European Shore Platform Dynamics

MAS3 – CT98-0173 ESPED

Final Report: Work Package 6

Modelling platform dynamics: implications for coastal zone management

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ESPED PROJECT

Contents

6.1 Introduction

A number of models of platform evolution have been proposed but there has been very limited field testing of the applicability, validity or accuracy of the models. Existing models focus on the roles of waves, tides and rock properties in the evolution of shore platforms and are concerned with long-term evolution over centuries and millenia. They pay little or no attention to sub-aerial weathering, or biological processes, nor to the actual downwearing of the platform surface. Yet, for the coastal manager it is platform downwearing that might undermine sea defences and change over years and decades that is of greater concern than evolution over centuries or millenia. ESPED was designed to collect data on current rates and patterns of platform downwearing over a range of European coastal environments and rock types in order to evaluate their implications both for models of platform evolution and for shoreline management.

The programme has succeeded in collecting a very large, body of data on characteristics, properties and erosion rates of cliffs and shore platforms around Europe’s shores. Data collection in the workpackages has included:

- detailed data on the geotechnical properties of shore platforms and cliffs, and of the susceptibility of the associated rock types to a range of simulated weathering and erosive processes:

- detailed mapping of the morphology of shore platforms:

- measurements of the rate and processes of cliffs retreat landward of the platforms:

- measurement of platform downwearing using laser scanning and micro-erosion meters:

- assessment of the role of sub-aerial, biological and marine processes in platform development and cliff retreat.

Collection of field data was focused on a number of sample sites with varied tidal ranges, exposure to waves and climatic conditions. Initially some 25 sites were selected for study of which 20 were subsequently monitored for erosion and downwearing. The programme has been site-specific, undertaking detailed work on this limited number of sites. Thus the programme has been geared towards developing our understanding of local factors responsible for controlling platform development and change.

The focus of the ESPED programme has been on the detailed mapping and characterisation of the surface morphology and surface downwearing of platforms and the back wearing of associated cliffs. The programme did not include any measurement of changes in platform width, nor of the retreat of the submerged low-water cliffline.

It had originally been planned to undertake analysis and modelling of the collected data as a discrete work package in the final three months of the project. However, delays in the development and delivery of the laser equipment and unusually adverse winter weather conditions for data collection at some sites during the winters of 1999-2000 and 2000-01 resulted in data collection continuing until the final days of the project. As a consequence this report is a ‘work in progress’ report rather than a ‘concluding report’ of the implications of the results for modelling and coastline management. In addition it became apparent as the work progressed that some of the modelling was best embedded within the separate work programmes. Thus, considerable conceptual modelling of the results has been carried out during the processing of data by partners. Detailed descriptions and explanations of these models are included in the final reports of the relevant work packages and they are only briefly summarised in this report, followed by discussion of their implications for coastal management.

Full analysis of the vast body of field and laboratory data collected by the programme remains incomplete and work is continuing. The results will be included in planned special volumes of two scientific journals, *Zeitschrift fur Geomorphologie* and *Continental Shelf Research,* dedicated to publishing the results of this project, and some related papers presented at the final conference with end users held in Brighton in December 2001. These journal papers and the results of continued analysis of the data will be forwarded to the Commission as they are produced.

6.2 Existing models of cliff erosion and platform development

Historically, ideas regarding shore platform development have involved a debate as to the relative importance of waves and weathering (Stephenson 2000). The role of biological processes has largely been ignored and is still not considered significant by many researchers.

Much of the recent work on cliff erosion and platform evolution has involved the application of mathematical models and hard ware models linked to field observation and testing. There are two basic designs of mathematical models (Stephenson, 2000). Both place emphasis on waves as the dominant mechanism and are concerned with the long-term evolution of cliffs and platforms over hundreds and thousands of years rather than shorter term changes over tens of years that are of greater interest to engineers and coastline managers.

That wave attack initiates cliff formation and platform development is generally accepted but once developed the relative contributions of wave, sub-aerial and biological processes to the subsequent erosion and downwearing of platforms remains uncertain. Some researchers favour the idea that waves continue to be the dominanat force (Trenhaile and Layzell, 1980, 1981, Trenhaile, 2000a & b and Sunamura, 1977, 1978, 1982) whilst others emphasise the role of subaerial weathering. (Stephenson and Kirk, 2000a & b).

One design of mathematical models, developed by Japanese workers, led by Sunamura (1977, 1978, 1982) is based on the relationship between the energy of the waves (**fw**) and the strength of the rock materials (**fr**). For cliff erosion to occur and platform development initiated **fw** >**fr**. The mean rate of cliff retreat (dX/dt) can be represented by the equation

$$dX/dt \; \alpha \; 1n\,(fw/fr)$$

in which

X is the horizontal eroded distance of the cliff.
t is the time
fw is the assailing force of the waves and
fr the resisting force of the cliff materials.

The fundamental problems in applying this model relate to selecting the most appropriate values of **fw** and **fr.** Additionally, once a platform has developed, there are uncertainties as to whether the rock-strength properties that control cliff retreat are the same as those that control platform downwearing. It is recognised that weathering weakens the rocks, and indeed weakening of the cliff materials by weathering may help to compensate for reductions in wave energy as the platform develops. (Tsujimoto, 1987).

By representing **fw** by wave pressure p and **fr** by rock compressive strength S_c, Tsujimoto (1987) found that for platforms to develop in Japan $p > 0.081S_c$, and that when these two factors are represented by shear force, r and shear strength S_s , the condition $r = 0.005S_s$ determines whether a sloping (Type A) or horizontal (Type B) platform develops. A sloping platform develops if $r > 0.005S_s$ and a horizontal platform when $r < 0.005S_s$.

The second group of models have been developed by Trenhaile and co-workers in Canada (Trenhaile and Layzell, 1980, 1981, Trenhaile, 2000a & b) who have been particularly interested in the evolution of platforms in macro-tidal seas and the resulting evolution of platform morphology over time. The underlying premise is that the critical control on erosion is the length of time a section of cliff or platform is vulnerable to potentially erosive wave energy.

Platform evolution was first modelled on the assumption that the rate of inter-tidal erosion is determined by 'tidal duration' i.e. the time that still water level occupies each elevation within the tidal range, by an erodibility factor comprising wave energy and rock hardness, by platform gradient and by the rate of submarine erosion (Trenhaile and Layzell, 1980, 1981).

