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Chapter 14

Modeling Shore Platforms: Present Status and Future Developments

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1. INTRODUCTION

A high proportion of the world's coasts are rocky, and much of it consists of cliffs with gently sloping shore platforms at their base. Most coastal research is presently concerned with beaches and other depositional features that change fairly quickly, and are vulnerable to rising sea level. Shore platforms, and the cliffs behind them, are an important source of sediment for estuaries and beaches, however, and the platforms are frequently covered by sandy or stony beaches, whose initiation, stability, and form are, in part, controlled by the morphology of their rocky foundations. We need to understand the dynamics and mode of evolution of cliffs and shore platforms to predict patterns and rates of erosion, to manage increasing levels of human activity, including housing, transportation, and recreation in coastal regions, and to determine how cliffs and shore platforms, and the beaches associated with them, will adjust to future rises in sea level. This chapter discusses a recent attempt to model shore platform evolution, and the modifications that need to be made to increase its general utility.

2. SHORE PLATFORM MODELING

Models have been frequently employed to predict rates of sediment transport by waves, wind, and tidal and other currents in the coastal environment, and to study the development and dynamics of beaches, dunes, barrier spits, deltas, and other coastal features. Modeling provides a particularly important means of investigating the long-term development of slowly changing rock coasts. The inherent complexity of these coasts makes it difficult, however, to adequately consider and represent all the variables that play a role in their development. For example, whereas there are only limited variations in the substrates of beaches, salt marshes, and sand dunes, there are enormous differences in the physical resistance of rocks, according to their chemical composition, the dip, strike, and thickness of the beds, joint density and orientation, the degree of weathering, the effect of biological activity, and many other factors. The morphology and dynamics of sandy beaches are largely controlled by waves and tides, salt marshes by tidal currents, and sand dunes by wind, but rock coasts are affected by waves, tidal variations, bioerosion, frost, chemical and salt weathering, wetting and drying, mass movements, and many other mechanisms. The relative and absolute importance of these mechanisms have also varied through time, with changes in climate and sea level, and with the characteristics of the rocks that are being eroded.

The earliest shore platform models were qualitative, and the platforms were considered in the context of an evolutionary cycle of erosion (Davis, 1896; Johnson, 1919; Challinor, 1949). Although a number of mathematical models have subsequently been developed, most have been concerned with erosion in tideless seas (Flemming, 1965; Horikawa and Sunamura, 1967; Scheidegger, 1970; Sunamura, 1976; 1977; 1978a). Japanese workers have developed mathematical models based on field data on wave height at the cliff base, and the compressive and impact strength of the rocks. Horikawa and Sunamura (1967) found that

$$\frac{dx}{dt} = C_R \cdot f \tag{1}$$

where dx is the eroded cliff distance in time dt, C_R is a coefficient representing the erodibility of the rocks, and f is the erosive force of the waves. This equation was modified using laboratory and field data from Japan (Sunamura, 1977)

$$\frac{dx}{dt} \propto \ln\left(\frac{f_w}{f_r}\right) \tag{2}$$

where dx/dt is the mean cliff erosion rate, f_w is the assailing force of the waves, and f_r is the resisting force of the rocks. Sunamura found that the ratio f_w/f_r can be approximated by $(\rho g H/S_c) + C$, where ρ is the density of sea water, g is the acceleration due to gravity, H is the wave height at the cliff base, S_c is the compressive strength of the rock, and C is a dimensionless constant. According to Sunamura (1982; 1992), the minimum height of a wave capable of eroding the base of a cliff (H_{crit}) is given by

$$H_{\mathrm{crit}} = \left(\frac{S_c}{\rho g}\right) e^{-\Gamma} \tag{3}$$

where Γ, a non-dimensional constant, is equal to $\ln(A/B)$. The value of A may reflect the abrasive effects of beach sediments, and B of discontinuities in the cliff material. Tsujimoto (1987) proposed that the assailing force of the waves equals A_p, where A is a non-dimensional constant representing abrasion, and p is the wave pressure. He suggested that the resisting force of the rocks equals BS_c^*, where B is a non-dimensional constant representing the effects of weathering, and $S_c^* = S_c(V_{pf}/V_{pc})$, where V_{pf}/V_{pc} is Suzuki's (1982) discontinuity index, the ratio of the longitudinal sound wave velocity measured in the rock body *in situ* and in cylindrical specimens without visible cracks in the laboratory, respectively. These Japanese studies have used variables that can be measured in the field, but although they have made valuable contributions to our understanding of rock coast processes, a myriad of other factors also need to be considered. They include the effect of tidal variations, the dip and strike of the rock, and the presence, mobility and quantity of the cliff-foot deposits and whether they function as a protective or erosive agent. It may be impractical at this time to use mathematical equations to represent the effect of many of these factors, and platform models may therefore have to rely, at least in part, upon empirical data.

Field evidence strongly suggests that most mechanical wave erosion occurs through processes that are closely associated with the water surface (Sanders, 1968; Robinson, 1977a; Trenhaile, 1987). Trenhaile (1983; 1989) and Trenhaile and Byrne (1986) modeled the evolution of shore platforms using expressions that represented erosion rates at the high and low tidal levels; this model did not, however, consider erosion rates at intermediate elevations. A previous attempt has been made to model inter-tidal wave erosion (Trenhaile and Layzell, 1981). This model was based on a limited number of variables, but it was the first to use tidal duration values, the total time each year that the water surface spends at each inter-tidal elevation, to calculate rates of erosion in macro- to microtidal environments.

