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ALTIPLANATION TERRACES AND SLOPE DEVELOPMENT IN VEST-SPITSBERGEN AND SOUTH-WEST ENGLAND

Abstract

Conspicuous among periglacial modifications of recently de-glacierized dolerite terrain in Ekmanfjord, Vest-Spitsbergen, are rock benches and terraces on moderately inclined slopes (7—25°) lying between 50 and 100 metres above sea-level. Field observations suggest that the benches are fashioned primarily by frost heaving, frost shattering and the gravitative transfer of debris. Their continuing development is converting formerly ice-smoothed, convex-upward slopes into stepped, but overall rectilinear, slopes which retain their steepness as they retreat.

A similar origin is suggested for terraces hillslopes displaying features akin to altiplanation terraces which are very characteristic of the higher parts of south-west England. The demonstration that these landforms are periglacial features not only supports the conclusion that many parts of Southern England exhibit relict periglacial landscapes. It also suggests that in some cases cryergic processes have created rather than smoothed out irregularities of slope. The mature or equilibrium slope of cryoplanation is indeed smooth and compounded of accordant elements the inclination of each of which represents the slope limit appropriate to the calibre of the debris that is moved across it. But the achievement of cryoplanation on certain moderately inclined initial slopes is effected via the production and development of altiplanation terraces or congelifraction benches. These are characteristic of those parts of Southern England of which for one reason or another the complete periglacial metamorphosis was never realized.

Altiplanation terraces were first recognised in Britain by Guilcher (1950). In 1950 he interpreted as relict periglacial features terraced hillsides developed on indurated arenaceous sediments (Middle Devonian *Hangman Grits*) near the north Devon coast. Six years later Te Punga (1956) described similar terraces from Cox Tor, a 435 m hill on the western margin of the Dartmoor granite upland. Both authors suggested that such forms might be found elsewhere on the upland terrain of south-west England; in fact, Te Punga mentioned five other sites which exhibit at least superficially similar morphological features.

Benched hillsides are indeed common on both Exmoor and Dartmoor; but they are not confined to the Palaeozoic oldland. It would appear that many, perhaps most, of the hillside „terraces" that are so widespread on the more coherent members of the Jurassic and Cretaceous formations of the English Plain are but man-made modifications of pre-existing features genetically related to the wholly natural, high-level benches of south-west England.

The following results of a comparative study of relict „terraces" on

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Dartmoor and currently-developing forms in Vest-Spitsbergen are offered as a contribution towards the elucidation of the origins and evolution of these landforms which are so characteristic of English landscapes.

HIGH-LEVEL BENCHES ON DARTMOOR

The upland of Dartmoor with an area of some 390 km² between 300 and 600 m above sea-level is developed on the outcrop of the easternmost