Thus

$$R_{n,t} = tW F_n \tan \alpha_{n-1}/V$$

Where:
$R_{n,t}$ is the erosion in cm occurring in t years at inter-tidal level n
W is the deep water wave energy delivered per hour
F_n is the tidal duration factor = the accumulated time (h y^{-1}) that the still water level has been at level n
α is the slope angle of the platform
and
V is the amount of energy required to erode 1 cm of rock

From running the model it was concluded that:

- platforms achieve an equilibrium state when rates of erosion become equal at all points on the platform. The equilibrium width increases with wave intensity and tidal range and inversely with rock hardness.

- platform gradient at individual intertidal levels increases with rock strength but decreases with wave energy and with tidal duration.

This is often termed the 'dynamic equilibrium' model because the results imply that as platforms extend horizontally by cliff retreat, the effective wave attack on the cliff is reduced until it reaches zero as the extending platform increasingly dissipates wave energy. Thus there is a feedback mechanism and a finite limit to the horizontal extension of platform width (Fig 1). Further retreat of the cliff can only occur if the platform also retreats. This concept of a dynamic relationship between cliff retreat and platform evolution predates the development of mathematical models and has been used to explain platform gradient as well as platform width (Trenhaile, 1974, 1980).

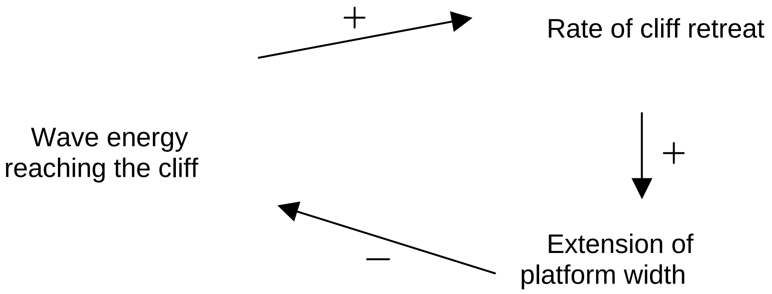


Fig. 1. The equilibrium model of cliff-platform dynamics

Subsequently Trenhaile (1983) worked with a rather different model that focused on the relative rates of erosion at the high and low tide levels rather than the distribution of energy within the tidal range. This model assumes that cliff recession takes place in two stages. First, the cliff is undercut to the point of collapse and then this is followed by removal of the debris In its simplest form the equation for the time ($T_{n\,x}$) required to develop the critical depth of undercut that results in cliff collapse is:

$$T_{n\,x} = (W)\,(x)(C_1 + HC_2)$$

In which:
W = intertidal platform width
x = the maximum depth of undercut before collapse occurs
H = cliff height
C_1 = a constant equal to tan α/UT_r
and
C_2 is a constant equal to tan α/ST_r
Where
α is the platform gradient
T_r is the tidal range
S the amount of debris removed each year, and
U the amount of cliff undercutting per year.

Recently, Trenhaile (2000a & b) has further developed and combined aspects of these models in a new mathematical model that considers the effects of deep water wave height spectra, period and wavelength, breaker height and depth, breaker type, the width and bottom roughness of the surf zone, the gradient of the submarine slope, an erosional threshold related strength of the rocks, the number of hours each year in which year in which the water level is at each intertidal elevation and the amount and persistence of the debris at the cliff foot.

The model is based upon two erosional equations. One is an excess force equation for intertidal erosion at the waterline at the head of the surf zone (Ey) where

$$Ey = M \sum_{W=1}^{5} \sum_{E1=1}^{5} (T_{d} W \, [512.61 C(H_{b}/0.78) \mathrm{e}^{-kWs} - S_{fmin}])$$

and in which:
Ey = the total erosion (in metres) accomplished by all the waves in the wave set at a specific inter-tidal level (E1)
M = a scaling coefficient (6.5 x 10^{-10}) used to convert the force exerted at the surf-rock interface into the amount of horizontal cliff and platform erosion that occurs during each model iteration
T_d = tidal duration
W = the hourly number of waves of each of five deep-water height categories H1 to H5 occuring each hour
512.61 is the breaker wave force in kg m^{-3}
C = a coefficient representing differences in the force exerted at the waterline according to the type of breaking wave
H_b = the breaking wave height
S_f = the surf force reaching the waterline.

The second equation:

$$E_S = E_y e^{sh}$$

Is a decay function used to calculate submarine wave erosion below and within the intertidal zone down to a maximum depth equal to 0.5 the wavelength, the critical value below which waves are thought incapable of causing erosion, in which:

Es is the total submarine erosion which occurs as the water surface occupies different intertidal levels during each iteration
s is the depth decay constant
h is the water depth

The results suggest that:

- Platform gradient and the rate at which platform width increases, decrease with time so that platforms may eventually achieve a state of equilibrium

- Platform gradient varies with tidal range with sub-horizontal platforms developing in meso-tidal environments and sloping platforms developing in macro-tidal environments.

- There is a direct relationship between platform width and tidal range

- There is an inverse relationship between platform width, rock resistance, platform roughness and the residence time of cliff collapse debris.

- In high tidal range environments the widest platforms develop in wave-exposed environments but in low tidal environments are widest in sheltered locations.

These models are all concerned with the long term modelling of platforms over centuries and millenia. Their focus is on the width and slope of platforms and the retreat of their landward and seaward, margins. The ESPED programme, which was designed to study platform downwearing rather than retreat, is not therefore a satisfactory test of any of these models. Indeed, as Trenhaile (2000a) acknowledges, it is very difficult to substantiate such models through any field measurement or experimentation, because rock coasts erode slowly over long periods of time.

Working on platforms at Kaikoura in New Zealand, Stephenson and Kirk (1998, 2000a & b) have recently argued that, however platforms may initially be developed, shore platforms are subsequently worn down primarily by sub-aerial processes. From measurements with a micro-erosion meter they found that rates of platform lowering were generally higher on the landward margins of platforms and decreased in a seaward direction, and that erosion rates were higher during summer than in winter. They interpret this as a consequence of wetting and drying and salt weathering being the dominant erosive processes rather than marine processes. Thus, whether or not platforms are initially 'cut' by wave action, it would appear that, in some cases at least, waves and other marine processes are playing a minor role in their downwearing at the present day. It was a particular aim of the ESPED programme to investigate and model the interaction and relative importance of waves, tides, sub-aerial weathering, biological processes and rock characteristics in determining the present day downwearing and morphology of shore platforms in the varied coastal environments around Western Europe.