Shore platforms and other elements of rock coasts develop very slowly, but although there have been marked variations in Quaternary sea level, most models have been concerned with the development of shore platforms and erosional continental shelves under stable sea level conditions. Only a few workers have considered the effects of changing sea level. They include Scheidegger (1962; 1970) and King (1963), who modeled the effect of a steady rise and fall in sea level on steep rock coasts; Sunamura (1978b), who modeled the development of erosional continental shelves, albeit in a tideless sea, during the Holocene transgression; and Trenhaile and Byrne (1986), who studied the effect of Holocene changes in relative sea level on the development of inter-tidal shore platforms. This latter model was also used to investigate the formation of continental shelves and coastal terraces with changing sea level over five glacial-interglacial cycles during the middle and upper Quaternary (Trenhaile, 1989). There have also been few attempts to investigate the effect of changes in the elevation of the land. Cinque et al. (1995) and Anderson et al. (1999) modeled the formation of erosional marine terraces on tectonically mobile coasts with Quaternary changes in sea level, but these models did not consider how wave energy is expended within the inter-tidal zone.

3. A TIDAL WAVE EROSIONAL MODEL

Basic wave equations are used in models that attempt to predict longshore and cross-shore sediment transport and beach profile evolution (Komar, 1976; Coastal Engineering Research Center, 1984; Horikawa, 1988; Trenhaile, 1997), but there has been little attempt to use them to investigate the long-term development of rock coasts. Therefore, although there have been significant improvements in our ability to model the evolution of shore platforms, until recently no models have considered the effect of such variables as breaker wave height and depth, the distance of the breaker zone from the shoreline and the minimum or threshold wave force capable of causing rock erosion.

A wave erosional model has recently been developed that uses basic wave equations to explore the interaction between wave dynamics, tides, coastal morphology, and rock erosion at the shoreline. The model has been used to study: the development of shore platforms under stable sea level conditions (Trenhaile, 2000); the contribution of weathering to platform evolution (Trenhaile, 2001a); the effect of variable sea level elevations in the last two interglacial stages on contemporary inter-tidal shore platforms (Trenhaile, 2001b); the evolution of shore platforms and erosional continental shelves on stable coasts during the Quaternary (Trenhaile, 2001c); and the formation of subaerial and submarine terraces in the Quaternary on tectonically mobile coasts (Trenhaile, 2002a). To avoid unnecessary repetition, only a fairly brief overview of the derivation and assumptions of this model are presented here: the reader is referred to Trenhaile (2000) for a more detailed discussion.

The most effective mechanical wave erosional processes are generally considered to be water hammer, abrasion, and especially air compression in joints, bedding planes, and other rock crevices (Everard et al., 1964; Sunamura, 1978c; Trenhaile, 1987; Sunamura, 1992). With the exception of abrasion, these processes are active in a narrow zone associated with the fluctuating waterline, where there are alternations of air and water. Abrasion by pebbles, sand or other coarse material can occur well below the water surface, but it is most effective in shallow water, and its efficacy rapidly decreases with decreasing agitation of the water at greater depths (Robinson, 1977b; Trenhaile, 1987; 1997). Large, unbroken waves can only attack cliffs that are standing in fairly deep water, and very few waves generate high shock pressures by breaking against steep, natural surfaces. Most mechanical wave erosion on gently sloping shore platforms is therefore accomplished by broken waves, and it is assumed that most of this erosion occurs at the water surface, at the surf-rock interface.

The elevation of the water surface, and therefore the level of most effective wave erosion, varies with the tide. The long-term elevation-frequency distribution of the mean water surface is bimodal, with maxima at, or close to, the mean high and low water neap tidal levels. Frequencies are roughly one-third lower at the mid-tidal level, and they decrease very rapidly from the neap maxima to the spring high and low tidal levels. As the tidal range decreases, the occurrence of the mean water surface becomes increasing concentrated between the neap tidal maxima (Carr and Graff, 1982; Trenhaile, 1987) (Fig. 1).

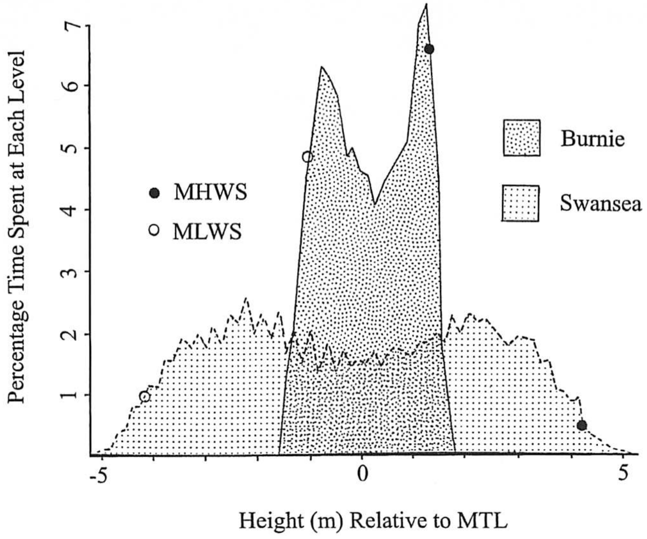

Figure 1. Tidal duration values (as a percentage of the time at each level) for a high (Swansea) and low (Burnie) tidal range environment (Carr and Graff, 1982). MHWS and MLWS refer to the mean high and mean low water spring tides, respectively.

