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MODELLING CLIFF DEVELOPMENT IN SOUTH WALES: SAVIGEAR RE-VIEWED

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ABSTRACT

R. A. G. Savigear's (1952) sequence of South Wales cliff profiles measurements is a frequently quoted example of successful space-time substitution. It provides a challenge to our understanding of slope development, which is taken up here in the context of slope evolution models. The model presented simulates creep/solifluction and wash as transport-limited processes. The long-term average behaviour of mass movements is related to the excess of transporting capacity over actual sediment transport, and corresponds to a weathering limited model for cliff slopes; but allows slope replacement down to lower threshold gradients. The model was run for three phases: (i) with a fixed basal point, corresponding roughly to inland valley development during a period of 50,000 to 500,000 years of mainly periglacial climate up to the end of the last glaciation; (ii) with cliff retreat at a fixed rate for up to 10,000 years; and (iii) with basal accumulation without removal for the remainder of a 10,000 year postglacial period. Sea levels were not varied, but related to present levels, because the uniform basal slopes in phases (i) and (ii) are little affected by changed basal elevation.

The observed upper convexities can only be developed in phase (i). The time required to produce them at presumed periglacial rates is 100,000 years or more. The slopes developed are not sensitive to wash rates or, over such a period, to the initial form of the slope. The landslide thresholds and retreat rates help to determine (a) the basal slope in phase (ii), and (b) the survival time for a steep cliff. To match these, the rate of cliff retreat is set at 0.001 (G - 0.4) m/yr for tangent gradient G, corresponding to an ultimate threshold gradient of 22^{o}, with no higher thresholds. The second expression controlling landslide rates is the average horizontal distance moved before coming to rest, which is set at 20 (0.7 - G)m, corresponding to a talus gradient of 35^{o}. With these values cliffs survive for 5,000 years with only moderate decline in gradient, and the basal slope angle after 150,000 years in phase (i) is 32^{o}. These values correspond to dominant slope facets observed by Savigear. In phase (ii) it is suggested that the rate of cliff attack has averaged about 5 mm/year before abandonment in phase (iii).

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1. Introduction

R. A. G. Savigear reported in 1952 a series of slope profiles between Laugharne and Pendine in South Wales. The area above high water, simplified geology and the positions of surveyed profiles are shown in figure 1. Figure 2 shows the forms of surveyed profiles identified on the map. The Old Red Sandstone in which all the profiles have been surveyed, is gently folded with dips of up to 10° in several directions. It consists of varying proportions of sandstone and marl with occasional thin shale partings (Strahan, 1909). The site was chosen by Savigear because progressive growth of dunes and marsh are thought to have taken place from Pendine towards Laugharne. He writes; "The cliffs from Pendine eastward have thus progressively lost contact with the sea and have been partially converted to sub-aerially weathered slopes. At Pendine the cliffs that formerly truncated the more gently inclined seaward slopes have been replaced by concave forms, but to the east, towards the Taf estuary, approximately vertical cliffs still terminate the seaward slopes below. Two distinct slope forms may, therefore, be identified; approximately vertical cliffs in the east and concave slopes in the west. Further, between these two extremes, intermediate forms exist representative of certain stages in the sub-aerial modification of nearly vertical slopes" (Savigear, 1952, p 31).

In other words, this sequence of profiles was selected as showing evidence of space-time substitution, and hence a sequence of slope evolution over time. It has been widely quoted as one of the most appropriate examples of space-time substitution. For this reason it has been used in the present study to test and provide parameters for a new slope model which attempts to incorporate the longterm influence of land-slide processes. It should be noted at the outset that no new field evidence has been taken into account, and the author is aware of no studies providing relevant radiometric dates or sub-surface sections which add to Savigear's profile data.

As was apparent to Savigear, the two sections of the slope, on either side of the Coygan peninsula, differ appreciably, and it is thought probable that they have undergone somewhat different histories, most notably in the duration of sub-aerial modification. The model is therefore primarily directed at comparison with the slopes to the east of the Coygan peninsular, falling from St John's Hill, which still show clear morphological evidence of former cliffing (profiles A to E). Even in this area, there is some divergence of opinion (Mottershead, personal communication, 1981), about the probable slope history. In particular, it is thought possible, in comparison with other coastline profiles in SW Britain, that the cliffs and abandoned cliffs are the product of re-exhumation of interglacial cliffs rather than fresh cliffing into substantially sub-aerial initial slopes. In both of these hypotheses, some recent sub-aerial degradation of the abandoned cliffs is assumed as the latest stage in slope development. Although no clear evidence will be presented below to discriminate between these theories, the model results suggest sites at which sub-surface stratigraphy might best provide relevant evidence.

2. The basis for a slope development model

Figure 3 (after Savigear, 1952, figure 6) summarises Savigear's conclusions on the surveyed slope sequence. In all cases it is implicit that the initial slopes, before cliffing began, consisted of a slope which was convex, at least in its upper parts, and with a maximum gradient of approximately 32°. It is not clear whether profiles in figure 3 are intended to represent a spatial sequence, or are also intended to represent an evolutionary sequence from a common starting point. The evolutionary sequence of cliff protection suggests that from a common initial profile (for the sake of simplicity) T years ago each profile has undergone a period pT as a marine cliff, and time (1 - p) T in subsequent degradation onto the marsh or back-spit lagoon surface, protected from wave attack. The sequence of profiles in figure 3 should then represent different values of the proportion p, increasing from zero (profiles 5 and 6) to unity (profile 1) from west to east. The reason for concentrating on the eastern set of profiles is that there is some reason to believe that the available time, T might be considerably greater to the west of the Coygan peninsula. To the east, it is reasonable to associate the available time with the post-glacial rise in sea-level and subsequent still-stand, so that cliffing might have begun up to 15000 years ago, and spit growth 6000 years ago or slightly before, as the rise in sea-level slowed down. In this view the sequence in figure 3 is not a strict evolutionary sequence since slopes evolve under both cliffing and degradation regimes. This sort of substitution is common in many cases where space-time substitution is claimed. Such a sequence should perhaps be termed a 'Savigear set' of profiles.

The initial form for all the slope profiles is evidently not one of active cliff retreat. It could therefore be viewed as either (a) an exhumed sub-talus rock-core from a previous period of cliffing to the full slope height followed by sub-aerial degradation, or (b) as a substantially sub-aerially degraded slope without rapid basal undercutting from the sea. The continuation of rather similar slopes into valleys (figure 2, profiles O, P and perhaps Q) which do not face the sea directly argues strongly either for (b), or for (a) followed by subsequent evolution of long enough duration to allow the profile forms to cônverge. Sub-aerial degradation is therefore assumed as the basis for the initial form for the Savigear set. A long period of low sea-level is required, and is therefore associated with glacial periods, either individually or cumulatively. Current evidence on Pleistocene climates, illustrated by figure 4, suggests that the present is exceptionally warm and ice-free, and that for about 80% of the previous half-million years, the climate has essentially been periglacial. Under such a climate landsliding and rockfall should be at least as active as at present, and stable slopes subject to solifluction rather than soil creep. In a simplified model therefore, processes should be simulated at periglacial rather than temperate rates, and time-spans of 10^5 years and more are available for slope development. The relatively brief interglacial episodes shown in figure 4 may have trimmed the slope base, as has the present interglacial, but its impact on the upper slopes is thought to be slight enough to be ignored, at least to begin with.

The proposed assumptions for modelling are as follows, based on the arguments above.