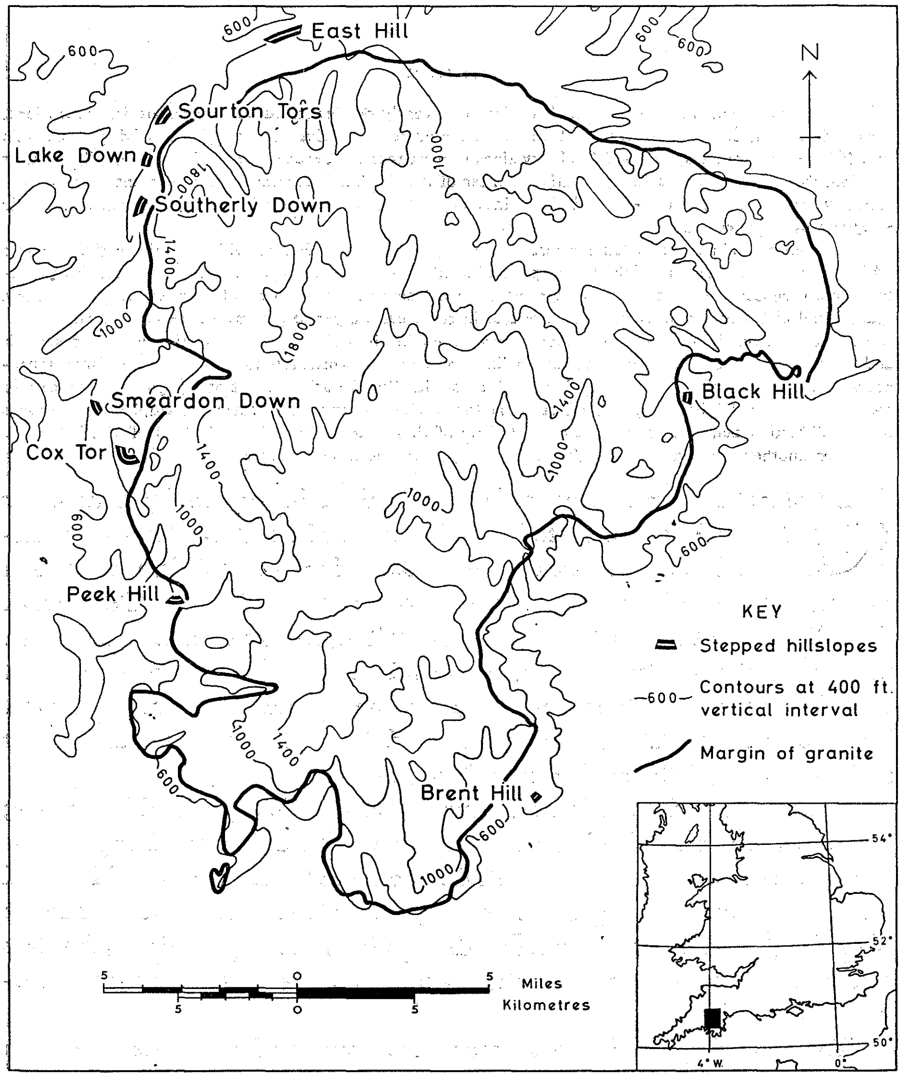

Fig. 1. Sites of altiplanation terraces on Dartmoor

and largest of the five major post-tectonic Armorican granite masses of south-west England and its aureole of altered Palaeozoic sediments and basic intrusions. Its bounding slopes rise distinctly and, in places, abruptly from the upper margins of the surrounding plateau-lands on unaltered country rock which decline gently from a little below 300 m to c. 120 m at the coast. It is these marginal slopes on the metamorphic aureole that are differentiated by benches and terraces, particularly between the 300 and 450 m contours.

Suites of well-developed benches have been mapped at nine localities on the western, northern and eastern flanks of the upland (fig. 1) and incipient or degraded forms can be seen at many other sites.

MORPHOLOGY

The stepped hillsides have mean slopes of from 8° to 14° (fig. 2). Their constituent steps possess gently-sloping treads of between 3° and 8° inclination and moderately steep risers of from 15° to 22°. The width