The wave force (kg m^{-2}) generated at the breakers (F_b) is given by (Coastal Engineering Research Center, 1984)

$$F_b = 0.5\rho_w h_b \tag{4}$$

where ρ_w (1025 kg m^{-3}) is the unit weight of water and h_b is the breaker depth. Waves break when (Balsillie and Tanner, 2000)

$$H_b = 0.78 h_b \tag{5}$$

Therefore, from equations (4) and (5)

$$F_b = 0.5\rho_w\left(\frac{H_b}{0.78}\right) \tag{6}$$

where H_b is the breaker height (m). A decay function was used to represent surf attenuation

$$S_f = 0.5\rho_w\left(\frac{H_b}{0.78}\right)e^{-kW_s} \tag{7}$$

where S_f is the force of the surf at the waterline (kg m^{-2}), k is a surf attenuation constant, and W_s is the width of the surf zone (m). Deep water wave characteristics can be used to determine breaker height (m) using the expression (Komar and Gaughan, 1972)

$$H_b = 0.39\, g^{0.2}(T\, H_o^2)^{0.4} \tag{8}$$

where g is the acceleration due to gravity, and T and H_o are the period (s) and deep water height (m) of the waves, respectively. For each broken wave, the excess surf force that is available for erosion is equal to

$$0.5\rho_w\left(\frac{H_b}{0.78}\right)e^{-kW_s} - S_{\text{fmin}} \tag{9}$$

where S_{fmin} (kg m^{-2}) is the minimum or threshold surf force capable of rock erosion. With the addition of the tidal duration value (T_d hrs a^{-1}) and the number of waves over the iteration interval, the required equation for inter-tidal erosion at the waterline, at the head of the surf zone (E_y) is

$$E_y = M\sum_{W=1}^{N}\left(T_d\, W\left(512.61\left(\frac{H_b}{0.78}\right)e^{-kW_s} - S_{\text{fmin}}\right)\right) \tag{10}$$

where $0.5\rho_w = 512.61$ kg m^{-3}, M is a scaling coefficient (m^3 kg^{-1}), W is the hourly number of waves in each of N deep water height categories in the wave set, and E_y is the total erosion (m) accomplished by all the waves in the wave set at a specific inter-tidal level. This calculation must be repeated at the end of each iteration for each of the specified inter-tidal levels (for example, the mean high and low neap and spring tidal levels and mid-tide).

A decay function was used to represent slower rates of submarine erosion (E_s), which can occur in the upper portion of the inter-tidal zone during high tide, down to a depth equal to half the wavelength of the wave—the greatest depth at which significant interaction between a wave and the bottom is generally considered to take place

$$E_s = E_y\, e^{sh} \tag{11}$$

where s (m^{-1}) is a depth decay constant and h is the water depth.

The model requires tidal duration values for the study area for each of the required inter-tidal levels; these can be calculated from published tide tables (Smart and Hale, 1987). The initial surface could be either a simple linear surface with a specified gradient or a representation of an actual platform surface, depending on whether the intent is to model the long-term development of a rock coast or to predict how an existing platform might evolve in the future. The deep water height and period also have to be specified; this can be for a single wave or for a number of waves (a wave set) representing different portions of a wave spectrum. The degree to which erosion at the cliff base is reduced according to the amount and persistence of the cliff foot debris can be varied by multiplying the erosion that would occur at an unprotected cliff foot by a constant (<1), or by a variable related to cliff height and debris mobility. To consider the long-term development of rock coasts it is also necessary to include changes in sea level and possibly, depending upon the area of interest, changes in the elevation of the land (Trenhaile, 2001c; 2002a)

The derivation of the values for the various constants used in the model has been discussed elsewhere (Trenhaile, 2000; 2001b; 2001c), and will not be repeated at length here. In general, because of a lack of relevant field data, it was considered important to use a wide range of reasonable values. For example, surf forces generated at the shoreline for different k-values and surf zone widths (equation (7)) suggested that with S_{fmin} values between 20 and 1000 kg m^{-2}, erosion of the most resistant rocks would only occur with the highest breakers and the steepest and narrowest surf zones, whereas erosion of the weakest rocks would occur for all but the lowest breakers and the widest surf zones. Suitable k-values were calculated in a similar way, using equation (7) to determine the proportion of the breaker wave force reaching the surf-rock interface for a range of surf zone widths and k values. It was concluded that k-values of 0.1 and 0.01 could represent high rates of attenuation in very irregular surf zones and low attenuation rates over smooth and even surf zones, respectively.

Erosion rates per model iteration, as calculated by equation (10), are consistent with annual erosion rates measured in the field (tabulated, for example, by Sunamura, 1973; Kirk, 1977; Sunamura, 1992). Nevertheless, although each iteration appears to be roughly equivalent to one year, uncertainty over the value of the constants M, k and S_{fmin} requires caution in converting model iterations into real time units. Therefore, until reliable field data are available for model calibration, a range of values should be used for each variable to compensate for the effect of over- or underestimation of the annual rate of erosion, as well as to represent a wide range of natural environments.

