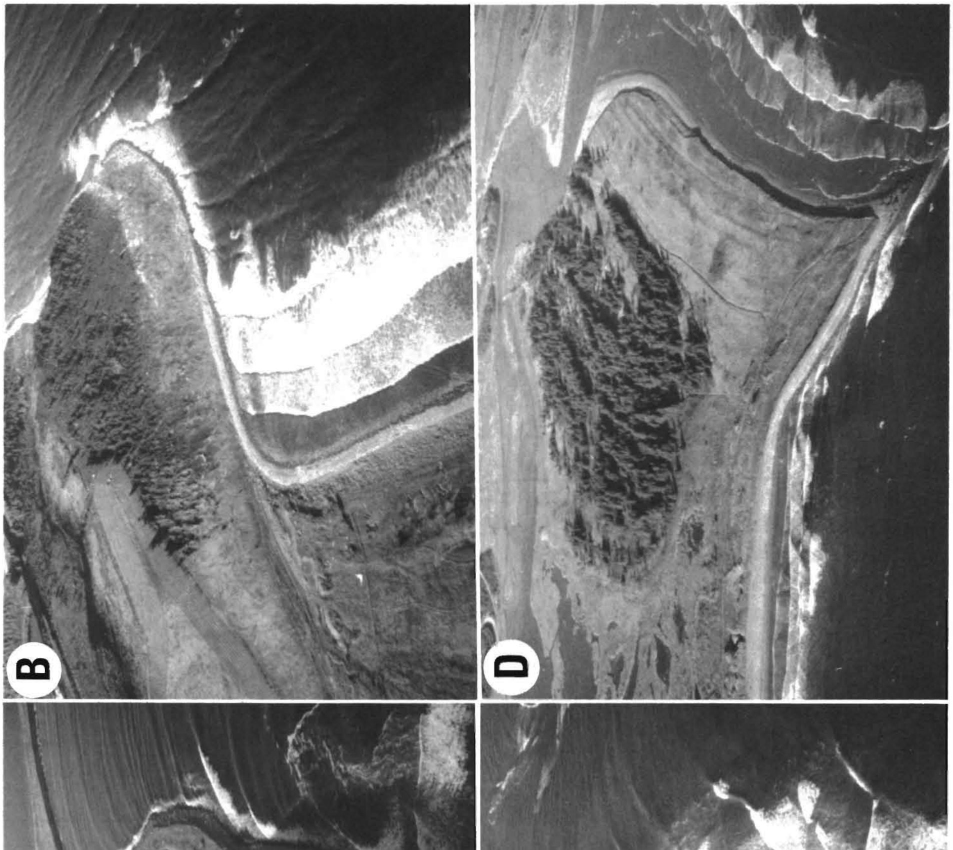
where ρ is the density of seawater, g is the acceleration due to gravity, C_b is the wave speed at breaking and n is a phase constant, which equals unity at breaking. The longshore component of wave power (P_L) is

$$P_L = P_N \cos \alpha_b \sin \alpha_b \qquad Jm^{-2}sec$$

Plots of P_L (Figure 9A) reveal the cell structure at the two headlands, including the nature and position of the drift divides. At each headland there is a very marked drift divergence, indicating that any transportable material will be moved rapidly alongshore, but in opposite directions. The lower graph (Figure 9B) indicates the percentage of longshore power relative to total wave power at each site. In this case, especially at Gaetz Head, it can be seen that P_L attains a maximum immediately adjacent to the headland divergence, and approaches the minimum towards the embayment convergence.

Morphology and Sediments

Changes in processes along the shore are reflected to some extent by both morphology and sediments. Surveys of the beach/cliff junction or notch around Gaetz head (Figure 10) indicate that this feature is at least a meter lower in front of the actively eroding headland than it is at those places where marine attack is absent. Clearly this is inversely related to wave height (and most likely wave run-up), and explanation would seem to lie more in the lateral transport and relative abundance of beach material. The beach profiles (C,E) immediately in front of the eroding cliff show that the run-up slope is incised into the boulder clay, while on the headland flanks (B) material has slumped down in places due to intermittent, sub-aerial instabilities. Further alongshore these simple concave profiles give way to more complex ridge forms (not shown).


