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Factors influencing the coastal landslide hazard zonation of parts of north and south Devon

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An overall assessment of cliff stability along more than 120km of coastline in north and south Devon has resulted in the preparation of ranked landslide hazard zonations of these areas. The zonations were achieved objectively by interpretation of existing geomorphological forms and processes and historical landslide data. The rankings of each zone describe the probability of cliff-top recession and the likelihood of falls reaching the cliff base. Subsequently the distribution of the hazard rankings around the coast has been analysed in order to assess the relative importance of factors which might cause or control the rate and style of landsliding. This analysis has shown the extent to which geological structure, lithology, Quaternary deposits, cliff morphology and aspect influence the pattern of hazards observed.

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Introduction

Coastal landslide hazard maps have been produced at 1:10 000 scale covering all the cliffs within the jurisdiction of two local authorities in Devon, the North Devon District Council (from Braunton near Barnstaple around the coast to the county boundary with Somerset) and the South Hams District Council in south Devon (between Plymouth and Torbay) (Grainger and Kalaugher 1987; Kalaugher and Grainger 1988). The hazard zonations are intended to be used for preliminary planning purposes for cliff-top properties and for guidance in deciding whether or not recreational use of cliff-base areas should be encouraged. The hazard zonations are not site specific and should not be considered as replacements for conventional site investigations.

In order to increase the usefulness of the zonations, they are ranked in two separate parts, as shown in the example from south Devon (Fig. 1 and Table 1), one part for the recession of the cliff top, the other for the hazard of impact by falling debris at the cliff base. The hazard zonations and their rankings have been obtained by interpretation of the present cliff morphology and direct evidence of active processes of instability. That is, they are based entirely on effects rather than on causes. An alternative approach, used in some previous landslide studies (Hansen 1984), is based on the statistical analysis of numerical rankings arrived at by assigning points to causative factors and to geomorphological features. This method was thought inappropriate for coastal studies because some of the features, such as landslide debris, may now be missing as a result of marine erosion.

However, in order to check that the zonations are in broad agreement with natural phenomena, and are not just arbitrary, follow-up studies were made on the distribution of hazard zones and their rankings, after the maps and reports to local authorities had been completed. Accordingly, the rankings were tested for correlation with some of the likely causative factors including lithology, geological structure and the combined effects of fetch and exposure of the coast to the prevailing winds.

Data acquisition and interpretation

The main data on the geomorphology of the coastline were obtained from oblique aerial photographs suitable for stereoscopic examination (Grainger and Kalaugher 1988). The interpretation of these photographs was backed up by associated fieldwork in selected areas during which terrestrial photographs (colour transparencies) were taken to enable key areas of expected high activity to be monitored. The transparencies can be compared with the directly observed view on a later visit, in a special optical device which makes any changes immediately obvious (Kalaugher 1984, 1985, 1986; Kalaugher and Grainger 1990). This technique provides a convenient method of checking short-term rates of landslide activity and enables slopes to be monitored in areas where an early indication of movement is desirable.

The remaining part of the data acquisition involved a historical review of any readily available aerial and terrestrial photographs, and geomorphological and geological literature covering the region. All of the photographic data were interpreted and provisional zone boundaries drawn up on the basis of the geomorphology of the coastal slopes, with particular emphasis being placed on any evidence of instability. For most stretches of coastline there was no pertinent information available other than the specially flown aerial photography. The hazard rankings were finalised upon completion of the fieldwork.

Distribution of hazard rankings

Having completed these two hazard zonations by considering only the landsliding effects, the distributions of zones and their rankings have been analysed and compared with some of the possible contributory causes.