3.1. Future Developments

The model has reproduced the morphology of contemporary shore platforms and erosional continental shelves, and replicated the relationships that exist in the field between tidal range and platform gradient and between other morphological and morphogenic variables (Trenhaile, 1978; 1987; 1999). To use the model to predict rates of cliff and platform erosion over fairly short time scales, however, as opposed to the very long time scales appropriate to geological investigations, would require the constants to be determined in the field. For example, because we lack an acceptable theory to describe water movement in the surf zone, k-values, which describe the relationship between surf attenuation rates and the roughness of bottom, will have to be determined from field data. The data should encompass a variety of geological conditions, ranging from horizontally bedded to steeply dipping rocks of variable resistance to erosion, striking parallel or perpendicularly to the shore.

The model is based on the assumption that the amount of erosion that occurs at each elevation is a function of the tidal duration distribution, the total time that the water surface spends at each elevation per year. There is also a relationship between wave energy and the elevation of the water surface, however, the most energetic waves occurring during storms, when the sea is raised above its tidal level. To incorporate this factor in the model requires analysis of the relationship between wave height and differences in predicted and recorded sea levels.

Many rocky coasts are irregular, consisting of a series of headlands and embayments, and because of wave refraction there are marked longshore variations in the energy reaching the coast. Theoretical considerations suggest that the plan shape of irregular rock coasts may ultimately attain a quasi-equilibrium state, when the erosion by refracted waves on the harder rocks of the exposed headlands becomes equal to the erosion by weaker waves operating on the less resistant rocks in the sheltered bays; this has important implications for the prediction and explanation of spatial and temporal patterns of cliff recession on rocky coasts. A three-dimensional version of the model, incorporating a wave refraction/diffraction subroutine, is needed to investigate this possibility, and whether there has been enough time during Quaternary interglacial stages to accomplish it (Trenhaile, 2002b).

3.1.1. Downwearing

The model is based on the assumption that cliffs and shore platforms develop through horizontal erosion, or backwearing, caused by mechanical wave erosional processes that are closely associated with the water surface. Annual rates of vertical erosion, or downwearing, ranging from about a tenth of a millimeter up to tens of millimeters, suggest that weathering and bioerosion, as well as abrasion where there is a beach at the cliff foot, are also important erosional processes. Downwearing can probably be ignored in attempting to predict the effect of rising sea level on cliffs and shore platforms over the next few decades, but it has serious implications for modeling their long-term evolution. Several workers have suggested that the negative feedback relationship between wave attenuation and the gradient of the bottom implies that shore platforms must ultimately develop a constant or equilibrium gradient and width (Edwards, 1941; Bird, 1968; Trenhaile, 1972), and this has been supported by the results of several wave erosional models under constant and oscillating sea level conditions (Sunamura, 1978a; Trenhaile and Layzell, 1981; Trenhaile, 1983; 2000; 2001c). The role of downwearing on platform evolution and equilibrium must be considered in future modeling, however, not only because of its direct effect on platform morphology, but also because of its indirect influence on wave attenuation rates and patterns.

Most precise measurements of platform downwearing have been obtained using micro-erosion meters—an instrument which consists, in its simplest form, of an engineer's dial gauge that records the downward extension of a probe, mounted on a low, triangular frame. In use, the meter sits on three bolts embedded in the rock surface (High and Hanna, 1970; Stephenson, 1997a). Micro-erosion meters cannot record wave quarrying or frost riving of large rock fragments and joint blocks, and although they can measure small amounts of platform lowering, the responsible processes must be inferred from the spatial and temporal characteristics of the erosional data. In several studies, the occurrence of faster downwearing rates in the summer when air temperatures are higher and wave action is generally weaker than in winter, has suggested that weathering rather than wave action is responsible for platform lowering (Robinson, 1977a; Mottershead, 1989; Stephenson and Kirk, 1998). Mechanical wave erosion is most effective on platforms where there are scarps in horizontal or gently dipping rocks, or upstanding strata in steeply dipping rocks, which facilitate air compression in bedding planes, joints, and other rock crevices. Conversely, broken waves crossing smooth, gently sloping profiles that lack pronounced irregularities may be ineffective erosional agents. Shear stresses and dynamic forces under broken waves on a platform in New Zealand, for example, did not exceed the compressive strength of the rock (Stephenson and Kirk, 2000a). It is unlikely, therefore, that platform downwearing measured by micro-erosion meters can be ascribed to wave action, unless there are abrasives present.