A
B
C
D

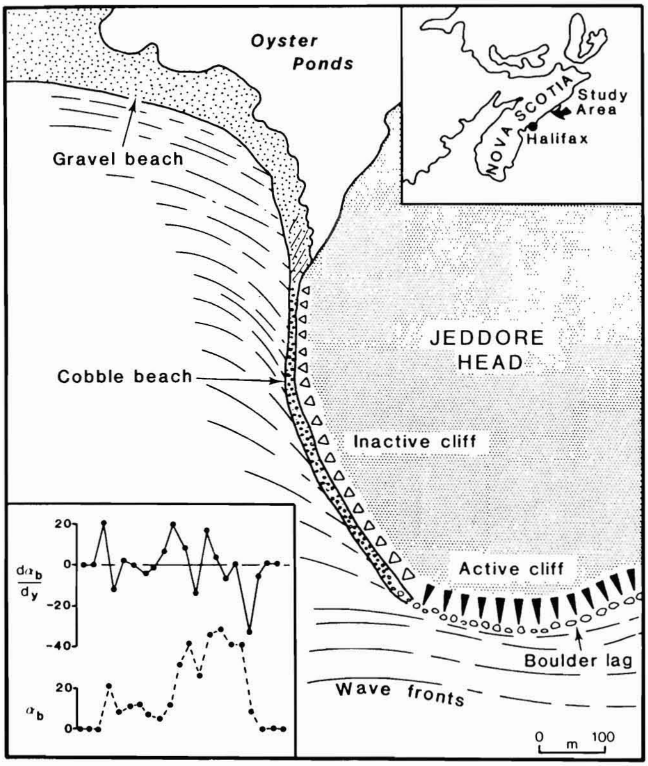


Figure 7. Variations in wave approach angle alongshore at Jeddore Head. Again both α_b and $d\alpha_b/dy$ (inset) rise and fall alongshore, indicating a series of sub-cells within the overall headland to bay gradient.

Material eroded from the headland is sorted and dispersed by wave and current action. We estimate (CARTER *et al.*, 1989) that only the coarsest 20% of the eroded sediment enters the headland beach transport systems with the other 80% being moved beyond the nearshore system into deeper water. At first the coarser material is sorted laterally, with the largest clasts (often > 1 m in diameter) forming the residual armoured scar left in the nearshore zone as the headland retreats. Some of the finer material tends to become trapped within this residue as an interstitial population, which may be partly remobilised through ejection during storms. However it is likely that lateral transport through this zone is relatively low. The headland shoreline around and seaward of the LWM evolves into a flat dissipative form, characterised by strongly spilling breakers. This is a direct contrast to the flanking beaches, which are highly reflective.

Figure 6 (*preceding page*). Four oblique air views (taken in September 1988) of Eastern Shore headlands. (A) Story Head shows a clear drift divide with two flanking barriers. While longshore wave gradients are very clear, note the considerable distance at the headland where waves are approaching almost normal to the shore. (B) Terminal Beach Head showing a single well-developed shoreline cell, within which the wave angle varies from zero at the headland to almost 90° and back to zero at the bayhead. (C) Half Island Point, showing the efficiency of flank erosion, where wave height plus longshore dispersal allow rapid cliff retreat. The headland itself is marked by two sub-aerial slumps which have not been removed by the sea. This pattern accentuates the headland promontory. (D) Fox Point, an example of a now-vanished drumlin source, but marked by a residual, narrow promontory. Note the beach ridge formation on the flanks, and the visual similarity to the May and Tanner proposal shown in Figure 1A.