Initially, within each zone, the hazard ranking at the cliff top was compared with that at the cliff base. A strong correlation was found between these two rankings, as might have been expected for a predominantly hard-rock coast with steep cliffs, where the debris from cliff-top recession rapidly falls or slides to beach level. Exceptions to the correlation occur in only a few areas where the debris which reaches beach level is not directly derived from cliff-top recession but originates from rockfalls or slides at mid-slope, and where debris from cliff-top recession is delayed by accumulation in gullies. Despite these few exceptions, it is justifiable to consider correlations between causative factors and cliff-top hazard ranking only.

As a basis for comparisons, Fig. 2 shows the distributions of the cumulative lengths of coastline within each category of cliff-top hazard for North Devon and South Hams Districts. The differences between the north and south of the county can be related to the differences in cliff height and style of landsliding, which are themselves related to geological structure and lithology.

In north Devon, the general dip of the bedding and cleavage is to the south, at angles which are usually steep and, in some places, nearvertical. The dips tend to be less steep and more variable in direction in the east of the study area. Toppling, therefore, is the main style of initiation of rock slope failure at the cliff top (Fig. 3a). The welljointed nature of the rock masses leads to disintegration into blocky debris and hence to rockslides on the lower slopes. Faulting is common on this coast, particularly in north-south and NW-SE directions, and controls the location of many gullies in the higher cliffs, and wave-eroded slots in lower cliffs. Comparing hazard ranking with rock type (Fig. 2a) suggests that the north Devon cliffs in sandstone-dominated and mixed-lithology formations pose greater hazards than those cliffs in slates. This is partly a function of the extremely high cliffs in the former lithologies.