6.3 The ESPED shore platforms

The conceptual model of shore platform dynamics that forms the basis of the ESPED work programme is shown in Fig 2.

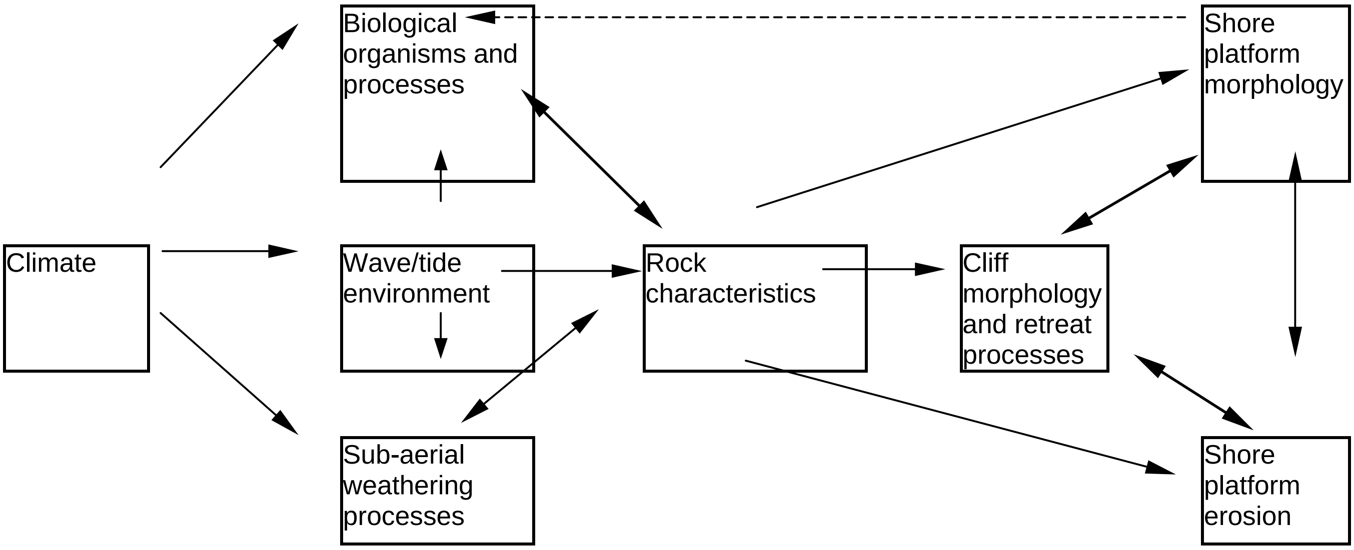


Fig. 2. Conceptual model of shore platform erosion dynamics

Climate, waves and tides deliver energy to the coast and determine the rise and fall of the sea surface. They influence the range of biological organisms that occupy the inter-tidal zone and determine the range of weathering and erosive forces to which the coastal rocks are exposed. The impact of these forces depends on the chemical, structural and mechanical properties of the rocks and these same rock characteristics have an influence on the range of biological organisms and weathering processes that may occur. The resulting rates of cliff retreat and platform erosion depend on the resistance of the rock to these assailing forces. Rock characteristics also influence the morphology of the resulting platforms and cliffs, and there are feedback mechanisms between the erosion and morphology of the platforms, and the rates of cliff retreat. The morphology of the platforms influences tidal duration on different parts of the platforms and determines the range of micro-environments available for occupation by biological organisms.

The ESPED work programme was designed to measure the relative importance of these various factors on shore platforms representative of the different climate, tide and wave environments that exist around the coasts of Western Europe. A decision was made at the start of the programme to restrict the study to platforms developed in a narrow range of geological materials and most, but not all of the platforms studied are developed in limestone or granitic parent materials. The 21 platforms selected for study by ESPED to represent the range of climate tide and wave environments in which European shore platforms develop were:

- Low energy, microtidal:

  cool temperate, low salinity environment of the Western Baltic,

  warm temperate, high salinity environment of the Western Mediterranean

- Moderate-high energy, meso–macrotidal:

  cool temperate environments of the Channel coasts of France and England.

  High energy, meso-macro-tidal, cool-warm temperate oceanic environments of Western France, Portugal and South Wales.

In the Baltic, land is currently rising relative to sea level as a consequence of isostatic adjustment following the last glacial period whilst along the Channel coast of Britain the land is sinking. Elsewhere, slow submergence is occurring as a consequence of global rises in sea-level.

The form of the platforms developed in these different environments showed significant variation (See Final Reports WP2). Those in the micro-tidal environments of the western Mediterranean tended to be narrow and sub-horizontal, backed by low cliffs. Those in the moderate to high energy, meso-macrotidal Atlantic and Channel coast environments were wider, generally backed by tall cliffs and sloped gently towards the sea. Those in the Baltic were also relatively narrow, but were varied in slope, in part because of the rate of isostatic uplift which means that the platforms are constantly rising relative to sea level and have had less time to develop.

These differences suggest that tidal range and wave energy may be of paramount importance in determining the macro-morphology of the platforms studied as is sea-level change. However, this may be misleading because sub-aerial and biological processes are just as sensitive to tidal range and duration as is wave action. Within particular wave-climate environments there is significant variation in detailed morphology, with geological structure exerting a strong influence on many platforms. Erosion is frequently focused on joints and discontinuities and this produces platforms that are very irregular in height and slope. Sections of reverse (i.e. landward) slopes or steps are not uncommon and stripping of rocks along inclined bedding planes often creates slopes transverse to the direction of dominant wave approach that are greater than the slope towards the sea. These variations have been largely ignored in most existing models of platform development

The relationship between the mass strength of geological materials and platform evolution, which forms the basis of several models of platform development is complex. Schmidt hammer readings or laboratory testing of compressive strength are the rock material characteristics that have often been measured. ESPED experimented with a range of different field and laboratory methods and the conclusion is that the relationship between material strength and platform erosion is complex and probably no single index of susceptibility to erosion is sufficient (See Final Report WP1). Susceptibility is probably process specific. Thus the geological control on wave quarrying of either cliffs or platform blocks is almost certainly different to that for abrasion, wetting and drying or solution. Rock strength characteristics of fresh rock can be very different to those of weathered rock after it has been exposed to many cycles of wetting and drying by tidal cycles.