Most probably some larger boulders escape from the lower foreshore in front of the headland, and move alongshore to form what BLUCK (1967) has termed the outer cobble frame (OCF), or in this case outer boulder frame (OBF). More rapid movement of small and medium sized clasts occurs in the gravel sorting zone (GSZ) below the HWM. This zone, usually 5 to 7 m wide and only one or two clasts thick,

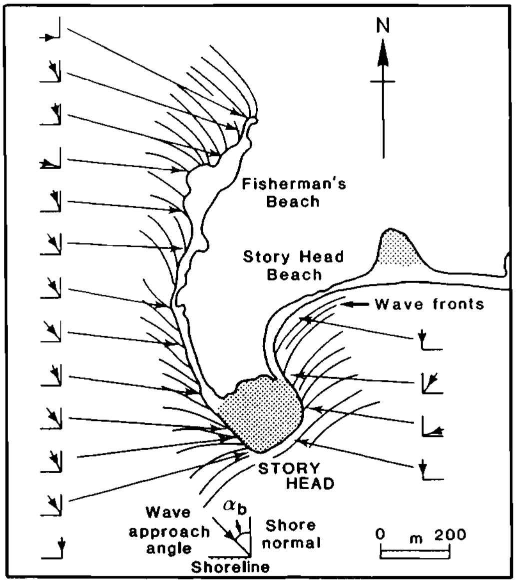


Figure 8. The complex sub-cell system associated with Story Head (also visible on Figure 6A). Within the overall gradient the morpho-sedimentary response (especially when the long-term supply is falling) is to develop secondary or sub-cells. Taken from Province of Nova Scotia air photo A14288-149, 1954.

is the main routeway for coarse material moving along the shore. At first this gravel sorting zone (GSZ) contains a heterogenous mixture of irregular sized and shaped clasts, but away from the headland this zone rapidly becomes sorted. In places the GSZ is formed of oblique transverse ribs extending down onto the cobble or boulder frame. At both Story Head and Gaetz Head these ribs are between 2 and 3 m apart and up to 0.25 m high. The downdrift side of the ribs comprises relatively large (ranging from 56 to 750 mm in one sample), imbricate clasts, while the updrift side is made up largely of smaller trapped infill. At the moment the exact origin of these ribs is unknown, although they may represent an immature rhythmic cusp form, associated with highly oblique run-up under strongly reflective wave conditions conducive to edge wave development. What is apparent is that the beach exchanges clasts between the OCF and the GSZ. At some times gravel is combed down from the sorting zone and incorporated in the frame as fill. At other times gravel is ejected from the frame and rejoins the more mobile sorting zone. The net result of this trading process is that transport rates are reduced, with the frame acting as brake on the longshore movement of material.

DISCUSSION

Headland erosion by marine activity consists of two processes. First material must be removed from the cliffs. This depends on the strength of the material and the force of the assailing waves (SUNAMURA, 1983). Headlands which protrude into deep water are able to 'capture' wave energy via wave refraction, so that wave heights and run-up are both enhanced. On this basis alone headlands are more liable to erosion. Second, erosion products must be removed from the base of the cliff. The mechanism most effective for removal depends on the material and characteristics themselves; thus fine-grained particles are dispersed by wave and tidal currents while coarser clasts are transported by nearshore surf and swash processes. As envisaged by MAY and TANNER (1973), headlands form important divergent boundaries. This is clearly borne out by our field measurements at both Story Head and Gaetz Head. Headlands are marked by a reversal in the longshore current, which is driven by oblique waves and, to a more limited extent by longshore variations in wave height (KOMAR, 1976). It is the presence of this current that is critical to the evolution of the headland, as it moves material from the apex towards the flanks. Notwithstanding the fact that the current may reverse over an infinitely small distance leading theoretically to high rates of change and a zone in which the current is accelerating, it will not necessarily exceed the entrainment threshold for the shoreline sediment. KOMAR (1985) is correct when he states that the maximum wave attack (measured in terms of total energy) in theory, takes place at the point of the headland, but he ignores two basic, although related, points. One, that equating power with erosion but without measuring transport effectiveness means that erosion in terms of headland migration is unlikely, and two, that any divergence in longshore processes must be accompanied by a null zone in which transport is not possible (*vide* MAY and TANNER 1973).