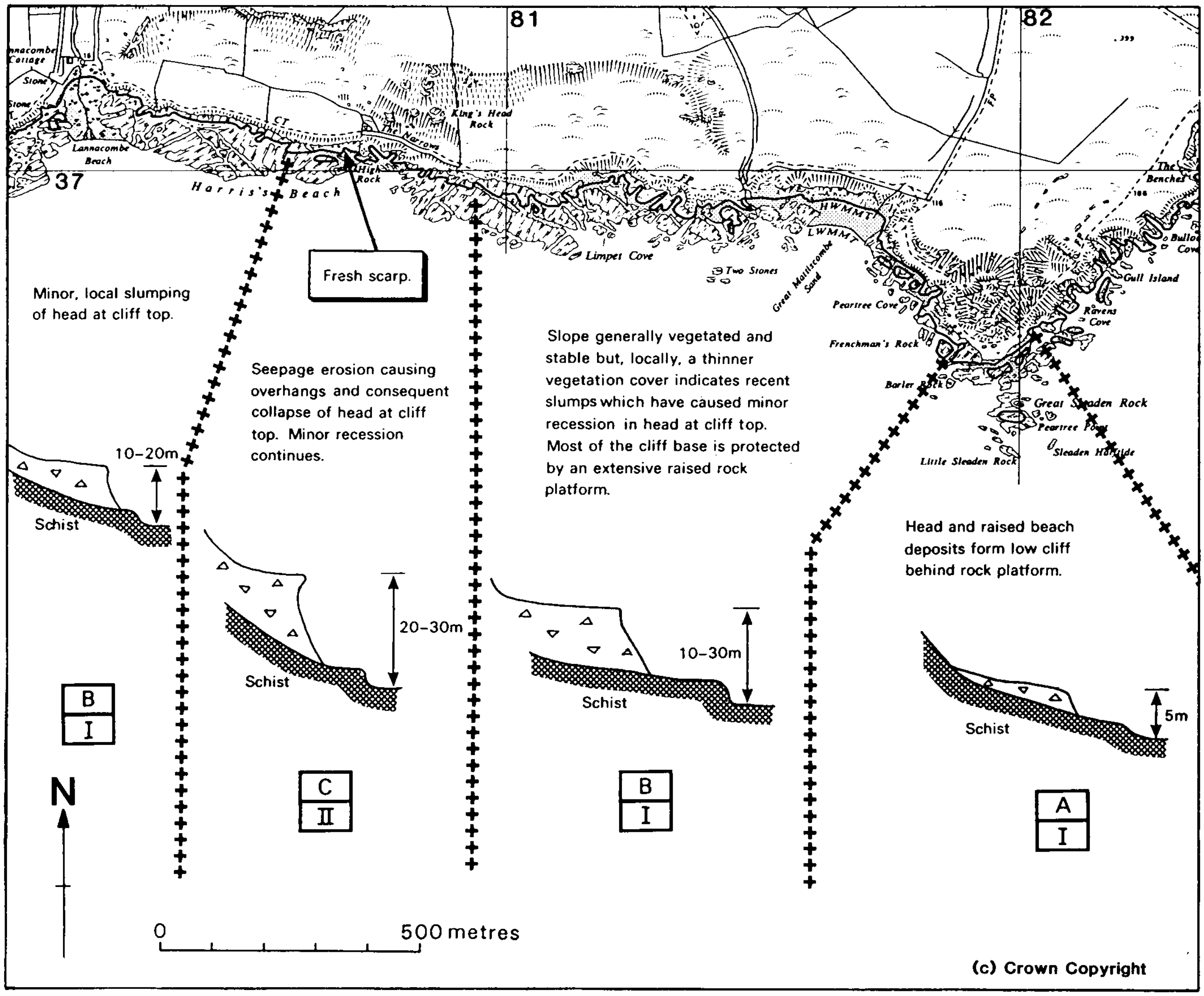

Figure 1. Example of hazard zonation of a length of coastline to the west of Start Point, south Devon. See Table I for definition of hazard rankings.

In south Devon the dip of the bedding and cleavage is in many areas at angles around 60 degrees, mainly to the south to SE. These dips are steeper than the overall slope of most of the cliff profiles, but sliding, controlled by the bedding or cleavage and cross-cutting discontinuities, is still the principal failure mechanism (Fig. 3b). Again, the highly fractured nature of the rocks results in disintegration rather than in the movement of large intact blocks. In contrast to north Devon, the slate formations of South Hams are more prone to landsliding than the stronger schists and sandstones (Fig. 2b), the Meadfoot slates being less stable than the Dartmouth slates. The cliffs extend in height up to only 130m (compared with 220m in north Devon) and there is no correlation apparent between maximum cliff height and the hazard ranking in each zone. Resistance to basal erosion, and the friction angle on cleavage planes, seem to be the controlling factors in the south.

Along both coastlines studied, the considerable local variation in the aspect (facing direction) of the cliffs has been averaged over the length of each hazard zone. The total length of coastline within each ten-degree interval of compass bearing has been plotted in Fig. 4, and the resulting histograms have been divided between higher hazard rankings (D-F) and lower hazard rankings (A-C). In north Devon relatively more of the higher hazard zones face between north and NW. This can be explained in terms of the difference in fetch of waves from the west compared with those from the east, down the Bristol Channel (with allowance being made for wave refraction into shallow water). In south Devon there are more of the higher hazard zones between south and SW than between south and SE, for the same reason, but here with respect to the English Channel. Besides having the greatest fetch, the SW facing lengths of coastline in south Devon also receive the full force of the predominant SW gales.

Quaternary features and deposits are preserved on parts of the coasts of both north and south Devon (Kalaugher and Grainger 1989). A typical profile consists of a low cliff of head (solifluction) deposits overlying a raised rock platform, in some places with weakly-cemented raised-beach sands at the base of the head (Cullingford 1982). Although the weak deposits exposed in these cliffs would be prone to rapid marine erosion, they have survived where the exhumed seaward portion of the rock platform protects them from direct attack (Saunton Down in north Devon is a good example). Thus there is a correlation between low, rather than high, hazard rankings and those cliffs composed chiefly of head deposits (Fig. 2a, b).