(a) A long initial period of slope development is allowed, from an arbitrary previous form, with basal removal at a fixed point. Processes are assumed to operate at periglacial rates, as interglacial periods are short and temperate processes less effective. Basal conditions, unless extreme, may be shown, in model testing, to have minimal impact on the upper slopes. The simplest basal condition has therefore been assumed, without regard to changes in either base-level or basal removal. The long period of development available also minimises dependence on the pre-existing form.

(b) In the postglacial period, of up to 15,000 years, a period of active cliffing is assumed to have been followed by degradation without basal removal. The proportions of this total time allotted to the two periods is allowed to vary to simulate the Savigear set of profiles. During active cliffing, the exact base-level is largely irrelevant to the resulting form. The level on which basal accumulation takes place is however critical, and it is therefore to this datum that the model refers. The changing sea-level is implicit in the overall course of development, but is not explicitly included in the model. Observations of abandoned caves near profile B in figure 1, in comparison with active cave levels on gently dipping Old Red Sandstone east of Stackpole Quay, suggest that substantial cliff erosion took place at sea levels within 1 metre of present levels of both the sea and the East Marsh. For a given cliff gradient, rates of basal attack have been assumed constant over time in the absence of alternative evidence. Deviations from this assumption are not expected to influence the outcome of simulations to a serious extent.

3. Model Structure and parameters

The structure of the model is a variant of current mass balance models, with two main differences. Firstly, the long-term effect of landsliding and rockfall was incorporated to match one set of dominant processes observed in the profiles. Secondly horizontal and vertical axes were exchanged to allow most readily for horizontal slope-base retreat under wave attack. Initial forms were normally then considered to cut back into indefinite horizontal plateaus, although other hilltop conditions could be chosen.

Landslides might be treated as producing transport-limited or weathering-limited removal, or a combination of the two. Transport limited assumptions not only violate accepted views on the nature of landsliding, but produce implausible models, since for example, gradients between cliff and talus angles are less stable than either, so that the required gradient dependence has a number of reversals of direction. Simple weathering-limited models are equally unsatisfactory, since they cannot allow cliffs to be replaced by screes, which are themselves also unstable in the long term. The conceptual approach adopted was of 'erosion-limited' removal in which slope retreat is proportional to the excess of transporting capacity over actual transport rate. This concept has been proposed a number of times before (Kirkby, 1971; Foster and Meyer, 1972; Bennett, 1974), but it has not previously been incorporated into a slope model for landsliding.

The continuity equation for mass balance on a slope with negligible wind transport may be written as

$$\frac{\partial S}{\partial x} = \frac{\partial z}{\partial t} \tag{1}$$

where S is the actual rate of sediment transport downslope
x is horizontal distance measured in an upslope direction
z is elevation above an arbitrary datum and
t is elapsed time

Exchanging horizontal and vertical axes, this equation may be rewritten in the form:

$$\frac{\partial S}{\partial z} + \frac{\partial x}{\partial t} = 0 \tag{2}$$

The change in sign is associated with a change in the sign of δS.

The erosion-limited concept may then be expressed as:

$$\frac{\partial x}{\partial t} = -\frac{\partial S}{\partial z} = (C - s)/h$$
$$= R - S/h \tag{3}$$

where C is the transporting capacity
R is the rate of horizontal slope retreat when sediment transport is zero,
and h is a variable with the dimension of length.

The variable h may be interpreted as the height through which detached material will travel before coming to rest. Thus the term S/h is the rate of (lateral) accretion from the transported load.

It is expected that R and h will depend primarily on gradient, and should be related to relevant stable gradients. Thus the rate of retreat should increase from zero at a limiting stable gradient, i, and a linear increase is a natural first approximation:

$$R = \alpha(i - i^*) \qquad (4)$$

for constant α. This expression should model the free degradation of a cliff with basal removal at a fixed point. Comparison with data from Hutchinson (1967) for London Clay suggests an adequate fit over a large range of gradients, with

$$= 2.5\text{m/year and } i^* = 0.1\ (5.7^\circ)$$

Alternative expressions for the rate of retreat might embody more than one threshold. In the present context it was considered unnecessary to invoke more than a single threshold, but there may be circumstances in which two or more are appropriate. For example, where inclined strata occur, thresholds may be relevant both for their inclination and for the stable angle in weathered soils.

The travel height, h in equation 3 is related to the talus angle, at least for clastic rocks, in that on steeper gradients material will travel indefinitely. A simple sub-model to derive an appropriate expression for the travel distance, or at least to comprehend its variation, is to consider material coming to rest by sliding on a surface with an angle of friction defined by talus angles. This conceptual view immediately gives indefinite travel on talus gradients or steeper. At lower gradients, the decelleration of a sliding mass on a slope at angle B is:

$$f = g\ (\cos B \tan \phi - \sin B) \qquad (5)$$

where ϕ is the effective angle of sliding friction.

The vertical height travelled from an initial velocity, v_* is then:

$$\begin{aligned} h &= v_*^2 \sin B/2f \\ &= \frac{v_*^2}{2g} \quad \frac{\tan B}{\tan \phi - \tan B} \\ &= h_o \ i/(i_o - i) \qquad (6) \end{aligned}$$

where $h_o = v_*^2 / 2g$

$i = \tan B$, the slope gradient, and

$i_o = \tan \phi$, the gradient on which talus will come to rest.

It is argued that the constant h_o should depend (a) on the difference between maximum and residual angles of internal friction (b) on effective cohesion and (c) position within the slide and on the slope. There may also be residual dependence on gradient. Nevertheless h_o has been taken as a constant for the present model, and the incorporation of these expected influences is, for the present, neglected. Within the range of gradients $i_* < i < i_o$ both the rate of retreat, R and the travel height, h are defined, and their product defines a capacity rate of sediment transport within this range (if, as normally, $i_* < i_o$ and it exists). Figure 5 illustrates the forms of the separate expressions for h and R in (a); and of their product, the transporting capacity in (b). The parameter values used are those finally adopted for the simulations. Choice of values was finally made on the basis of comparisons between model and prototype forms, but their approximate values can be derived on the following criteria.

The talus threshold, i_o is obtained by observation as the gradient on which debris will eventually come to rest, and for the largely clastic material, a standard value of 0.7 (35^o) is fully appropriate. The ultimate stable angle, i_*, should correspond to the gentlest straight slope segments observed in the field. Savigear's field measurements suggest 21^o to 25^o as the appropriate range of values, and the value of $i_* = 0.4$ (22^o) lies in the lower part of this range. For infinite planar slides with saturated soil, this gradient corresponds to an angle of friction of $\phi = \tan^{-1}(2i_*) = 39^o$, which lies slightly above values obtained by Carson and Petley (1970) for colluvial soils ($\phi = 35^o$) and distinctly below taluvial values ($\phi = 46^o$), and so in a plausible range.

The chosen value of the rate constant, α of 0.001 metres per year is very substantially less than that estimated for London Clay, as might be expected, and is of the same order of magnitude as estimates made from Carson and Petley's data for Exmoor Gritstones (Kirkby, 1973). Some confirmation of this value will be seen below in the time required for initial degradation to the 32^o slope commonly seen (ca 120,000 years), and in the time taken for degradation of a 70^o cliff without basal removal (15,000 to 20,000 years). These comparisons help to confirm not only the value of the rate constant, α, but also indicate that its value is indeed reasonably constant over the range of gradients.

The second rate constant, h_o has been derived as an indicator of the effective initial velocity of a slide mass. The value used, of $h_o = 20$m, is equivalent to an initial velocity of 20m/sec, which is the free-fall velocity from a 20 metre height. The influence of this rate constant in the model is most strongly felt at the base of a talus slope, where it controls the degree of concave 'run-out' at the slope base. The value used should therefore be chosen to represent the momentum of blocks falling from cliffs, which should on average be represented by their mid-height. The value of 20m free-fall is thus roughly in keeping with cliffs of 33m, although the exact value has been obtained by comparison with talus concavities.