The immediacy of the moment, as epitomised

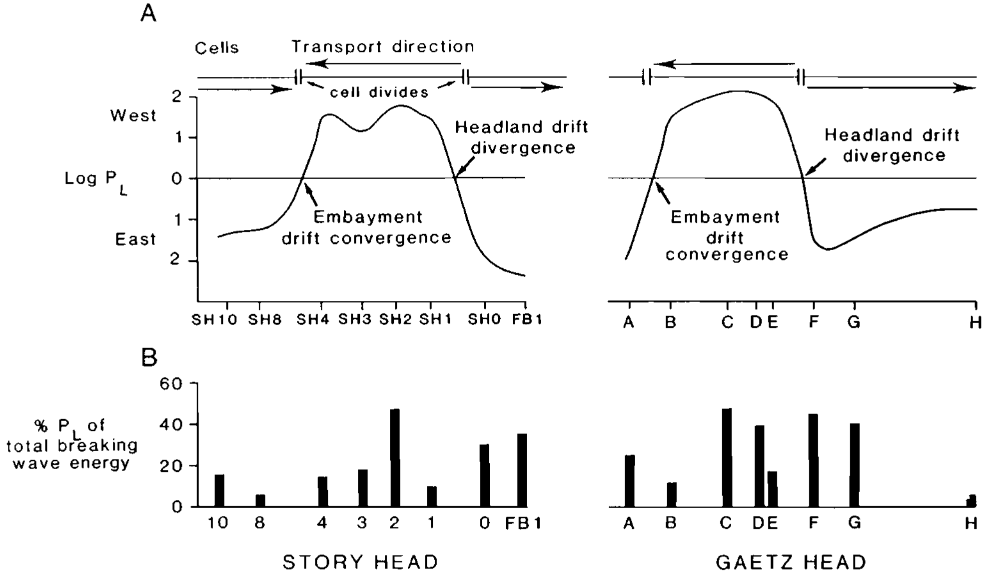


Figure 9. Littoral cell structures as defined by P_L values. These cells confirm the existence of divides. The pattern on both headlands is essentially the same.

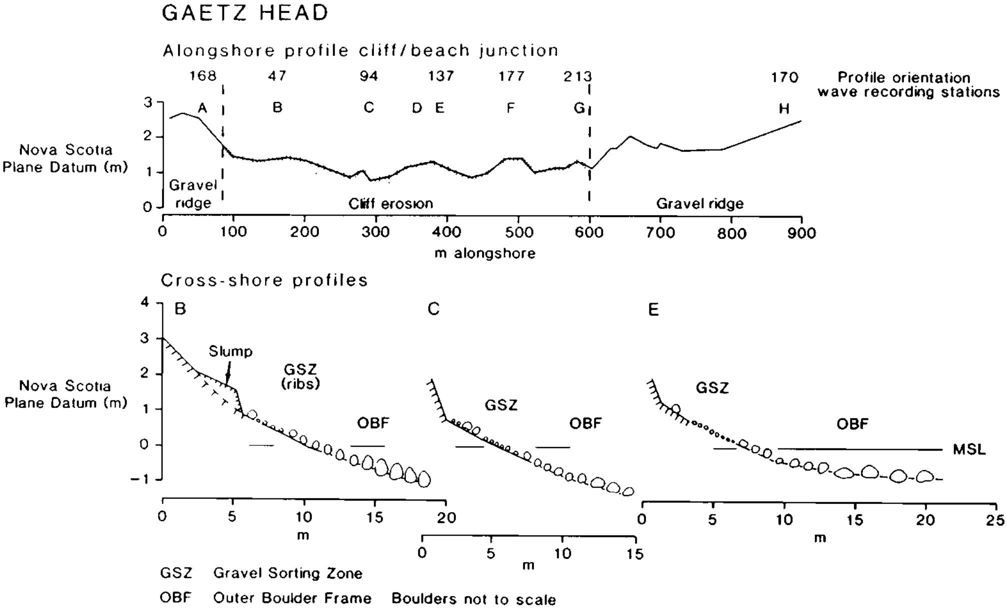


Figure 10. Longshore and cross-shore profiles around Gaetz Head.