It should also be noted that present-day beaches, where of considerable volume, can provide significant or even total protection of cliffs from wave erosion. Low hazard rankings (or zones of no classification because cliffs do not exist) therefore correlate with the occurrence of such beaches. The zonation then has to be qualified with the proviso that a natural or artificial reduction in beach level or volume may drastically alter the hazard ranking of the cliffs. This can be demonstrated, in retrospect, at Hallsands in south Devon, where artificial lowering of the beach early this century has resulted in the

Table 1. Definitions of hazard rankings for cliff-top recession and for impact by debris at beach level (after Kalaugher and Grainger 1988).

HAZARD RANKINGS AT THE CLIFF TOP

A Cliff-top recession is likely to be negligible (less than one metre) everywhere in any 10 year period, and so the total recession is nowhere likely to exceed 10m in 100 years.

B Locally cliff-top recession could be as much as 2m in any 10 year period, but the total recession is nowhere likely to exceed 10m in 100 years.

C Locally, in landslides, cliff-top recession could be as much as 5m in any 10 year period, but the total recession is nowhere likely to exceed 10m in 100 years.

D Locally, in landslides, cliff-top recession could be as much as 10m in any 10 year period, but the total recession is nowhere likely to exceed 10m in 100 years.

E Locally, in major landslides, cliff-top recession is likely to be as much as 10m in any 10 year period, but elsewhere the total recession is unlikely to exceed 10m in 100 years.

F Where major landslides are already developing, cliff-top recession is likely to exceed 10m in the next 10 years. The effect of these landslides on longer-term stability of adjacent cliff-top areas is unpredictable.

HAZARD RANKINGS AT THE CLIFF BASE

I Potentially injurious rockfalls, slides or slumps unlikely to reach the base of the cliff each year.

II Potentially injurious but minor falls, slides or slumps are likely to reach the base of the cliff each year.

III Major falls, slides or slumps are likely to reach the base of the cliff within 10 years. Minor falls, slides or slumps, also potentially injurious- are likely each year.

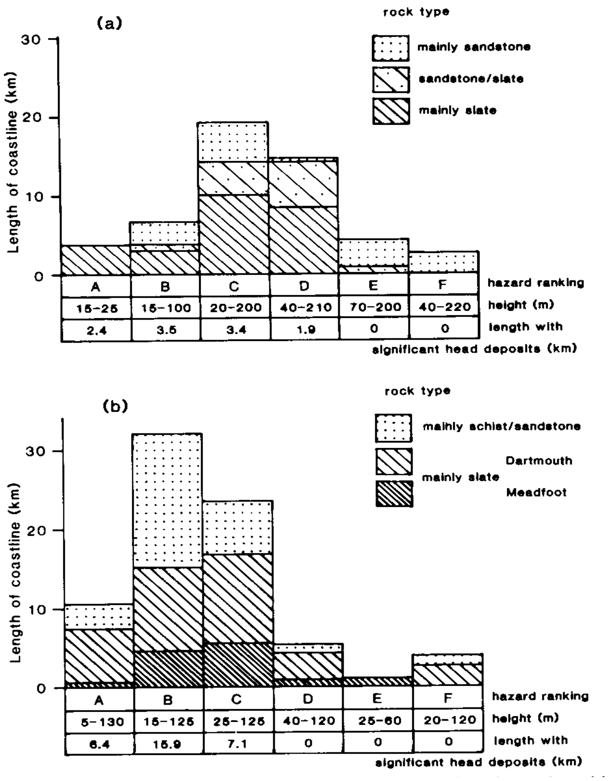

Figure 2. Cumulative lengths of coastline plotted against hazard ranking (increasing A to F), for a) north and b) south Devon. In each ranking category, the rock types, the maximum heights of cliffs and the extent of cliffs with a significant component of head deposits are also shown.

loss of the lower village and severe undercutting of the cliff below the upper village.

Conclusions

The objectives of the research described in this paper were to assess the geological and geomorphological validity of the hazard zonations carried out previously by the authors in north and south Devon. The choice of the size and location of each study area does not bias the data as the area boundaries are those of the local authorities for whom the original surveys were conducted, and thus they have no geological significance. On the other hand each area is large enough to contain a statistically meaningful number of hazard zones.