The other processes considered in the model were creep/solifluction and wash. Solution was not included, and subsequent work (Kirkby, 1981) reinforces the view that its impact is small over the post-glacial time-span which is of primary concern in this paper. It has been argued above that periglacial process rates are relevant for the evolution of slopes towards the initial form of the Savigear set. Recent estimates of soil creep rates suggest some agreement (Kirkby, 1967; Finlayson, 1976; Young, 1978) on an average rate of

$$C = ki \tag{7}$$

where C is the capacity transport rate
$K = 10^{-3}\ m^2$/year is the rate constant, and
i is the local gradient

Work on solifluction rates is less conclusive, but suggests a similar linear dependence on gradient, and a rate about 10 times more rapid (Carson and Kirkby, 1972, ch 7; Harris, 1977). The rate adopted has therefore been

$$C = 10^{-2} i \ \ m^2/\text{year}$$

Wash processes were also considered in the model, but it was concluded that their effect could not be distinguished. Given the solifluction rate adopted, this means that their rate was estimated to be less than 1,000 times as great as current temperate rates. Wash was therefore not effective in the model, and was excluded from further consideration. This conclusion is perhaps surprising, in that periglacial conditions might be expected to reduce vegetation cover and increase wash rates appreciably. However the persistence of landslides as the dominant process near the slope base for periods of 200,000 years or more appears to have prevented even moderately accelerated wash from producing diagnostic basal concavities. Figure 5b shows the assumed solifluction rates in comparison with the transporting capacity assumed for landslides. It may be seen that landslides are dominant on gradients down to $i = 0.5$ ($26\frac{1}{2}^{o}$). It is assumed, following generally accepted views, that solifluction is a transport-limited process, so that transport is at the capacity rate. Combination of landslide and solifluction rates is achieved by re-writing equation 2 in the form:

$$\frac{\partial x}{\partial t} = -\frac{\partial (S_L + S_s)}{\partial z} \tag{8}$$

where S_L, S_s are respectively the rates of landslide and solifluction transport.

The model has been used as a basis for digital simulation using an explicit method to solve the differential equations, with a variable time step calculated to limit the ratio

$$\left| \frac{\Delta(x_n - x_{n-1})}{x_n - x_{n-1}} \right|$$

where x_n, x_{n-1} represent neighbouring values of x, and Δ indicates the change in them over a time increment. This procedure limits the change in gradient in a time step, and prevents instabilities and overhangs (which are excluded by the infinite retreat rate assumed for vertical cliffs). The slope height has been divided into 20 equal vertical intervals for computation.

4. Model performance

The influence of model components on landforms is most readily seen for the simple case of uniform lateral retreat at rate, G. The total sediment transport at elevation z is then:

$$S = G(z_o - z) \tag{9}$$

where z_o is the elevation of the assumed summit plateau. Where creep or solifluction is acting alone, that is at gradients less than the landslide threshold i_*, Equation (7) immediately gives:

$$i = G(z_o - z)/k \tag{10}$$

$$z = z_o\left[1 - \exp(-Gx/k)\right] \tag{11}$$

Gradient thus increases linearly with drop below the crest, and the slope profile form is that of an exponential saturation curve.

If landslides are also taken into account, then:

$$G - G_s = R - (S - S_s)/h$$

where G_s, S_s denote solufluction contributions. Substituting from Equation 7 and re-arranging

$$Ki\frac{di}{dz} = G + \left[G(z_o - z) - Ki\right]/h - R \tag{12}$$

Figure 6 illustrates a family of solutions as the rate of retreat, G, is changed, with the parameter values of figure 5. Up to three sections of the curve are apparent:

(a) The summit shows a convexity produced by creep/solifluction alone, given by equation 10. This section extends down to the threshold gradient i_*. All profiles show this section.

(b) For moderate rates of retreat, the profile then straightens out towards a uniform gradient. This behaviour is found where the eventual gradient is less than that for talus. That is if $G < \alpha(i_o - i_*)$.

(c) For more rapid rates of retreat, the creep/solifluction convexity gives way to sharper convexity at gradients above the landslide threshold, which then gradually straightens out to a uniform cliff slope at an angle which is above that for talus accumulation.

Those categories of profile appear to provide a plausible classification of the most commonly observed cliff top forms for a uniform lithology, with cliff top convexity sharpening as cliff angle steepens.

If the creep/solifluction terms in equation 12 are neglected, then gradients can also be derived for negative rates of retreat. These correspond roughly to talus accumulation conditions. In this case, sediment transport falls to zero at the base of the profile ($z = 0$), so that

$$-A = R - Az/h \tag{13}$$

where $A(= -G)$ is the rate of lateral accretion.
The toe of the curve, below the landslide threshold, is then given from equations 6 and 13 by:

$$A = Az/h = Az(i_o - i)/(h_o i)$$

or

$$i = i_o z/(z + h_o) \quad \text{for} \quad i < i_* \tag{14}$$

This is a concave run-out profile, which is strongly scaled by the travel distance parameter, h_o. Above the landslide threshold, the profile concavity is less marked, and straightens out upwards towards the taulus gradient. The profile is then given from equations 4, 6 and 13, by:

$$i/i_* = + \beta + \left(\beta^2 + \frac{A}{\alpha i_*} \cdot \frac{z}{h_o} \cdot \frac{i_o}{i_*}\right)^{1/2} \tag{15}$$

where $\beta = 1 - A(1 + z/h_o) / (2\alpha i_*)$

The times taken to approach the equilibrium conditions described above are related to the rate of retreat or accretion, and position on the slope. Equilibrium form is reached at the base of the slope first for retreat, and at the top of the accumulation zone for accretion. The horizontal rate of advance of the equilibrium zone is of the same order of magnitude as the retreat/accretion rate. Since gradients are lower for lower rates, the total time required to approach equilibrium close to the crest increases at a rate much higher than $^1/|G|$. Thus at G = 5mm/year, a 100m high cliff equilibriates in approximately 8,000 years; whereas at 0.1mm/year about 4 million years are required. The normal expectation should therefore be that equilibriation is confined to the cliff itself and a narrow transitional zone to a relatively unaltered pre-existing slope form. Even this deduction should be viewed in the light of particular histories of recent cliff-falls, and of fine lithological detail.

Figure 7 shows a model simulation for a 100m cliff initially at 70^{o}, which has been allowed to decline passively with basal accumulation onto a horizontal surface. Parameter values are as described above for landslide and solifluction rates. Field evidence for the survival of post-glacial cliffs suggests that they must survive for 5,000 to 10,000 years as recognizeable cliffs. This criterion sets an upper limit on the rate constant, α for free degradation (in the post-glacial period). Figure 6 shows that the values used are at the upper limit set by this survival criterion. The simulation mirrors qualitative observations of talus form in that it produces a concave profile, with the concavity lessening as the cliff is progressively buried. The broken line shows the envelope of successive profiles, which gives the shape of the contact between talus and in-situ bedrock. The convex form of this bedrock core also mimics previous talus models (since Fisher, 1866) and observed forms (in other areas). As a talus accumulation model, the present simulation differs from most previous ones in allowing the cliff to decline in gradient over time. This feature is considered to be an improvement in many cases, as is the tendency for the lower part of the cliff to show a narrow concavity, becoming almost tangent to the talus at their contact. The present model is therefore thought to behave fairly realistically as a talus model in both quantitative and qualitative terms. Its most serious failing in this respect is that no allowance is made for any change in bulk in conversion from rock to scree.