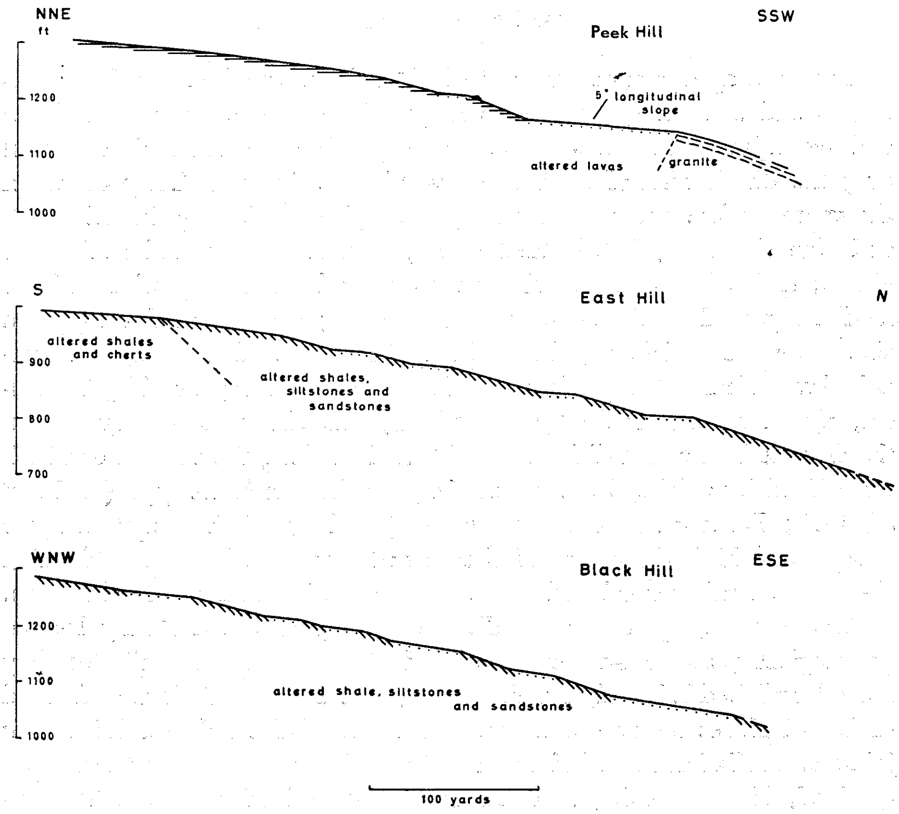

Fig. 2. Profiles of benched hillsides on Dartmoor

of the steps varies from 10 to 90 m, and the height of the backs ranges from 2 to 12 m. The longitudinal dimension of each step always exceeds its transverse dimension; indeed, some benches may be traced along the slope for over 800 m. But although the successive treads and risers appear to follow the contours very few of them are, in fact, longitudinally horizontal. Normally they display a longitudinal slope that is less than, but occasionally equal to, the transverse slope of the treads (pl. 1).

Although the hillsides are for the most part covered with a moorland vegetation of grass and/or heather, buttresses of bare rock diversify some of the risers and near the tops of the slopes on basic intrusives they may form free faces up to 100 m in length. Thus the uppermost benches on Cox Tor and Sourton Tors are backed by vertical rock cliffs instead of by steep, vegetated slopes (pl. 2). Even the isolated buttresses on the metasediments commonly extend to the top of the riser but rarely do they project above the tread of the superjacent step (pl. 3).

STRUCTURAL RELATIONS

It would appear from the geological evidence provided by these buttresses and free faces, by occasional quarries in the steeper back slopes and by adjacent stream sections that there is little lithological control over the distribution of the benches within the aureole. They occur on the more or less contact-altered representatives of interlaminated shales and fine siltstones; interbedded shales, thin limestones and radiolarian cherts; shales interbedded with siltstones and alternating with beds of medium-grained sandstone up to 0,5 m thick; fine- to medium-grained sills of oligoclase-dolerite; fine-grained albite-biotite dyke rock, and vesicular lava. Near to the granite margin the shales are represented by hornfelses, the calcareous rocks by calc-flintas, the siltstones by quartzites, the dolerite by a tough diabase-hornfels and the lava, the vesicles of which were filled by calcite, by a banded rock of the calc-flinta type (Reid *et al.* 1912; Dearman & Butcher 1959). Many of these metamorphic rocks also exhibit the effects of fissure metasomatism by means of which they were further hardened through silicification and tourmalinisation.

These rocks, apparently so diverse lithologically and hardly less so petrologically, are nonetheless possessed of one common attribute: they are all well bedded and/or well jointed, and between their well-defined divisional planes they are uniformly hard and relatively dense. With their joints and foliation these indurated rocks are less massive than the coarse-grained, biotite granite, and less laminated and friable than the non-metamorphosed shales. But within these broad limits the density of parting planes is by no means uniform. Variations in the spacing of both joints and foliation planes occur in each lithological group, and they are reflected in the calibre of the debris yielded by the different outcrops. Consequently any attempted explanation of the origin of the benched hillsides on the flanks of Dartmoor must take account of this variable structural attribute which might be expected to encourage the differential action of any erosional process.

A more obvious, but equally indirect and subtle expression of structural influence is seen in the longitudinal attitude of the benches. They are horizontal where they extend along a hillside parallel with the strike of the subjacent rocks, but if they are aligned in any other direction they assume a gentle longitudinal slope. This slope is always in the same sense but rarely as steep as the apparent dip of the bedding (normal or inverted); and it is always in a direction away from the granite [1].

DEBRIS-MANTLE

It is obvious from the evidence furnished by various exposures that the benches are cut in solid rock. Although the steps carry variable thicknesses of debris — up to 2 m on some treads and 20 cm on the risers — they are not built features. Consequently the morphology of the stepped hillsides cannot be explained in terms of the disposition of superficial material.