Rates of cliff retreat (see Final Report WP3) and platform downwearing (see final Report WP5) recorded for the three years of measurement are also very variable with the greatest rates experienced on the exposed, meso- to macro- tidal environments of Atlantic and Channel coasts and the lowest in the more sheltered Baltic and Mediterranean environments with their low tidal ranges.

Often, the rates and patterns of erosion are more heavily influenced by geological structure and bedding than the strength of intact rock. On many platforms, the quarrying of blocks along bedding planes is the dominant erosive process and, once stripped, subsequent downwearing of exposed surfaces can be very slow. Karstic solution features on limestone platforms confirm the short-term stability of many platform surfaces and the dominance of sub-aerial weathering over marine processes of denudation. Downwearing of some platform surfaces may relate to the strength of intact rock but the weakness of bedding and jointing patterns is of equal or greater importance in determining rates of cliff retreat and platform development in many locations.

The platforms exhibit considerable variation in biological colonisation and range of organisms (see Final Report WP 4). The importance of the role of biological organisms in platform development has come increasingly to the fore in recent years. Some biological organisms can cause erosion directly. Limpets for example can significantly add to surface lowering by grazing the rock surface (Andrews and Williams, 2000, Naylor, 2001). In other cases they may contribute to the lowering by, for example, weakening the rock by boring holes or aiding chemical dissolution. Other organisms can protect the underlying rock by trapping sediment or by reducing drying of the rock surface during periods of low tide and hence the number and severity of wetting and drying cycles. Some organisms can increase a rock's resistance to erosion by secreting chemicals that cause surface hardening of the rock surface.

6.4 Platform development in different European coastal environments.

As outlined in section 6.1, the focus of ESPED has been on rates of cliff retreat and platform downwearing. The range of platforms studied have displayed very different morphologies and the ESPED studies indicate that they are the result of significant differences in both the rates and processes of retreat and downwearing. Rates of downwearing for individual survey points vary from a maximum of nearly 60 mm y^{-1} to some sites that have no measurable annual erosion and a few that show actual increases rather than decreases. The latter is something that has been found by other researchers such as Stephenson and Kirk (2000 a & b) and is interpreted as being the result of rock expansion caused by sub-aerial weathering processes. Mean rates of weathering for entire platform transects vary from > 8 mm y^{-1} to < 0.01 mm y^{-1} The highest rates of downwearing are on the chalk coasts of the Channel , the lowest on the granitic rocks of the Mediterranean and the Baltic.

6.4.1 Data collection problems and limitations

At the commencement of the programme, considerable efforts were made to try and harmonise sample design and methods of data collection between partners at the various sites. However, in practice, this sometimes proved impossible for a variety reasons, primarily because of variations in the size of cliffs and platforms under study. In the Baltic, platforms undergoing isostatic rebound are backed by no active cliffs. In the Western Mediterranean, long-term cliff recession rates proved difficult to obtain because the scale or quality of available maps and air-photograph were inadequate to measure the very slow retreat rates of the cliffs (see the Mallorcan Report on WP3). Attempts to measure the input of debris from cliff falls during the monitoring period proved impossible in southern Britain because a high frequency of falls occurred during storms and a considerable proportion of the resulting debris was often removed during the same stormy period in which a fall occurred. However, accurate long term measurements for the retreat for each 50 m stretch of this coast (Dornbusch *et al,* 2001) allowed good estimates to be made of average annual inputs of both flint and chalk debris from cliff retreat.

The sample design for the collection of data on platform downwearing varied according to the type of platform. On the inter-tidal platforms developed on the Atlantic and Channel coasts, data was obtained by means of transects running seawards across the platforms from the base of the cliff. Along each of these transects 10 micro-erosion meter and three laser scanning sites were located at regular intervals. On the narrower platforms of the Western Mediterranean and Baltic coasts, the monitoring sites were located much closer together and distributed in transects designed to measure the micro-environments that exist at different elevations on the platforms. Collection of data was hindered somewhat by reliability problems with the laser equipment and in southern England by the loss of some monitoring sites beneath cliff fall debris, beneath large boulders that moved across the platform or beneath accumulations of shingle that drifted on to the platforms. Also in southern Britain high rates of erosion at some sites destroyed the reference points used to standardise the laser readings thereby making some repeat measurements difficult or impossible at some monitoring sites. Sites established in Southern Brittany were lost due to the pollution by oil, and subsequent cleaning operations, following the spillage from the tanker Erika.

Unfortunately, there were also minor problems with the experimental software that had to be developed to run the modified version of the laser scanner developed for this programme (see Final Report WP5 for details) and not all scans produced usable data. Overlying the scans and calculating downwearing rates from the laser scanning proved more complex and time consuming than initially anticipated and data from this source became available only days before this report was written. As a consequence, the information available to date on rates and patterns of platform downwearing that are included in this report are almost entirely based on micro-erosion metre measurements.

Because of the delays in the final collection and processing of field and laboratory data, only limited analysis and modelling of this data has been possible. This has mostly been confined to groupings of sites from similar wave-climate environments. Nevertheless, considerable progress has been made in modelling the factors determining the morphology of some of the platforms and in the analysis of the patterns and processes of platform downwearing in relation to cliff retreat. Further work on the data collected will continue over the coming weeks ready for publication in scientific journals.

In addition, to the work originally included with the ESPED programme, it has proved possible to model the fractal nature of the platform surfaces using high resolution linear scans obtained with the laser scanner. A description of this modelling and its results are included as Appendix 1.

6.4.2 Modelling of wave and tide data.

At the start of the study, no data on shoreline wave conditions at the study sites was available. This has therefore had to be modelled from offshore wave and climate data. Details are included in Appendix II. The onshore wave power is greatest for the exposed Portuguese sites where it reaches a mean annual value of 44.8 Kw m^{-1} but drops to a minimum of 6.3 Kw m^{-1} at the sheltered Avencas-Parede site on the same coast. Detailed analysis of the relationship of this data to erosion rates and platform morphology has not yet to been possible.

6.4.3 Shore platforms and cliff retreat on the Atlantic and Channel coasts

Detailed measurements were made at six sites along the Channel coasts, four in England, two in France. All platforms studied were developed in Chalk. An additional platform was monitored in the UK, in South Wales, developed in Liassic limestone. Three sites were studied Portugal developed in marl, marly limestone and flysch (see Final Reports WP 1 and WP 4 for details). All the sites were backed by high cliffs, but one site at Peacehaven on the English Channel coast was separated from the cliff by a concrete sea wall surmounted by an access roadway. As mentioned above, two sites established on granite in southern Brittany were subsequently lost as a result of onshore oil pollution from the Erika.