Robinson (1977a) obtained a mean erosion rate of 1 mm yr^{-1} on a gently sloping shale platform in northeastern England, which he attributed to dessication of the shale in summer and subsequent removal of the loose fragments by waves. Abrasion is important on the more steeply sloping ramp at the cliff foot, where there is a sand and pebble beach, and it is most active in winter when the waves are largest. Ramp erosion rates, which vary from 1 to 30 mm yr^{-1}, are strongly influenced by the depth of the deposit and possibly by grain size. In southwestern England, a seven year record indicated that greenschist in the supratidal zone is being lowered at a mean rate of 0.625 mm yr^{-1}. Rates are much faster in summer than in winter, which suggests that the main erosive processes are crystallization and thermal expansion of halite from spray (Mottershead, 1989). Micro-erosion meters have been employed recently in the ESPED (European Shore Platform Erosion Dynamics) project, a multi-institutional, multidisciplinary study of European rock coasts. Although much of the data are not yet publically available, Foote et al. (2001) reported that there are considerable variations in the average rates of downwearing on the chalk platforms of southern England and northern France, ranging from 8.83 to 0.68 mm yr^{-1}. In southern Australia, Gill and Lang (1983) found that the average downwearing rate on primarily greywacke platforms is 0.37 mm yr^{-1}, compared with a mean backwearing rate, which is fastest at the cliff base, of 9 mm yr^{-1}. The 20 year record of Stephenson and Kirk (1996) indicated that the mainly mudstone platforms of the Kaikoura Peninsula in New Zealand are being lowered at a mean rate of 1.43 mm yr^{-1}.

Differences in tidal duration values and bottom gradients account for spatial variations in the efficacy of mechanical wave erosion in the model, whereas changes in such factors as breaker depth and height and the width of the surf zone, which vary with bottom gradients, are responsible for temporal variations. To model downwearing by abrasion and weathering we need to determine if there are any spatial and temporal patterns in its occurrence. Only a few investigations have employed sufficient micro-erosion meter sites along shore-normal profiles to compare rates of downwearing with elevation, relative to the tides. Robinson (1977b) found that downwearing is fastest on the highest, most landward part of the shore platform in northeastern England, and it also increases landwards on the ramp at the cliff base. Foote et al. (2001) found a persistent bi-modal distribution on the chalk platforms of southern England and northern France, with a downwearing maximum in the abrasion zone near the cliff foot, and a secondary maximum on the central portion of the platforms. Kirk (1977) reported that downwearing rates are higher on the inner and outer margins of platforms on the Kaikoura Peninsula in southern New Zealand, but Stephenson and Kirk (1996), using a much longer record, found that rates are generally higher in the inner landward areas and decrease seaward.

Plotting downwearing rates, using data from a number of studies, failed to reveal any relationships with elevation (Fig. 2). Rates are higher along some profiles near the base of the cliff, but there is little evidence in these studies of any persistent trend down the platform with decreasing elevation. Most of the data in each of the studies were obtained from platforms with similar morphology and rock type: Gill and Lang's (1983) data were almost entirely from horizontal, supratidal greywacke platforms; Foote et al.'s (2001) from sloping chalk platforms; and Robinson's (1977b) from sloping shale platforms. On the Kaikoura Peninsula, however, the data were from mudstone platforms that either slope gently into the sea, or terminate abruptly seaward in a low tide cliff, the former having lower compressive strengths than the latter, or from gently sloping platforms in limestones. Stephenson (1997b) identified several significant relationships by correlating downwearing rates against elevation, the frequency of tidal wetting and drying cycles, and cross-shore location for each of the three morphological and lithological categories (Table 1). Multiple regression demonstrated that elevation was the significant variable for both types of mudstone platform ($R = 0.72$ for platforms that slope into the sea, and $R = 0.6$ for platforms with low tide cliffs), although distance from the seaward edge was the significant variable for the sloping limestone platforms ($R = 0.57$). Although much of the variance was unexplained by elevation, the Kaikoura data suggest that downwearing rates in platform models should be a function of the elevation of the site. Stephenson's (1997b) data also suggest that the decline in inter-tidal downwearing rates with elevation, and consequently with the number of wetting and drying cycles, is about three times greater on the mechanically weaker (sloping platforms) than on the mechanically stronger (horizontal platforms) mudstones. Mudstones are particularly susceptible to alternate wetting and drying, however, and it remains to be determined whether the same relationship occurs in other types of rock, or where other downwearing processes are dominant; the lack of a relationship between downwearing rates and elevation in other studies, as well as on the limestones at Kaikoura, suggests that it may not.

Although high values from abrasion are to be expected at the rear of some platforms, one would also expect to find that downwearing rates vary down a platform according to changes in the frequency and duration of tidal inundation events; this would also imply that these rates vary through time, as the surface is lowered. The lack of strong relationships between downwearing rates and site elevation and time is therefore surprising. If platforms are lowered at a constant rate, with typical downwearing rates of 0.5 to 1 mm yr^{-1}, they would have been reduced by 1.5 m to 3 m in the approximately 3,000 years since the sea reached its present level in much of the northern hemisphere, and 3 m to 6 m in much of the southern hemisphere, where sea level reached its present level about 6,000 years ago. It is difficult to accept that this degree of downwearing has actual taken place. Rapid downwearing cannot be reconciled with the occurrence of last interglacial beach deposits (probably 120,000 to 130,000 years in age) on the landward portions of shore platforms in Galicia, northwestern Spain (Trenhaile et al., 1999), or with inherited shore platforms of last interglacial age in southern Australia (Bryant et al., 1990; Young and Bryant, 1993; Brooke et al., 1994). This paradox is unlikely to be resolved, however, until we have a much larger body of downwearing data, collected from a greater variety of sites and over much longer periods of time than is presently available.