by our field surveys, must be replaced by pragmatism about longer-term changes and the stationarity of the divide. Any open coast wave field will change through time, moreover, any wave spectrum may well include the effect of directional trends as well as significant variations in wave height. Therefore as waves incident on the shoreline change, so too will the associated longshore processes. The null point at the headland, referred to above, will migrate up and down the shore, sweeping the headland debris onto the flanks. (This factor alone will ensure that many headland planview profiles are rounded rather than pointed.) It is noticeable that the more rounded headlands on the Eastern Shore are further seaward in more exposed wave zones and adjacent to deeper water. In contrast, the more needle-like headlands (Figure 6) are in relatively sheltered positions where refraction has reduced directional variability in the wave field. Many of the Nova Scotian examples show an asymmetry which is due to a slight offset between the dominant wave direction and the alignment of individual drumlins. Over time, material is eroded from the flanks along the length determined by the effectiveness of the transport system (which leads to lower beach-cliff junctions). Eventually the headland becomes so narrow and unstable it collapses, causing rapid shoreline retreat. The Eastern Shore of Nova Scotia embraces an ergodic sequence of headlands conforming broadly to the May and Tanner model. In the most advanced example, Fox Point, the headland has all but vanished, leaving the beach ridges exposed. However the inheritance of the headland is retained in the refraction pattern (Figure 6D).

The sediment supply rate from eroding headlands will often be episodic, and the nature of this periodic availability may well influence longshore transport patterns and the evolution of the flank deposits. In addition the proximity of headlands to each other may serve to influence long-term erosion patterns (CARTER and ORFORD, 1988). On both the Nova Scotian coast and in western Ireland we have observed a well-established morphodynamic hierarchy controlling coastal evolution (CARTER *et al.*, 1989).

What is not revealed by the May and Tanner model or the Komar model is the strong organization that develops within the sediment dispersal system. The initial sorting of material by gross textural characteristics precedes a far more sensitive partitioning within restricted size, shape or lithological categories. Adjustments to the process gradients are manifest not only in terms of shoreline orientation but also textural and facies arrangements. At both Story Head and Gaetz Head shoreline processes are influenced strongly by the presence of the outer frame, introducing a flat-sloped, hydrodynamically rough element into the nearshore zone. In many cases roughness length equals or exceeds wave height, creating a highly dissipative system. One result of this is that actual longshore currents fall well below those predicted (Figure 11), a fact which must impair the transport efficiency of the littoral zone. If this constraint is added to that of moving finer material over a 'carpet' of coarse particles, then it is clear that sediment fluxes are doubly constrained. Thus erosion of these headlands is subject to strong negative feedbacks. This feedback is reinforced through the width and roughness of the OCF. Where the OCF is coarsest and widest the shoreline is largely dissipative, but where it is finer and narrower, more reflective conditions assume importance.

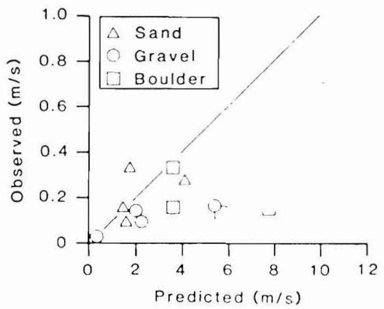


Figure 11. Actual versus predicted longshore current velocities around the two headlands.