Details on the morphology of the platforms in Britain and France along with analysis and modelling of the platforms are included in the final report of WP2. In summary, the platform gross morphology is controlled mainly by tidal parameters and exposure. The key summary diagram of a model of the dynamic relationships between tidal range, mean sea level and exposure. (Final Report WP2 Fig 55) is included here as Appendix III and the relationships between tidal range, exposure platform width and platform slope are summarised in Fig 3. Platform width increases with tidal range. Platform slope increases with exposure.

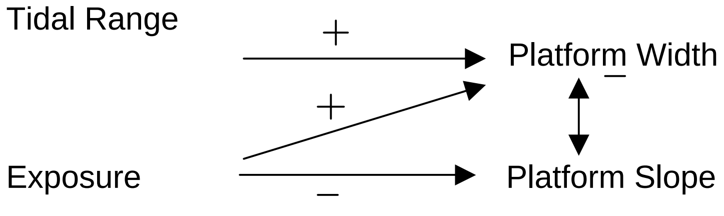


Fig. 3. Relationship between tidal range, exposure, platform slope and platform width (for details see Final Report WP 2)

These relationships with tidal range and exposure are most clearly developed on simple, uniform platforms such as those developed on the chalk. On more irregular platforms developed on harder rock with more complex structures, such as the granite of the southern Brittany coast, where complex remnants of an old topography persist on the contemporary platform as upstanding reefs, these act as localised cliffs. Platforms radiate from their foot in multiple directions with profiles that vary according to their degree of exposure (Appendix III, Fig 62).

The mean rates of downwearing for study sites on the Channel coast are shown in Fig 4, the pattern of downwearing values across the platform are shown Fig 5. The greatest erosion was at Friars Bay, Peacehaven, on the English coast. The two transects on this site lie 100 - 150 m east (i.e. downdrift) of coastal protection works comprised of a concrete wall and groynes, that stretch westward from this point for several kilometres. For each of the English sites downwearing is very high towards the top of the platforms, close to the base of the cliffs. This is not apparent on the French sites. In Portugal, a pattern of high erosion close to the cliffs is present at the Monte Clerigo site, but not at the other two sites. For sites on both sides of the Channel, downwearing also seems to be a little higher than average between 70 and 110 m from the cliff base but more data is really required to be certain that this is true. The zone of rapid abrasion close to the cliffs is the result of abrasion by flint shingle. This abrasion zone is very visible in the field as a stretch of rather, smooth white chalk that lacks any of the vegetative cover, surface pitting or boring that characterises the rest of the platform. Erosion in this zone is most marked in winter (Fig 6) when storm wave energy is greatest whilst elsewhere on the platforms it is summer or autumn. This strongly supports the suggestion that erosion in the abrasion zone is wave driven, but elsewhere sub-aerial or biological weathering processes are more important (see discussion in Final Report WP2).

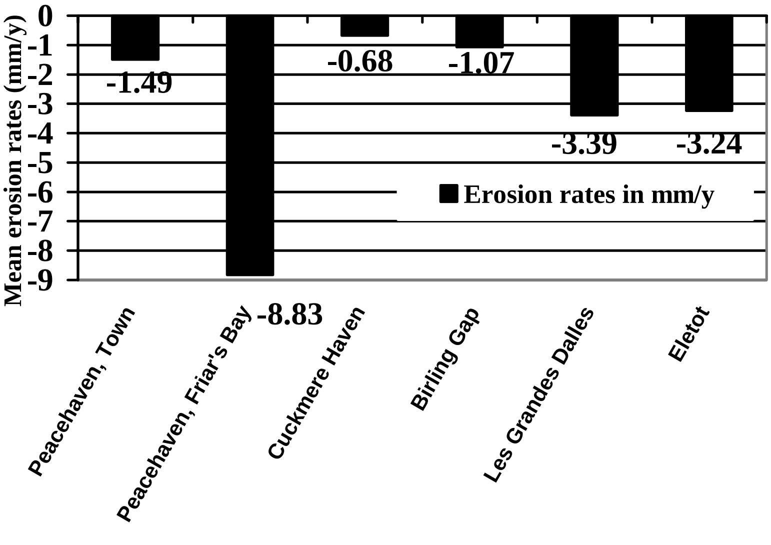


Fig. 4. Overall annual mean erosion rates per shore platform (1999-2001) (From Foote, Plessis and Robinson,

2001)

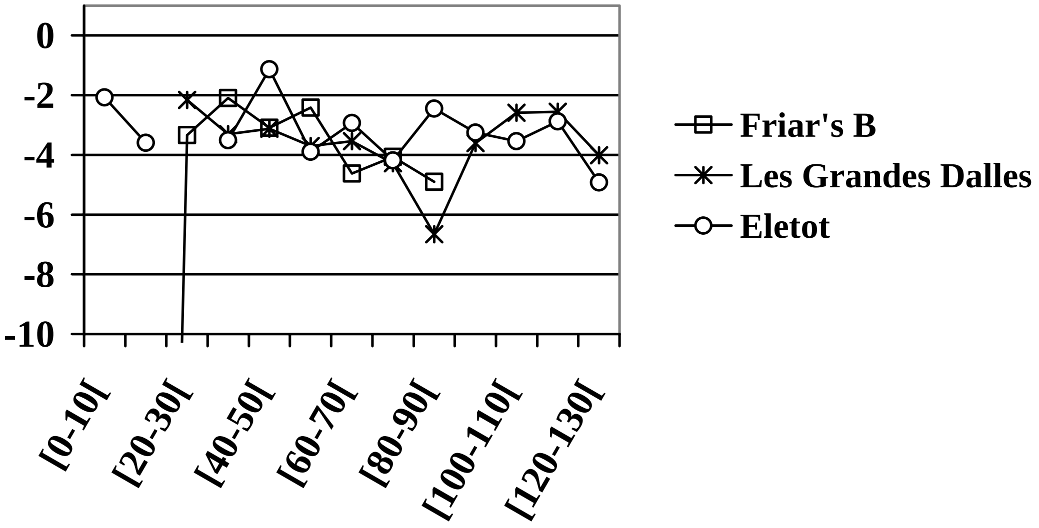


Fig 5. Distribution of downwearing rates as measured by MEM for Channel coast platforms (From Foote, Plessis and Robinson, 2001)