Figure 8 shows a model simulation for a 100m high slope for an initial 70^{o} cliff cut into a horizontal summit plateau. Basal removal has been allowed from a fixed point at the foot of the initial cliff. The relevant time scales are much longer, although some comparison may be made between the upper portions of the profiles for 20,000 years in figure 7 and for 25,000 years in figure 8. For the period from 25 to 100 thousand years, there is some tendency to slope replacement, although without the distinct slope facetting described by Carson & Petley (1970). From 100 thousand years, the lower part of the slope appears to be declining steadily in gradient, and shows a substantial length of almost uniform gradient. These profiles should be compared with the initial forms for the Savigear set.

The extent of the upper convexities shown in the profiles in figure 2 varies considerably. In some cases, like profiles C and J, there is an abrupt convex break in slope form approximately 7^{o} to 32^{o}. Perhaps the best comparison with the assumed infinite plateau of the model is found for profiles A, F and I which extend (figure 1) to a broad summit or along the length of a ridge. In these cases, the elevation ranges from the summit to the straight slope at 30^o or more are respectively about 25m, 60m and 50m. These convexities are largely produced, in the model, by creep/solifluction. At the assumed rate ($k = 0.01m^2/year$), figure 8 shows that times of one to five hundred thousand years are required to produce convexities of these sizes. It is therefore inferred that more than one, and probably several glacial periods would be required to produce summit convexities of the dimensions found in the field for plausible solifluction rates. Alternatively, it might be inferred that summit convexities are appreciably younger, and that solifluction rates were greater in direct proportion. The total available time span is presumably the sum of periglacial periods during which summits have been above sea level. Without evaluating this time span here, it is thought sufficient to allow for observed convexities at the modelled solifluction rate.

If time spans of 100,000 to 500,000 years are assumed, then the most widespread straight slope segment (at 32^o) is readily interpreted as the straight slope segment shown in figure 8. It is argued that the common life span of the slopes produces a strong convergence of gradients for such a segment, and that this is a sufficient condition to produce widespread straight segments at an angle which is not itself a threshold. Plainly if a threshold of some sort is found at a particular angle, its influence will be to make this angle even more widespread, and of longer duration at each site. It is however argued that evidence like that found on the surveyed cliffs, of a widespread straight slope gradient, does not necessarily require the postulation of a coincident threshold. This argument is reminiscent of those used by Daly (1905) and Hack (1960) for the accordance of summit levels as evidence of a shared history rather than of coincidence with a former peneplain level.

Figure 9 shows the decline of maximum slope gradient with time for the simulation in figure 9. The curve is however very insensitive to basal conditions; and sensitivity to initial form decreases with time, provided only that there is a steep enough initial gradient. The time scale is directly related to the magnitude of the rate of retreat constant, α. Thus to attain a gradient of .625 (32^o) in 100,000 to 500,000 years, implies that α lies between .00025 - .00125m/year. It is clear that only much higher values of α ($>$.01m/year) could produce the 32^o segment in postglacial timespans, and that under those circumstances cliffs would survive recognizeably for only about one thousand years.

In adopting a value for α, there is some conflict between alternative values, although little doubt about the order of magnitude. The range of values given by the 32° segment are related to decline during periglacial periods. Rates might then have been higher than for the more temperate conditions to which the rates of postglacial cliff attach and talus accumulation relate.

5. The set of cliff profiles

In modelling the Savigear set of cliff profiles, a common initial form has been adopted. This corresponds to the $2x10^5$ year profile in figure 8, with a straight slope segment of 0.54 ($28\frac{1}{2}^{\circ}$). The summit height of 100m is similar to that of St Johns Hill (figure 1) on which profiles A to D (figure 2) were surveyed. These values have little impact on the profiles of cliff formation and degradation. Little postglacial reshaping of this initial form occurs above the top of the degraded cliff. The crucial parameter in determining the set of forms is the rate of marine cutting at the cliff base, which has been treated as an independent variable, although it plainly interacts with the resulting supply of rock fall debris. The observed maximum cliff height of approximately 30m cut into a 32° slope requires about 50m. For modelling purposes, this retreat is assumed to have been at constant rate over a 10,000 year period, at 5mm per year.

Figure 10 shows the set of profiles corresponding to 20mm/year wave attack. The small extent of change in form above the cliffs is evident in all cases, despite the time elapsed and the very different basal conditions from the fixed base for which the initial form was derived. The cliff base position is shown for each profile by the contact between talus and in-situ bedrock. At the end of the period of wave attack, all cliffs initially stood at an angle of 87° (from equation 4). The profiles with the shortest periods of wave attack naturally had the lowest cliffs, and they have been degraded for the longest time. The size of the talus slope is increased both by the length of the degradation period and by cliff height. Since these influences act in opposite directions, their combined effect is to produce the largest talus accumulations under rather young and high cliffs, with an abrupt decline towards still-active cliffs and only a gradual decrease in talus height towards the older cliffs. In this example, it may be seen that not only is wave attack too rapid, but also that the cliff does not survive long enough. The possibly insufficient cliff survival is also shown in figure 11, which shows the lower 50m height of a Savigear set corresponding to basal retreat at 5mm/year, with profiles corresponding to 5,000 (at left) to 10,000 (at right) years of cliff retreat and subsequent basal accumulation onto the marsh. This range of timespans is thought appropriate from the evidence of Savigear's profile D (or Z in his figure 5), which shows a cliff-top remnant at approximately 16m above the marsh: that is at about half the height of the active cliff in profile A.

It is concluded that landslide retreat may have been at a reduced rate in post-glacial times (and/or that the rate constant, α, is substantially lower for cliff gradients than at gradients closer to the ultimate threshold). Evidence of accelerated landsliding in late-glacial cold periods in S.E. England (Skempton & Weeks, 1976) lends support to this view. Similarly it is appropriate to reduce slow processes from solifluction to creep rates for the postglacial period. Although this reduction makes a negligible difference to the total postglacial sediment accumulation it nevertheless helps to maintain the sharpness of the clifftop shoulder. The total talus and rock-core cross-section below the cliffs is determined largely by the rate of marine attack which dictates the cliff angle. The rate of cliff retreat is therefore initially equal to the rate of marine attack as basal accumulation begins slowly reducing as the cliff angle reclines. The talus cross-section is thus not a sensitive indicator of the rate of retreat parameter, α. Cliff angle is similarly insensitive to α, ranging from 80° - 90° at 5mm/year wave attack, for values of α from 0 to 0.001m/year. Savigear (ibid. p.40) estimated that cliff gradients ranged from 60° to 90°, probably averaging 80°. Perhaps the most sensitive indicators of the postglacial rate of retreat constant, are (i) the extent of cliff gradient decline and consequently the extent to which the talus and rock core apron has encroached upon the degraded cliff; and (ii) the survival of the cliff top angle as a recognizeable feature for about 5,000 years (using the model timescale).

Figure 12 illustrates the best compromise found, with postglacial cliff retreat unchanged from its glacial rate ($\alpha = 0{\cdot}001$), but with creep instead of solifluction rates. As in figure 11, the block diagram is shown for the lower half of the slope only. Comparison shows the markedly better preservation of the cliff shoulder, while retaining a substantial alluvial apron. The effect of cliff retreat during degradation has been to raise the cliff shoulder, so that profile D is perhaps a little older than the extreme left-hand profile shown. Figure 12 is seen as an adequate model of the observed Savigear set of degraded cliff profiles, with parameter values adequately determined through comparison between model and prototype.