It is even more difficult to determine mean rates of erosion and the spatial and temporal effects of microflora and a host of grazing and boring marine organisms in different environments. Much of the available data are simply estimates; some refer to the erosion rates of single organisms, some to the total bioerosion accomplished by all organisms, and some to all the erosion accomplished by all agencies including marine organisms. The distribution of organisms in the vertical plane is of crucial importance. Tides determine the availability of water, and the time that each part of a

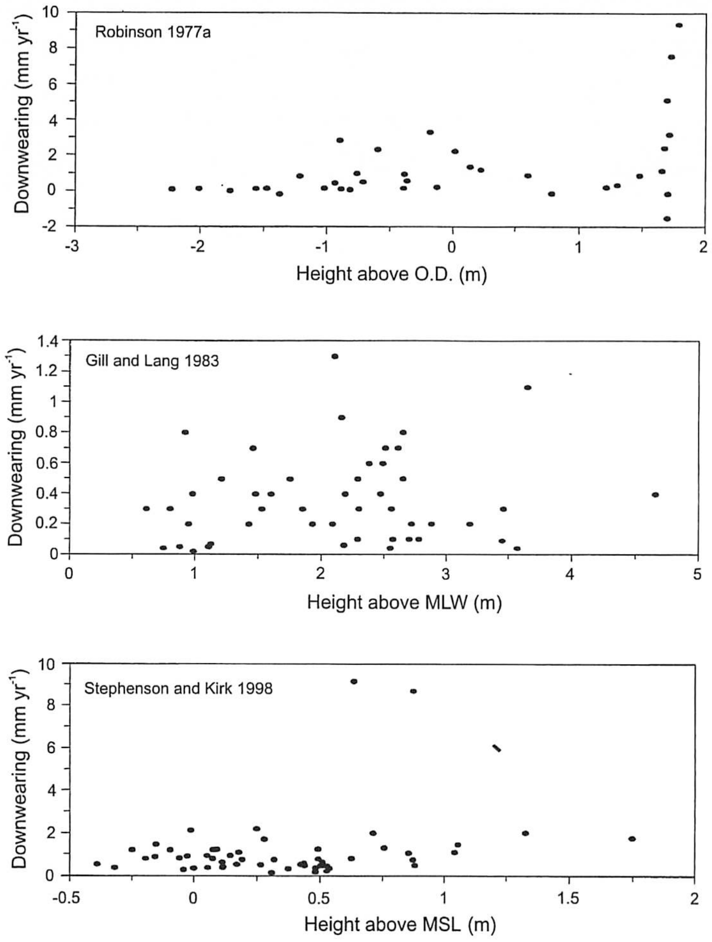

Figure 2. Micro-erosion meter downwearing rates and elevation. Elevations are expressed according to the data used by the authors. Because the datum of Gill and Lang corresponded to a biological horizon in the field, and therefore was poorly defined, and also because no direct comparisons were made between the three studies, no attempt was made to standardize the data. O.D. refers to ordnance datum, MLW to mean low water, and MSL to mean sea level.

Table 1

Correlation coefficients between downwearing rates and elevation, wetting and drying frequency, and location on the shore platforms of the Kaikoura Peninsula, New Zealand (Stephenson, 1997b).

Platform Lithological and Type	Number of Profiles[2]	Number of MEM[3] Stations	Elevation Above Mean Sea Level	Number of Wetting and Drying Cycles	Distance from Seaward Edge
Mudstone 1[4]	2	17	0.721[1]	0.621[1]	0.691[1]
Mudstone 2[4]	3	24	-0.23	0.601[1]	0.411[1]
Sloping, Limestone	2	14	-0.27	0.32	0.541[1]

[1] Significant at the 0.05 level

[2] Shore normal profiles from the cliff to the seaward edge

[3] Micro-erosion meter

[4] Mudstone 1 platforms slope into the sea whereas Mudstone 2 platforms terminate abruptly seaward in a low tide cliff. Mudstone 1 also have lower compressive strengths than Mudstone 2.

platform is inundated or exposed to dessication, and they play a crucial role in determining zonation and species composition. Wave intensity and the nature of the substrate also determine the occurrence and efficacy of erosive organisms. In general, biological activity is probably most active in the lower inter-tidal and sub-tidal zones, particularly where dessication occurs for long periods in the upper inter-tidal and supratidal zones of areas with a significant tidal range. It is generally considered to be most effective on tropical calcareous rocks, however, which appear to be eroding at rates of about 1 mm yr^{-1}, possibly reflecting the boring rate of endolithic microflora (Schneider and Torunski, 1983), and it does not appear to be a dominant factor on shore platforms in cooler, more vigorous wave environments at higher latitudes.

4. DISCUSSION

Loose blocks of rock and fresh erosional scars often testify to the importance of backwearing by wave quarrying during high intensity, low frequency events. Because we are only able to measure and document small amounts of platform downwearing with micro-erosion meters, however, there is a danger that downwearing will be assumed to be more important than backwearing on shore platforms today. Most micro-erosion meter data suggest that in the absence of abrasion, downwearing rates generally range up to about 1 mm yr^{-1}. For a 150 m wide platform, this maximum figure is equivalent to removal of 0.15 m^2 yr^{-1}, which would be matched by annual removal of a joint block along the shore-normal profile, 38.7 cm by 37.7 cm in size. Whether this takes place depends upon the morphogenic and geological environment. Backwearing is more important than downwearing in wave-dominated environments if there are favorable geological conditions. In the Vale of Glamorgan in southern Wales, for example, downwearing processes fail to penetrate the horizontally bedded limestones before the rock is removed by backwearing of the scarps (Trenhaile, 1972). Conversely, wave quarrying and backwearing are secondary to downwearing processes on the mudstone platforms of the Kaikoura Peninsula in New Zealand, where the waves are highly attenuated and pronounced rock scarps are generally absent (Stephenson and Kirk, 1998; 2000a; 2000b).