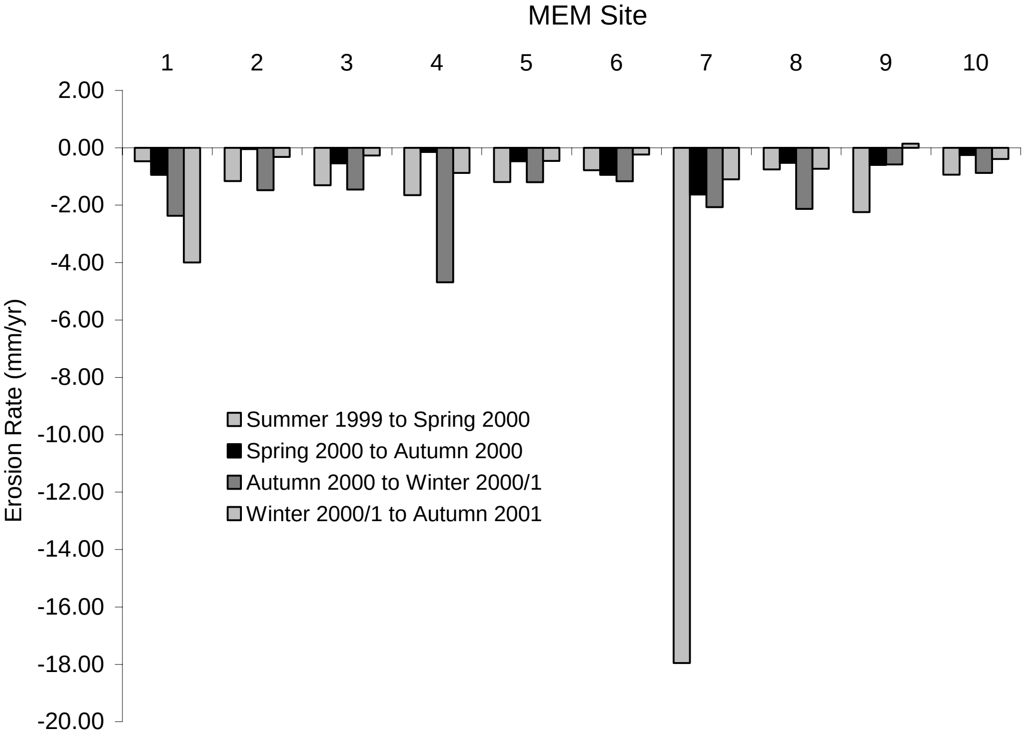
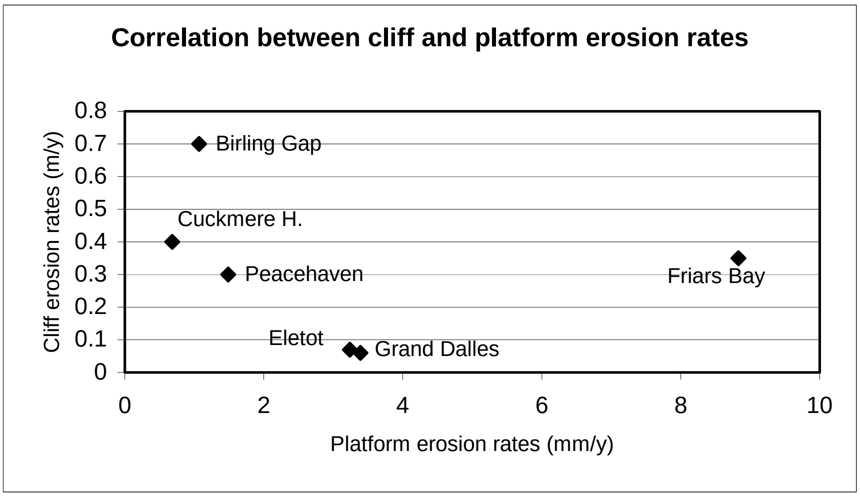


Fig 6. Seasonal variation in MEM measurements: Peacehaven Town 1999/2001 (From Foote, Plessis and Robinson, 2001)

The mean annual rates of cliff retreat measured for the Channel sites are markedly higher on the English side than on the French side. Retreat rates of the French cliffs are typically between 0.05 and 0.10 m y^{-1} whilst the average rate for the Sussex cliffs is 0.28 m y^{-1}. The rates show no correlation with the rates of platform downwearing (Fig 7). If the platforms and cliffs are in equilibrium, one might expect a positive relationship between rates of platform downwearing and rates of cliff retreat. The absence of any correlation may be because of the different time scales over which these two rates have been measured. However, if they are not in equilibrium it suggests that either equilibrium models are incorrect, or that some factor or factors have created a disequilibrium. This could be human intervention such as the installation of coastal defence works that interfere with the natural drift of shingle along the coast, or it could a consequence of sea level rise resulting from a combination of negative isostasy and global warming, possibly assisted by increased storminess.



Timescales

Cliff retreat rates: 126-162 yrs
MEM erosion rates: 2-3 yrs

Fig 7. Relationship between cliff and platform erosion rates for Channel sites

On the harder limestones of South Wales, rates of recorded erosion were low and display no clear down-shore pattern. Several MEM sites recorded swelling rather than erosion of the platform surface. It is indicative of the limited erosive action of waves on this platform surface and the importance of sub-aerial weathering processes weakening the rock and causing it to expand. This is despite the high wave energy and macro-tidal environment of this site.

6.4.4 Shore platforms in the Western Mediterranean and the Baltic

Micro erosion measurements were made at five sites in the Western Mediterranean, four on Mallorca developed in calcarenites, dolomites, and limestones, and one on the mainland Spain in Catalonia, developed in granite. Laser scanning was done at the Mallorcan sites, but not on the mainland (see Final Reports WP1, 4 for details). The platforms were all narrow and some parts received wash and spray but were not subject to regular wave or tidal submersion. They ranged in total width from 1 – 8 metres but the mean widths varied from <1.5 – 5.0 m. Except during periods of high barometric pressure the inter-tidal platforms lie below mean sea level. Erosion on these platforms is mainly biological in nature because seagrass and biological crusts protect the surface from the generally low energy wave action. On the higher, supra-