The model is thought to show well the most apparent elements of the surveyed profiles, namely the gradual decrease in cliff shoulder height from east to west; and an abrupt rise in cliff/talus contact near the fresh cliffs at the eastern end, with little change in its elevation westwards, while the talus apron becomes broader and less steep. Detailed comparison suggests that the cliffs at sites B, C and D have been abandoned for periods of about 500, 1,000 and 6,000 years respectively, assuming a total postglacial span of 10,000 years for wave attack.

The exposures of bedrock in the abandoned cliff profiles, and the rate of post-glacial cliff retreat argue for the retreat of fresh bedrock cliffs along the Eastern section of the surveyed coastline. If exhumation were taking place, retreat rates might approach the very much higher values quoted above for London Clay slopes for historic times.

The surveyed profiles west of the Coygan peninsula show no evidence of cliffing as recent as those discussed above, but conform closely to profiles obtained for basal accumulation throughout at least the whole postglacial period, and perhaps much longer. Evidence for buried former cliffs is not apparent from the profile forms, but model runs suggest that stratigraphic sections could reveal two or more stages of cliff retreat and partial exhumation alternated with periods of basal accumulation. The expected stratigraphic relationships are sketched in figure 13.

In comparing this site, in the centre of Carmarthen Bay with other cliffed coasts in southwestern Britain, it is unusual in the gentle offshore gradients. A striking difference is found, for example, in comparison with the north Devon cliffs falling from Exmoor, which fall to 20 fathoms within 2-3km of the shore, in comparison with 15km in Carmarthen Bay. Where offshore gradients are gentle, small differences in sea-level have a strong influence on the position of the coastline, so that wave attack has less opportunity to erode and exhume a cliff line than on steeper coasts. Carmarthen Bay may therefore not be representative of southwest Britain as a whole.

6. CONCLUSIONS

The model presented is thought to offer a useful advance in realistically simulating slope evolution including landslides over time spans much longer than the interval between individual slides. Two threshold gradients are associated with the model; a higher talus threshold (35°) above which slides will not come to rest, and a lower threshold of ultimate stability (22°) in the very long term. In an area of common lithology and history, the period of common slope development is thought to be sufficient to produce dominant straight slope segments (32° in this area) which lie between these thresholds, but are not themselves a threshold. This proposal is seen as an extension of some arguments for accordant summit levels.

The degree of summit convexity is considered to argue for a period of at least 100,000 years of periglacial climate for its development. In other words the relief is thought to predate at least two glacial periods. With this time-span a more or less constant rate of slope retreat (at any given gradient) is appropriate for both glacial and postglacial periods, although solifluction is thought to have given way to soil creep, at a rate approximatel; one tenth as rapid.

The series of former cliff profiles east of the Coygan peninsula is though to have evolved as proposed by Savigear. Marsh encroachment from west to east has progressively curtailed marine attack and replaced it by conditions of basal accumulation. Model and prototype are thought to show good agreement within the range of variability expected in variable strata.

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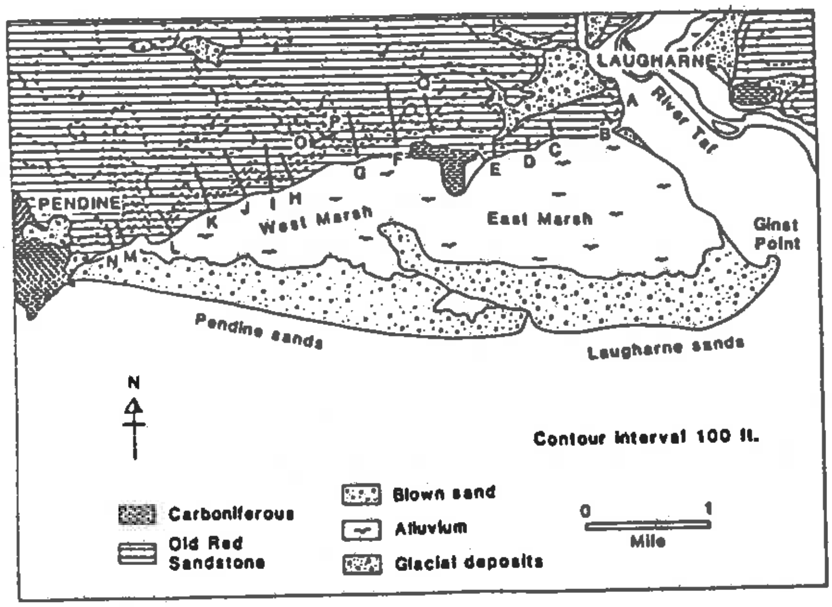
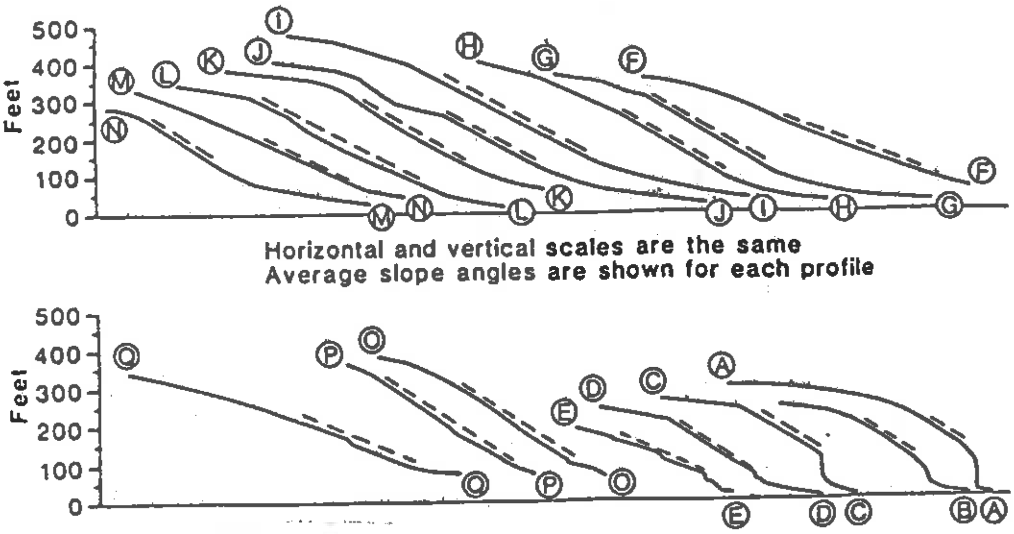
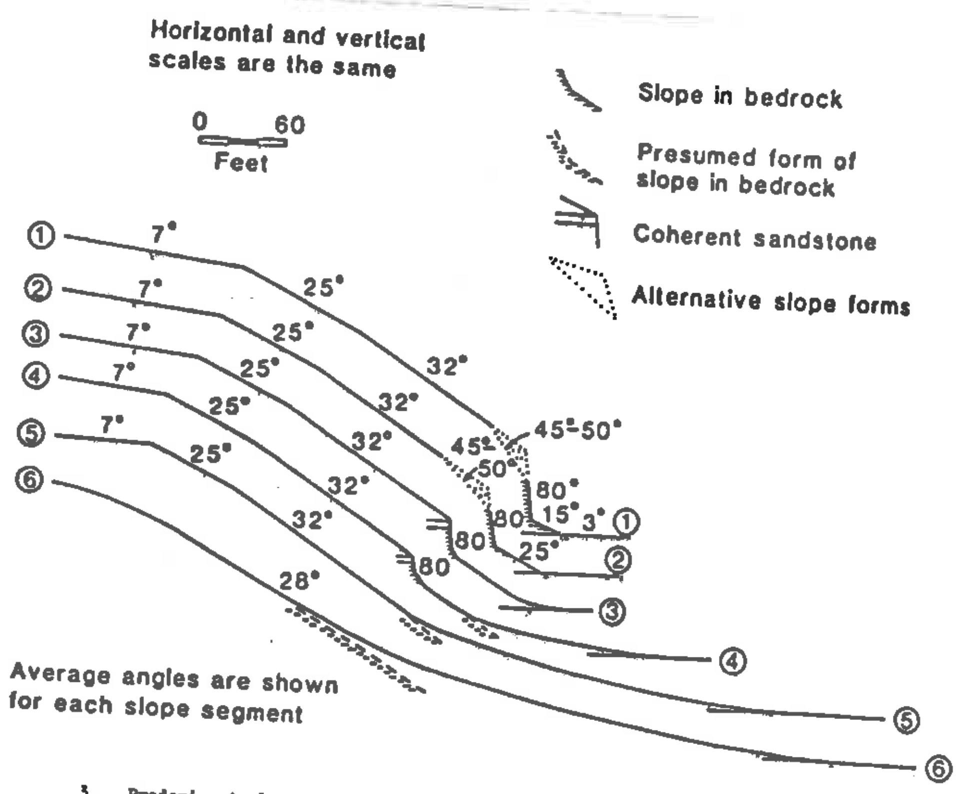