Correlations and trends can be found in the data which demonstrate the links between cause and effect of coastal cliff instability in north and south Devon. In particular the high hazard areas occur where adverse geological structure and lithology combine with high cliffs facing in directions of maximum wave intensity. However, it would not have been possible, because of the number of exceptions and wide scatter of the data, to have erected the hazard zonations on the basis of factor analysis instead of the observational approach adopted. Furthermore, any statistical approach would require a very large area to be studied before any conclusions about the hazard ranking of a particular short length could be reached. The hazard zonation procedure developed by the authors can be applied to any length of coast down to about one kilometre without loss of accuracy. It forms a good basis for individual geotechnical site investigations at a more detailed scale, because such investigations start with a similar observational approach. It is, nevertheless, encouraging that analysis of the possible causative factors in the extensive studies in north and south Devon has shown that the rankings do largely correspond with natural phenomena and therefore have some scientific validity.

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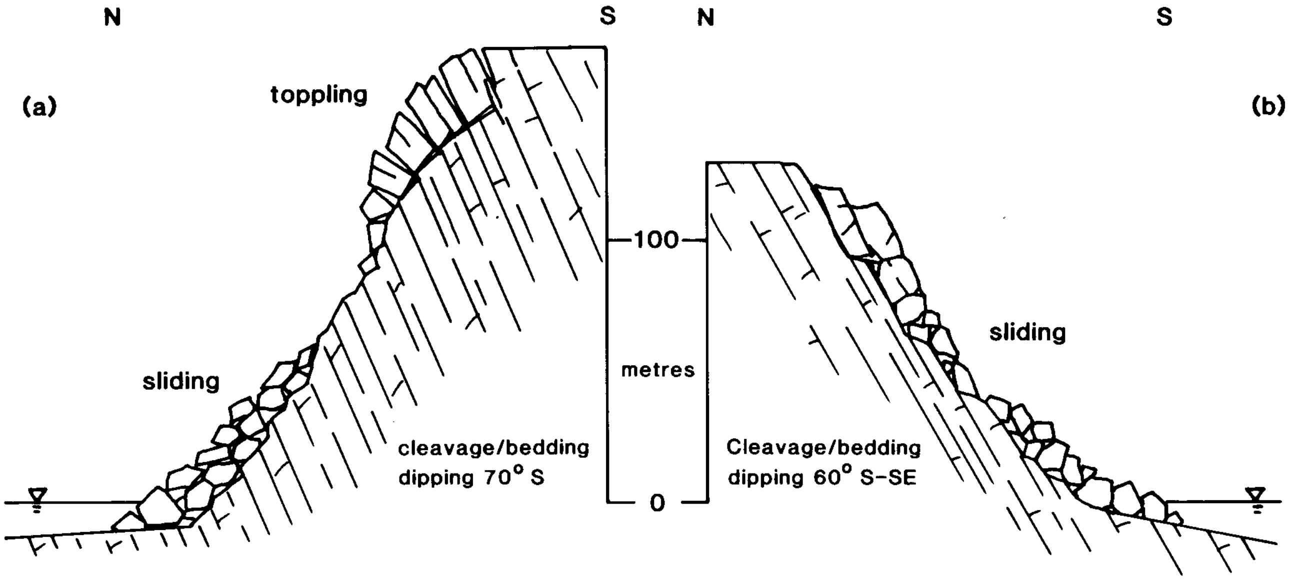

Figure 3. Schematic cross sections through typical cliffs in a) north and b) south Devon, showing failure mode and generalised geological structure.