tidal parts of the platforms, salt and other forms of sub-aerial weathering are in evidence. As a consequence the shore platforms tend to have a very uneven surface evidenced by the high roughness values recorded with the laser scanner (See Final Reports WP5, and WP). The detailed morphology of the platforms is determined by the interplay between seawater inputs in the form of spray, splash or swash, biological activity and sub-aerial weathering processes. A model linking the hydrodynamic, morphological and biological components of the shore-platforms and cliffs characteristic the rock shores in the Western Mediterranean has been developed and is described in detail in the supplementary report on WP2 (Asensi, *et a*l., 2002). For completeness, the summary diagram of this model is included as Fig 8.
The results of both MEM and laser scanning show that rates of erosion on these platforms are everywhere very low, close to, or beyond, the limits of accuracy of the instruments (Williams et al 2000; Final Report WP5). Mean values range from 0.16 to 0.38 mm with rates of erosion on the
inter-tidal parts slightly greater in the supra-tidal zone. In the inter-tidal zone, some examples of surface swelling were recorded, presumably as a consequence of sub-aerial weathering processes. As outlined in 6.4.1 it proved impossible to measure long term rates of cliff retreat but current erosion of the cliffs was assessed by the use of sediment traps placed at the foot of the cliffs. At the daily scale erosion mostly proceeds by granular disintegration and rates of between 1100 mm^3 m^2 day^{-1} and 13,050 mm^3 m^2 day^{-1} were recorded. On an historical timescale, larger falls of rock can be identified.

Platforms in the Western Baltic are also relatively narrow, but the long cold winters limits the biological organisms and processes. Rates of recorded erosion are very low and at the very limits of the instrument capability (Final Report WP5). No measurable annual erosion was measured at several individual measurement sites. The greatest erosion was recorded on the limestone platform at Färo on Gotland, but even here the maximum recorded by laser scanning was only 0.271 mm y^{-1}. Unlike the Mediterranean platforms those in the Baltic exhibit fairly uniform surfaces with low roughness values Laser scanning suggests that some sites undergo small amounts of flaking in summer, but frost action appears ineffective on the hard granitic, gneiss and doleritic rocks despite the harsh winter climates. At Rotisdan in the north, considerable annual movement of some large boulders was recorded, sometimes up-platform, which is interpreted as movement by sea-ice driven onshore by easterly winds.

6.4.5 Biological Processes

A particular feature of the ESPED programme has been a focus on biological processes (See Final Report of WP4). The studies have shown that biological processes are important in the erosion of the platforms, in protecting their surface from wave action and in trapping and accumulating sediment on their surface. The effects are least on the cold platforms of the northern Baltic coasts. Elsewhere they are markedly seasonal, especially in along the Atlantic and Channel coasts. Bioerosion rates vary according to lithology, decreasing with rock strength, but increasing with the abundance of organisms and exposure. Sediment trapping does not seem to occur in the Western Mediterranean where the platforms terminate in deep, sediment free water. It has not yet been possible to quantify the relationships but a preliminary model of bioerosion has been developed (Fig 9).

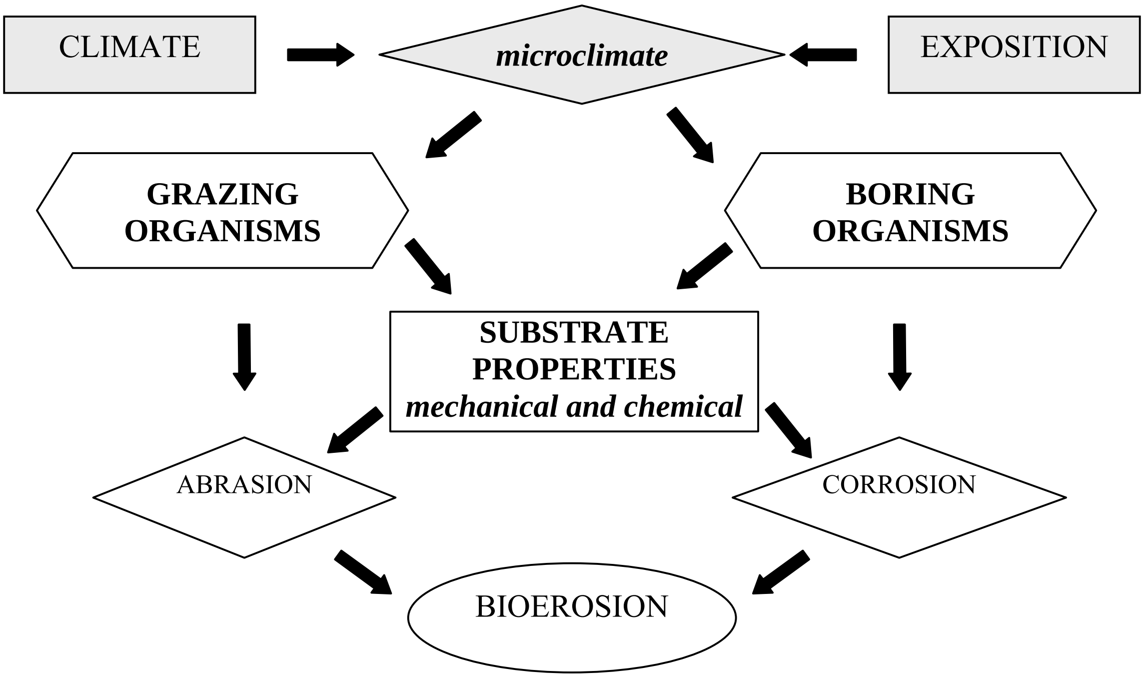


Figure 9. Simplified model of bioerosive processes for limestone coasts. (From Fornos, Sous-Dias, Pons and Melo 2001)

6.5 Implications for shoreline managers

Over the ESPED monitoring period weather patterns along the Atlantic and Channel coasts have been very disturbed and cliff collapse and retreat has been rapid at a number of sites, especially along the English coast. It is tempting to relate this to predicted climate change and sea-level rise, but there is insufficient reliable long-term data to be certain of the extent to which the past three years have been atypical. The extent to which marine action actually erodes the cliffs rather than simply removes the products of mass wasting by sub-aerial processes remains uncertain in some localities. However, at many sites platform downwearing is active to the very base of cliffs and this cliff foot is often the zone of maximum surface loss. Patterns of erosion that show maximum erosion beneath the cliff foot and little erosion by across much of the remainder of the platform are difficult to reconcile with equilibrium models of cliff retreat and platform development that suggest erosive power decreases as platform width increases. They may however be explained by sea level rise, accelerated cliff retreat and platform extension, or by human action in the coastal zone such as interference with the volume and distribution of sand and shingle by groyning and other coastal defence works. The unusually rapid erosion at Friars Bay (Fig 4), which is located immediately east of an extensive stretch of groynes and sea wall, strongly suggests that such human disturbance can lead to very rapid platform downwearing and cliff retreat. At Peacehaven Town where the platform is backed by a sea wall the mean erosion rate is only a little higher than on the unprotected sites further east, but close to the sea wall the annual erosion rate in the abrasion zone reached >18 mm y^{-1}. Such a high rate clearly threatens the long-term stability of the adjacent sea wall and groynes.