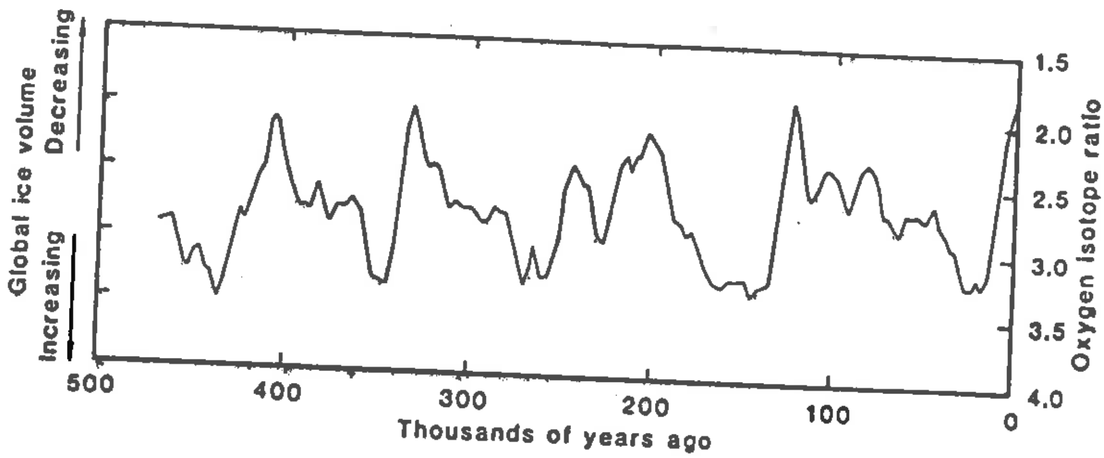
1. The area of the surveyed profiles between Pendine and the Taf estuary (after Savigear, 1952).



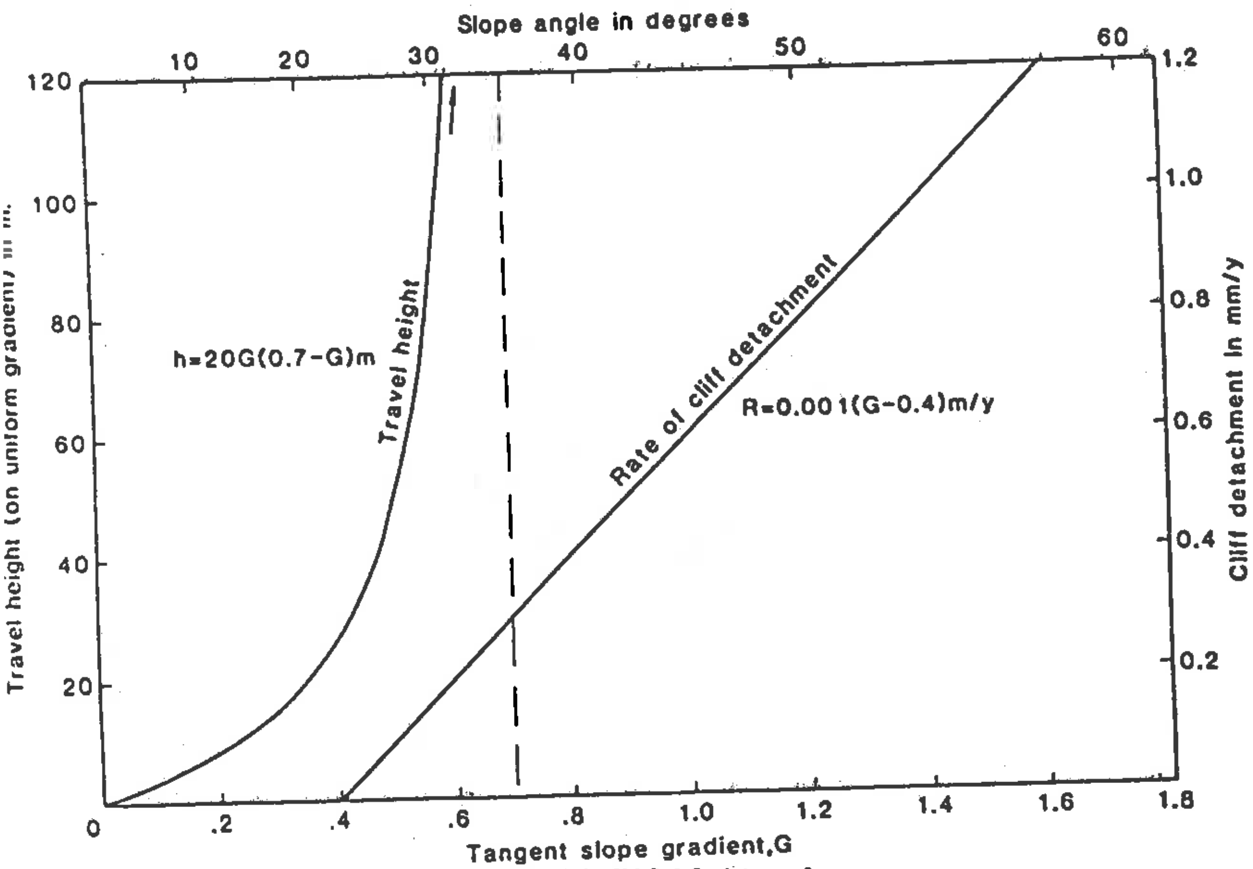
2. The surveyed profiles shown in figure 1 (from Savigear, 1952).