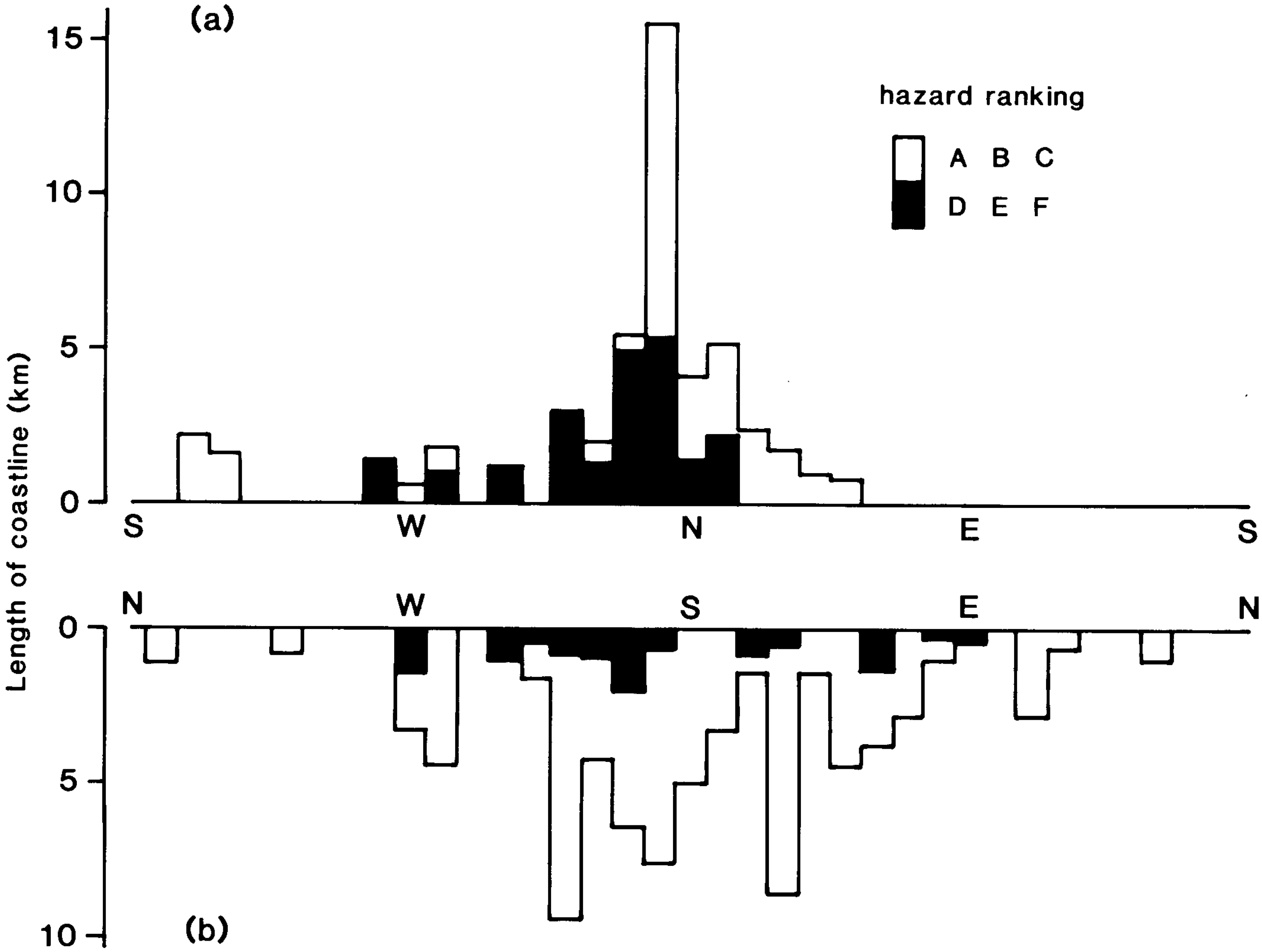

Figure 4. Cumulative lengths of coastline plotted against aspect (facing direction) of the cliffs in a) north and b) south Devon. Lower and higher hazard rankings are differentiated.