The mantle consists of a mélange of coarse and fine debris in variable proportions. On the altered sediments and lavas the coarse fraction (>2 mm) comprises flat, angular rock fragments of gravel and stone up to 20 cm in length (hornfels and calc-flintas $<$ 10 cm, quartzites $<$ 20 cm); on the altered basic intrusives it includes large boulders up to 1,0 m long. The boulders are concentrated at the base of the diabase cliffs but are also scattered on the treads of subjacent steps. By contrast, the stone and gravel grades of the coarse fraction are fairly evenly distributed. However, across the steps there appears to be some variation in the proportions of coarse and fine material in the mantle. The bulk of the debris is coarse near the backs (upper margins) of the treads; and the proportion of fine

[1] The longitudinal slope of the hillside benches on the Jurassic and Cretaceous rocks of the English Plain is approximately equal to the apparent dip of the bedding. Therefore it is not unreasonable to suggest that on the margins of the Dartmoor batholith the structural controls are not the bedding planes but planes of weakness produced during the initial emplacement (late-Armorican) and subsequent uplift (Miocene). Recumbent folds on the northern and western margins of Dartmoor were certainly tilted outwards by the granite and considerable movement occurred on pre-existing fault-planes during the Miocene (Dearman & Butcher 1959).

earth increases progressively towards their fronts where it frequently exceeds 50% (by volume). In the uppermost 1 m of this heterogeneous debris near the front of the terrace it is usual for the stones to be disposed vertically, and sometimes the material is particularly well sorted (pl. 4).

On the steps that are developed on or adjacent to the outcrops of the altered basic intrusions the texture profile of the soil exhibits features which are unlikely to be due solely to pedological processes. It comprises a virtually stoneless silty loam surface horizon over a sandy loam with angular rock fragments of all sizes. The large boulders that are more or less densely scattered over these steps protrude through the soil which itself is disposed in closely packed, grass-covered mounds. The circular mounds, first noted by Te Punga (1956) on Cox Tor, are up to 1 m across and 30 cm high. Their origin and preservation would appear to be unrelated to the presence of the boulders. The most perfect forms occur above 390 m on or near to dolerite and diabase outcrops; subjacent steps on calc-flints exhibit degraded heather (*Calluna*) — clad mounds which less clearly surmount intervening grassy furrows.

HYDROLOGY

On nine days out of ten there is no surface water flow on the stepped hillsides, though at certain spots near to the upper margins of the treads the ground may be damper underfoot than elsewhere. But after a period of continuous rain springs emerge at the erstwhile damp spots and braided streamlets follow the steepest slope towards the front of the treads (pl. 5). The streamlets have no channels; the water merely oozes up through the grass sod, flows over it in barely perceptible depressions and sinks into it again before reaching the lower edge of the terrace. There is consequently no obvious surface erosion; yet little depressions up to 1 m deep and 3 m broad head at the feet of some risers and extend for a few metres across the steps, becoming shallower downslope and finally dying out altogether. These depressions are indicative of a transfer of fine earth along narrow belts from the backs to the fronts of the treads. The effects of this transfer of material are well seen on steps with earth mounds. Within the relatively narrow zone of surface water movement, the mounds are absent from the back of the step, form well-defined islands in the middle and are partially buried towards the front. It is possible that the transfer of fines is effected by a kind of sub-cutaneous „flow" or mass movement which is more effective than the soil creep which operates elsewhere. If not, then it may reflect the more vigorous operation of existing processes either during abnormal weather conditions or during slightly different bioclimatic conditions in the very recent past. If, as seems likely, these relatively insignificant depressions are currently-developing forms they are an indication not only of the ineffectiveness of existing processes so far as the modification of pre--existing slope forms is concerned; they also show that the steps themselves are relict features, the results of processes which are no longer operating.

STEPPED SLOPES IN VEST-SPITSBERGEN

Comparable benched slopes have been studied in Vest-Spitsbergen — on Blomesletta, the south western part of the peninsula between Ekmanfjörden and Dicksonfjörden (fig. 3). They are best developed on the outcrop of a discordant dolerite sill which forms the backbone of, and the highest ground within, the northern half of the low-lying (100 m), glaciated peninsula built largely of Permo-Carboniferous cherts, limestones, dolomites