The roles of backwearing and downwearing in the development of shore platforms vary both spatially and temporally. Many factors determine their relative and absolute importance, including: the stage of platform development, equilibrium morphology; bed dip and thickness; offshore slope; the chemical and physical composition of the rock; the orientation of discontinuities, bed thickness, joint density; wave and tidal environments; and climate. Although we do not really understand how such factors as slope gradients or tidal inundation/exposure ratios influence the efficacy of downwearing mechanisms, it is possible to speculate on how they might vary through time. Mathematical models suggest that shore platforms become progressively wider and more gently sloping as they evolve, at least until they attain an equilibrium morphology (Sunamura, 1978a; Trenhaile, 2000; 2001c). During the early stages of development, higher gradients would facilitate mechanical wave erosion because of low wave attenuation, higher wave pressures generated against steep structures, and air compression in bedding planes and joints that face, and are accessible to, the approaching surf front. Steep surfaces also drain quite rapidly, and downwearing may not be rapid enough at this time to penetrate strata before they are removed by wave quarrying and backwearing. As gradients become progressively gentler, increasing wave attenuation and less accessible rock crevices reduce the efficacy of the waves, and downwearing must become relatively, and in some cases absolutely, more important. The roughness of the surface must also be considered. Uneven platforms, which generally reflect the occurrence of horizontal or dipping beds of variable resistance to erosion, allow waves to exert high forces in crevices and against scarps and upstanding beds of rock, although there may also be effective bioerosion in pools of standing water in the intervening troughs. Smooth platform surfaces generally develop in rocks that are weak and thinly bedded, or in fairly homogeneous rocks that lack marked variations in their erosive resistance. Mechanical wave erosion can operate on smooth platforms in well jointed rocks when they are still steep, but downwearing is likely to become progressively more dominant as gradients decrease through time.

The model primarily attributes platform development to the distribution of wave energy within the inter-tidal zone, and it is therefore suitable for environments dominated by wave quarrying of coarse, weathered or unweathered, material (Trenhaile, 2000; 2001a). It cannot be used, however, if the role of the waves is limited to washing away fine-grained, weathered material. Stephenson and Kirk (2000b) proposed that the mainly mudstone platforms at Kaikoura in southern New Zealand have developed in the vertical zone where tidal wetting and drying operate most frequently, and this is supported by the moderately strong relationship that exists in this area between downwearing rates and elevation (Stephenson 1997b). A program was written to calculate the annual number of wetting and drying cycles from predicted high and low tidal levels, in mainly semidiurnal tidal environments. The frequency distributions are single modal, with flat summits representing the zone of most frequent wetting and drying, which extends from the lowest of the neap high tidal levels to the highest of the neap low tidal levels, with the ratio of the period of drying to the period of wetting increasing with elevation within this zone. The maximum value is essentially constant for semidiurnal tidal regimes (2 cycles per day), although it is lower for mixed, and especially for diurnal regimes. The vertical extent of the zone of most frequent wetting and drying increases with the tidal range, and frequencies decrease very rapidly at higher and lower elevations, (Fig. 3). The relationship between tidal duration and wetting and drying frequency distributions and tidal range therefore provides a possible explanation for the global relationship between mean regional platform gradient and tidal range (Trenhaile, 1978; 1987; 1999), irrespective of whether the platforms are dominated by wave quarrying or by weathering (Fig. 4). Assuming that alternate wetting and drying of argillaceous rocks can undercut cliffs and produce shore platforms, as opposed to lowering and otherwise modifying wave-cut platforms, their development can be modeled by substituting tidal wetting and drying frequency distributions for tidal duration distributions.

There is a fundamental problem with all theories that attribute platform formation to subaerial (Bartrum, 1916) or inter-tidal (Stephenson and Kirk, 2000b) weathering, while relegating the role of

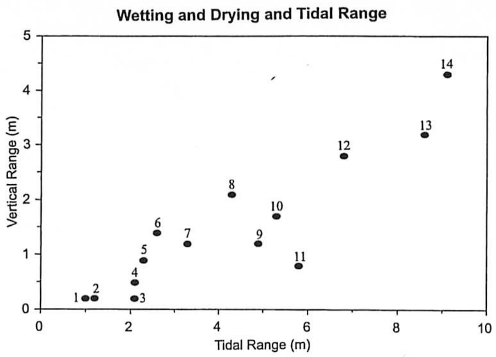

Figure 3. The relationship between the vertical extent of the zone of maximum wetting and drying frequency and spring tidal range for: (1) Apia, Samoa; (2) Bergen, Norway; (3) Kuantan, eastern Malaysia; (4) Halifax, eastern Canada; (5) Taku, northern China; (6) Mersey River, Tasmania; (7) Lisbon, Portugal; (8) Margate, southeastern England; (9) Mackay, northeastern Australia; (10) Prince Rupert, western Canada; (11) Port Hedland, northwestern Australia; (12) Le Havre, northern France; (13) Swansea, south Wales, UK; and (14) St. John, eastern Canada. All sites have semidiurnal tidal regimes, with the exception of Kuantan, which is mixed.