The role of the accumulations of shingle and/or coarse sand, that frequently cover the upper parts of platforms, on rates of platform erosion varies with the thickness of accumulation. Thin layers of mobile shingle are moved by waves, abrade the platform and produce the highest rates of platform erosion. This result agrees with that of Robinson (1977a,b&c) who worked on the northeast coast of England. Larger accumulations are more stable and help protect the surface from erosion, because only very large waves can move particles buried beneath accumulation >0.1m in thickness. Coastal defence works that reduce the volume of shingle in areas of unprotected cliff foot, such as at Friar's Bay, or result in low volumes of mobile shingle in front of sea defence structures such as at Peacehaven Town can clearly lead to substantial increases in rates of shore platform erosion.

The high rates of cliff erosion recorded at the rear of some platforms, especially of high cliffs along the Channel coasts are a significant safety threat to coastal property and recreational users of these beach and cliff environments. Sea level rise and wetter winters with a higher incidence of storms as a result of climate change may be accelerating these rates of retreat, but a major contributory factor highlighted by ESPED is the high rate of shore platform downwearing in the cliff foot zone. The main cause of this high rate of downwearing is abrasion by thin layers of mobile shingle, and it is significantly higher than rates elsewhere across the platforms. Historically coastal management has increasingly depleted many areas of cliffed coastline of shingle by building up beaches in vulnerable, low lying areas by groyning and other actions. In addition, supplies of shingle to the beaches has decreased due to the implementation of coastal protection measures such as sea-walls, designed to reduce or halt coastal retreat. If cliff foot erosion and cliff retreat is to be reduced, every effort should be made to try and increase protection of the cliff base through the implementation of policies to build up shingle volumes rather than deplete them.

Investigation of whether rates of cliff erosion have been accelerating as a consequence of climate change, sea level rise or human interference with natural shoreline processes was not an aim of the current project. However, measurement of historic rates of cliff retreat carried out as part of the ESPED suggest that cliff retreat may well have increased in recent decades. Further research to investigate whether this is indeed the case and if so why, of how it will impact on coastal users and communities, and how the threat might be mitigated should be a future research priority.

Rates of platform erosion and cliff retreat in Mediterranean and Baltic sites are so low that they pose no significant threat to coastal users or communities. They absorb little wave energy but in the Mediterranean provide an important array of micro-habitats for biological organisms.

6.6 Summary

The ESPED programme has successfully collected a large volume of data on shore platforms and cliff erosion from around the coasts of Western Europe. No comparative range of data on these landforms has ever previously been collected, either in Europe or anywhere else in the world. Field collection and post-collection processing of some data has taken longer than anticipated and as a consequence quantitative analysis and modelling of the data is still proceeding. Processes of platform erosion and morphology differ significantly between the wave and tide dominated environments of the Atlantic and Channel coasts and those of the micro-tidal low wave energy environments of the Western Mediterranean and Baltic.

Whatever process originally created the platforms, the results indicate that at the present day waves are playing a minor role in their surface erosion. This may in part be because the project focused on downwearing of platform surfaces and did not look at the excavation of the stripping of beds of rock that form risers across many platforms. However, as far as surface downwearing is concerned, sub-aerial and biological processes of weathering and erosion appear dominant. That biological processes are the dominant form of erosion on Mediterranean platforms, and that biological crusts provide extensive protection from erosive processes, are particularly important discoveries. Existing models of platform erosion in temperate environments have never assigned a significant role to biological processes. Models of platform evolution based solely on the actions of waves and tides are clearly inadequate and in future they need to incorporate the important roles of sub-aerial weathering and biological processes. These vary significantly between platforms developed in different environments and a single model of platform development is unlikely to suffice. Also, because the dominant processes of erosion tend to differ between platforms, or between parts of the same platform, it is unlikely that a single index of rock strength can predict the resistance of rock types to erosion in a platform environment.

Thus, separate explanatory models have been developed to explain the very different morphologies of the platforms developed in the meso-macro-tidal environments of the Atlantic and Channel coasts and those of the Western Mediterranean. In addition, a qualitative model of the role of biological processes has also been produced..

In so far that waves are important in surface downwearing, it is as the motive force for abrasion caused by the movement of coarse sand, shingle, and less commonly, larger material across the platform. Away from an upper abrasion zone this movement is limited and tends to be focused along runnels some, but not all of which, are joint controlled. The rise and fall of tides may be of equal importance as a motive force.

Rates of downwearing are highly variable both across platforms and between platforms. They are greatest in macro-tidal areas on soft rock and least in micro-tidal areas on hard rock. Mean rates on chalk are much higher than for other rocks most of which fall in the range measured by past researchers. Rates in the Western Mediterranean and the Baltic are very low and present no serious issues for coastal managers.

In Atlantic and Channel storm wave environments downwearing is concentrated particularly in an upper abrasion zone (if abrasion material is available) with possibly a less prominent peak in a mid-platform zone. The importance of tidal range and exposure on platform width and gradient is confirmed, but this need not indicate that waves are the dominant force, because sub-aerial and biological processes are just as sensitive to ‘tidal duration’ as is wave action. In so far as the data has been analysed, rates of platform downwearing and cliff retreat appear unrelated. There is a problem in the different timescales of measurement, but this result suggests that the platforms are not currently in a state of equilibrium with the rate of cliff retreat. This may be because ideas of equilibria are incorrect or that climate change, sea-level rise and human actions have disturbed the balance. However, it must also be recognised that equilibrium is a dynamic state operating through feedback loops to correct ‘disequilibrium’ conditions and thus over the short time period of ESPED disequilibrium conditions may be more apparent than equilibrium conditions (Schumm and Lichty, 1965).

Any interference to the supply or movement of shingle that reduces the volume of cliff foot shingle to a thin, mobile layer is likely to enhance lowering of the platform at the cliff foot by abrasion and accelerate the risk of cliff collapse. In front of protective walls and groynes, rates of downwearing of platforms developed on relatively soft rocks such as chalk are sufficient to destabilise the structures in less than 50 years.

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