3. Predominant slope processes after Savigear (1952).



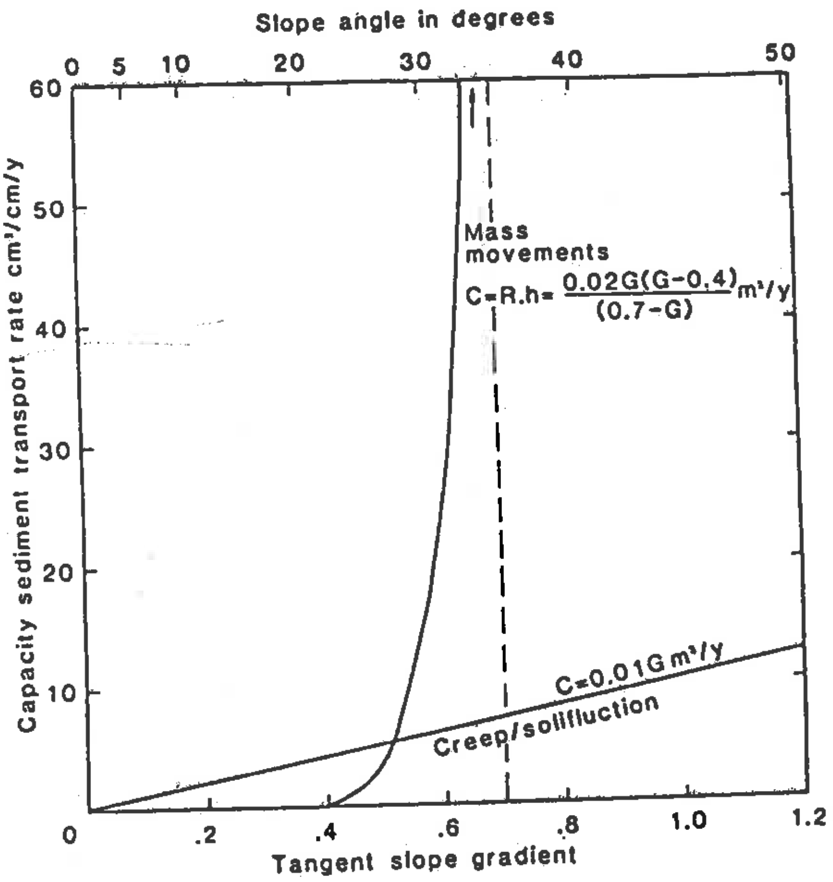
4. Climate of the past half-million years. (Data from J.D. Hays et al., 1976)

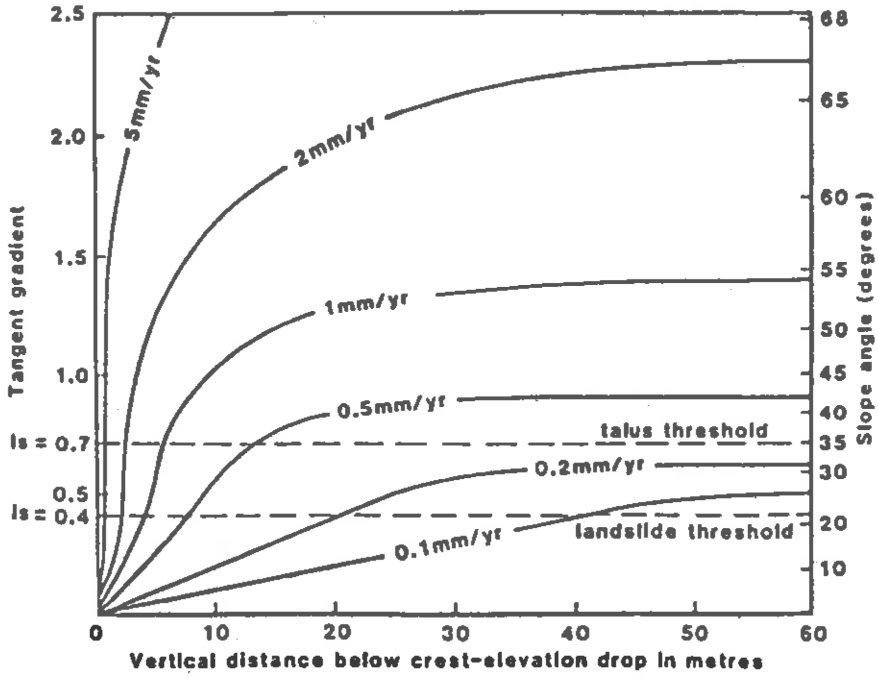


5. Modelled rates of landslide transport in Old Red Sandstone of study area

↑ (a) Travel height on uniform gradient and Rate of cliff detachment

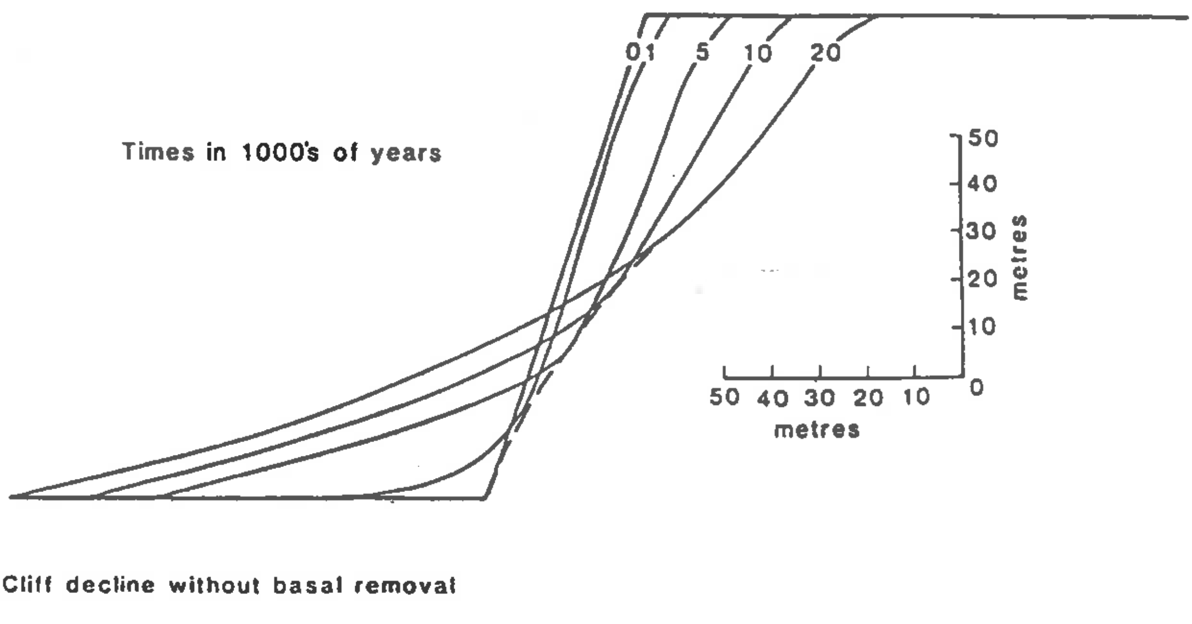
↓ (b) Capacity transport rate (where defined) in comparison with solifluction rates.

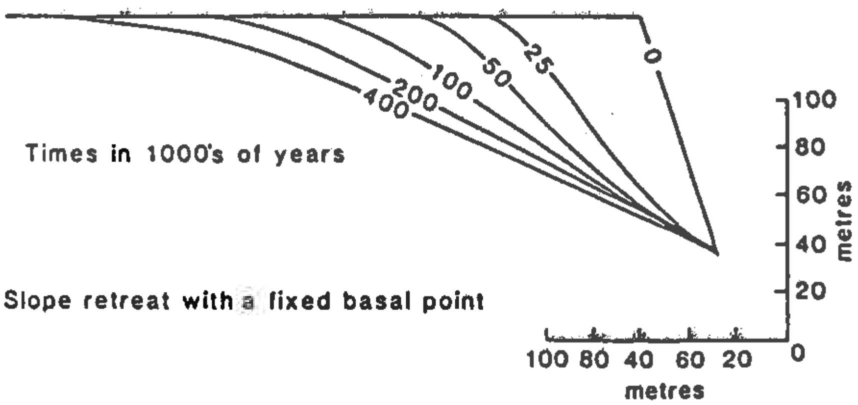




↑ 6. Slope gradients in equilibrium with constant rates of lateral retreat, expressed in terms of elevation below plateau crest.
For landslides : $i_s = 0.4$: $i_o = 0.7$: $= 0.001$m/yr : $h_o = 20$m
For creep/solifluction : $k = 0.01m^2/yr$.