CONCLUSIONS

Although limited, the process data collected around two actively eroding headlands tend to confirm the original cell structure postulated by MAY and TANNER (1973) in that headlands can indicate cell divides. KOMAR's (1985) objection is valid only inasmuch as he is correct in identifying the focus of erosion, but this does not account for the longshore transport condition needed to remove material eroded from the headlands. Initially, at least, on-shore/off-shore transport must also play a role in headland evolution, but in time as the drumlin shoreline becomes armoured this must be reduced. The examples from Nova Scotia illustrate that headland erosion can leave narrow promontories, but that short-term wave field variation and longer-term headland interaction may, in time, 'blunt' needle-like forms.

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☐ RÉSUMÉ ☐

Les processus associés à l'érosion des promontoires ont été débattus par May et Tanner (1973) et Tanner (1985). Plusieurs hypothèses ont été proposées sur le déroulement de l'évolution de ces formes. Des mesures de terrain ont été effectuées sur deux promontoires situés en Nouvelle Ecosse. Ces mesures révèlent une divergence de la dérive apicale et des forts gradients: de hauteur des vagues le long de la côte, des angles d'incidence et des courants dispersants associés qui érodent le matériel des flancs. Ce sont les transports littoraux qui finalement contrôlent l'évolution des promontoires, bien que l'érosion y soit maximum, et les promontoires en aiguille, prédits par May et Tanner ne sont en réalité pas aptes à se former n'importe où (variabilité du champ de houle). On observe sur les deux sites que lorsqu'il y a décroissance progressive de l'angle d'approche de la houle, le triage transversal et la répartition des sédiments érodeés montrent une réduction du transport potentiel, et par conséquent du taux d'érosion.—*Catherine Bressolier (Géomorphologie EPHE, Montrouge, France).*

□ RESUMEN □

Los procesos asociados a la erosión de los cabos han sido analizados previamente por diversos autores como May y Tanner (1973) y Komar (1985). El presente artículo presenta medidas de campo realizadas en dos cabos de Nueva Escocia; dichas medidas muestras una divergencia de transporte y gradientes longitudinales muy fuertes de altura de olas, ángulos de rotura y corrientes a lo largo de los flancos del cabo. Aunque el potencial de erosión es máximo en los cabos, es el transporte en las zonas adyacentes el que controla la evolución de los mismos. Los promontorios en forma de aguja descritos por May y Tanner son, en realidad, de ocurrencia muy improbable. En ambos lugares ensayados, la clasificación del sedimento, junto al progresivo decrecimiento del ángulo de alcance del oleaje, condujeron a una reducción del transporte potencial y, por tanto, a un descenso de la erosión.—*Department of Water Sciences, University of Cantabria, Santander, Spain.*

□ ZUSAMMENFASSUNG □

Die Prozesse, die die marine Erosion von Landspitzen—("headlands") steuern b2w. mit ihr assoziiert sind, wurden von MAY & TANNER (1973) und KOMAR (1985) diskutiert. Es bestehen divergierende Meinungen bezüglich einer sequentiellen Entwicklung der Headlands. Feldmessungen an Headland-Lokalitäten in Nova Scotia (Kanada) lassen eine apikale Driftdivergenz und starke "longshore"—Gradienten in Wellenhöhe, Brechungswinkel und Strömungen, die das orodierte Material entlang der Flanken verteilen, erkennen. Obwohl an den Headlands das Maximum des Erosionspotentials lieght, ist es letztendlich aber das Transportsystem entlang der Küstenlinie, welches die Entwicklung der Headlands kontrolliert—obwohl es in Wirklichkeit unwahrscheinlich ist, daβ die engen, nadelartigen Ausläufer ("promontories") von MAY & TANNER überall aufgrund der Variabilität im Wellenfeld gebildet werden können. An beiden Untersuchungspunkten bewirkt die Sortierung und Fraktionierung des erodierten Sediments aufgrund von Texturunterschieden, zusammen mit einer fortschreitenden Abnahme des Wellenwinkels, eine Reduzierung des Transportpotentials und somit eine Abnahme der Erosionstrate an den Headlands—*Ulrich Radtke, Geographisches Institut, Universität Düsseldorf, F.R.G.*