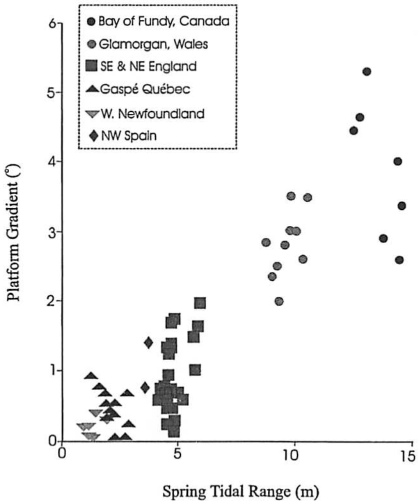

Figure 4. Regional mean shore platform gradient and spring tidal range. Each data point represents the mean of a large number of surveyed profiles.

the waves to removal of the fine-grained debris. This is concerned, in the absence of a role for wave strength and attenuation, with the apparent lack of a mechanism responsible for determining maximum platform width. Whereas wetting and drying produces fine-grained material that can be washed away by weak waves, however, cliff undercutting can bring much coarser, unweathered material down to the back of the platform. Platform width may therefore be limited by the eventual inability of attenuated waves to remove this debris. Modeling the development of platforms dominated by alternate wetting and drying would therefore require both a modified version of equation (10), to determine rates of debris removal according to the strength of the broken, attenuated waves, and a downwearing equation based on tidal wetting and drying frequency distributions and downwearing-elevation relationships to determine rates of cliff erosion and platform lowering.

Other types of downwearing mechanisms probably have different spatial and temporal relationships from wetting and drying, and would therefore have to be represented in a different way in the model (Trenhaile, 2001a). Tidally induced frost action occurs when inter-tidal rocks freeze in air during low tide and thaw in water during high tide. Theory, and field and laboratory experimentation, have suggested that this mechanism is most effective in the upper inter-tidal zone, which experiences the longest periods of exposure during tidal cycles (Robinson and Jerwood, 1987a; 1987b). Salt weathering, by hydration and crystallization, is also dependent on the degree of exposure of the platform surface, and is therefore probably most effective in the upper inter-tidal zone, where there is the greatest variation in temperature and moisture content. Bartrum (1916) first proposed that shore platforms in sheltered locations are formed by weak waves washing away weathered material above an inter-tidal level of permanent sea water saturation. More recent field and laboratory investigations have shown that the water content in surface rocks gradually decreases from the high to the low tidal level, however, which suggests that there is a corresponding decrease in the intensity of chemical weathering down the inter-tidal zone (Trenhaile and Mercan, 1984).

5. CONCLUSIONS

Platform models must consider erosive conditions within the inter-tidal zone, and they must also be flexible enough to encompass the wide range of wave, tidal, and geological conditions that occur in the field, as well as changes in sea level and climate. The model described in this chapter is the first to use basic wave equations to simulate the erosion of rock coasts in the inter-tidal zone. In its present form it can be used to study the long-term evolution of wave-dominated coasts with geological conditions that facilitate the formation of seaward-facing scarps or other upstanding irregularities. Field calibration of the constants in the model would also permit its use to predict platform and cliff erosion in specific areas with rising sea level, over much shorter time scales.

Although there have been several attempts to model shore platforms, they are all based on the assumption that platforms develop through wave erosion operating in the horizontal plane. The model in its present form does not consider the effect of bioerosion, weathering, or other downwearing mechanisms, although micro-erosion meter data suggest that they are important and in some cases dominant factors on some platforms today. The model can be modified fairly simply to allow downwearing processes to operate in conjunction with wave generated backwearing, but although we have a growing body of data on downwearing rates in different environments, it is unclear at present how spatial and temporal variations with changing elevation should be represented.

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LIST OF SYMBOLS

E_s — amount of submarine erosion each year (m)
E_y — amount of inter-tidal erosion each year (m)
F_b — wave force at the breakers (kg m^{-2})
g — acceleration due to gravity (m s^{-2})
h — water depth (m)
h_b — breaker depth (m)
H_b — breaker height (m)
k — surf attenuation factor related to bottom roughness
M — coefficient (6.5 x 10^{-10} to 3.25 x 10^{-8} m^3 kg^{-1}) to convert the excess surf force into the amount of inter-tidal erosion during each model iteration
MHWS — mean high water spring tidal level
MLW — mean low water
MLWS — mean low water spring tidal level
MSL — mean sea level
MTL — mean tidal level
N — number of deep water wave categories used to represent the spectrum
O.D. — ordnance datum
p — wave pressure
s — submarine erosion depth decay constant (m^{-1})
S_f — surf force at the waterline (kg m^{-2})
S_{fmin} — threshold erosional strength of the rocks (kg m^{-2})
T — wave period (s)
T_d — tidal duration value, the time each year that the water level occupies each inter-tidal elevation (hr yr^{-1})
W — hourly number of waves of each of the five deep water heights gradient of the bottom extending from the breakers to the waterline
W_s — surf zone width (m)
ρ_w — unit weight of sea water (1025 kg m^{-3})

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