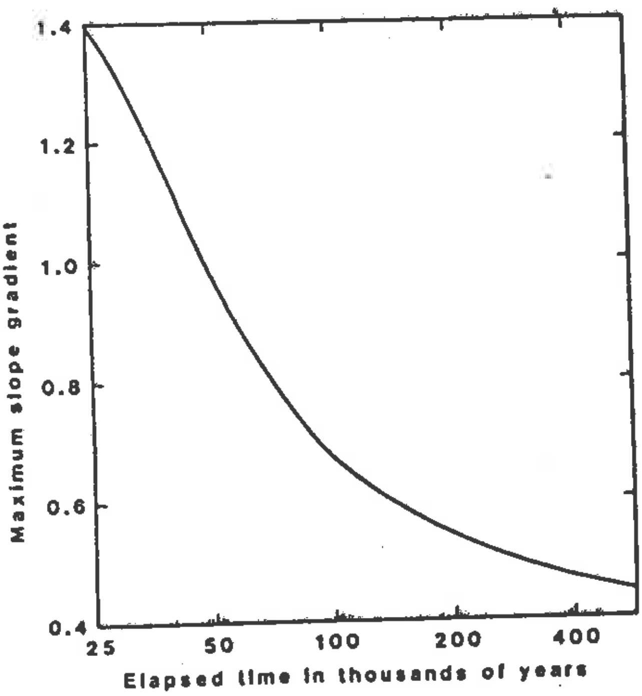
↓ 7. Modelled cliff decline with basal accumulation on horizontal foot slope. Times in thousands of years.

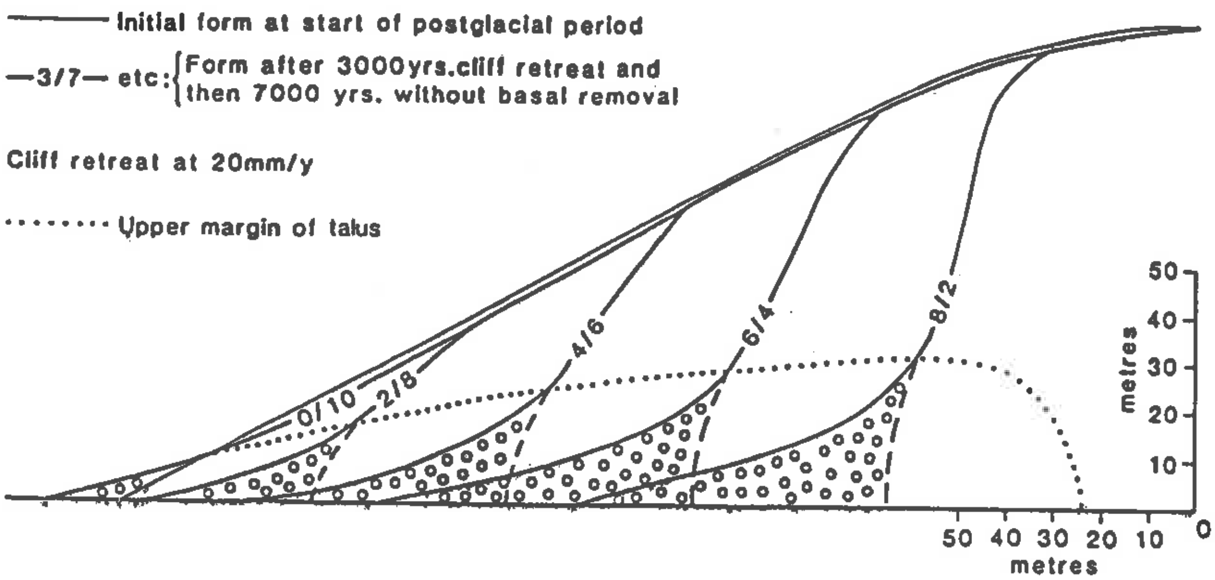




↑ 8. Modelled slope decline with a fixed basal point.
Initial slope a 70° cliff cutting a summit plateau.
Times in thousands of years.

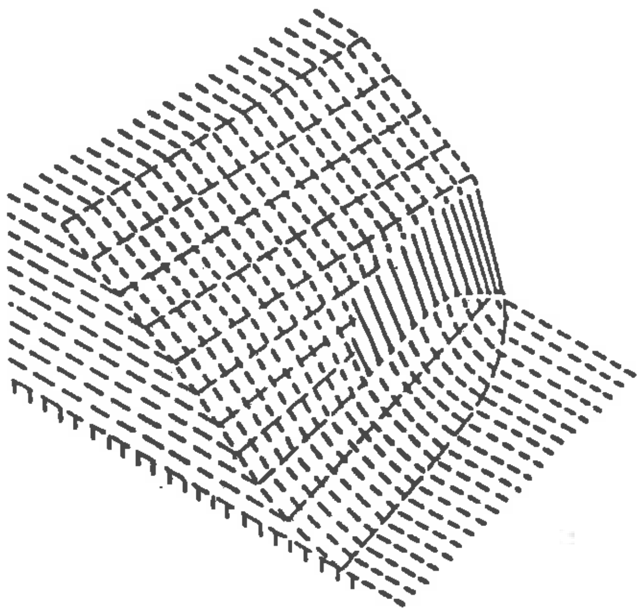
↓ 9. Modelled decline of maximum slope gradient over time, starting from a 70° cliff at time zero.



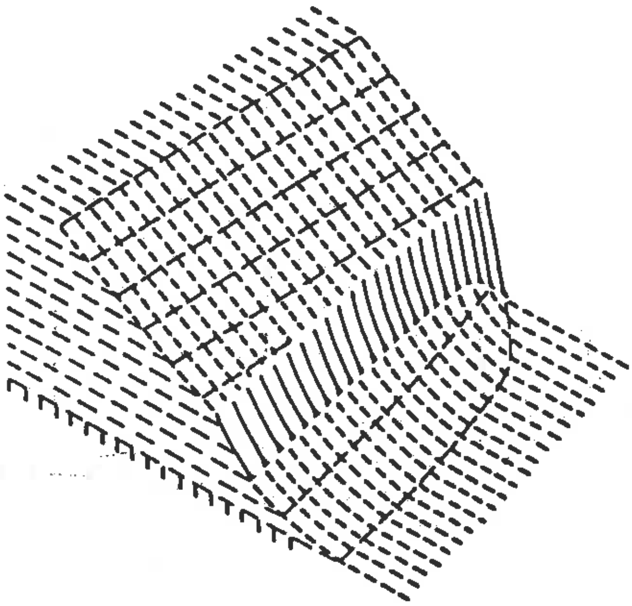


↑ 10. Modelled Savigear set of profiles for 20mm/year basal retreat for periods of 0-0,000 years and basal accumulation for the remainder of a 10,000 year period.

↓ 11. Isometric block diagram showing a modelled Savigear set of profiles for 5mm/year basal retreat, for periods of 5,000 - 10,000 years in 250 year increments. Lower half of slope only. Scale ticks and contours at 5m intervals. For landslides = 0.001m/yr. For solifluction $K = 0.01m^2/yr$.



Scale ticks and contours at 5m. intervals



Scale ticks and contours at 5m. intervals

↑ 12. Isometric block diagram as in figure 11, but with creep replacing solifluction, sharpening shoulder of cliff edge. $K = 0.001m^2/yr$.

↓ 13. Schematic relationship between older and younger colluvial/talus deposits if a cliff is cut and partly re-cut, with alternating periods of basal accumulation.