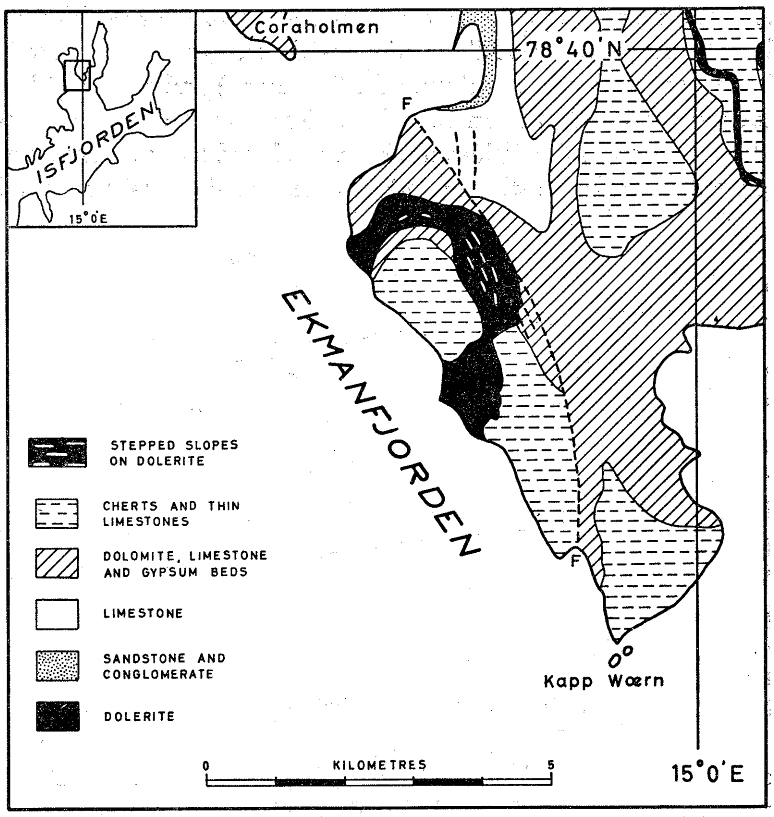

Fig. 3. Geology of Blomesletta, Vest-Spitsbergen (after Bates and Swarchzacher)

and gypsum beds (Bates & Swarchzacher 1958). The dolerite outcrop is marked by an approximate semi-circle of ice-smoothed hills which rise above low, shingle-covered plateaux and meet the coast in prominent headlands. The ridge of hills is broadly asymmetrical in cross-section, with steep outward-facing slopes (free faces and scree slopes) and more moderately inclined, inward-facing slopes which descend to a kind of strike vale between the ridge and the chert plateau. It is these moderately sloping hillsides that are diversified by the rock-cut benches (pl. 6). The hillsides are rarely rectilinear; more commonly they exhibit convex upper segments and concave lower parts which may be separated by more or less extensive, uniformly sloping elements.

MORPHOLOGY

The benches are not limited to one particular part of the slope, though their size and morphology do appear to be related to their position on the hillside. On the steeper middle portions with average slopes of from 12° to 15° the steps tend to be narrower (c. 5 to 10 m) and flatter (1° to 2°) than they are lower down. In fact, it is clear that the overall concavity of the lower parts of the hillsides has been produced by the more extensive development of their constituent terraces, the treads of which may have

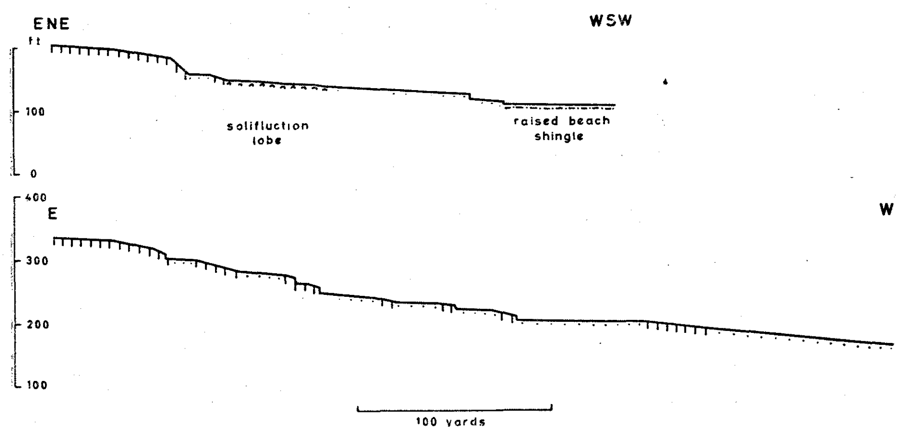

Fig. 4. Profiles of stepped hillslopes on Blomesletta

widths of up to 60 m and mean slopes of between 2° and 5°. The backs or risers are most commonly vertical and only 1 or 2 m high (fig. 4). On the upper parts of the hillsides where the steps are mere nicks in the slopes, the vertical backs pass upwards into convex segments of the pre-existing, glacially-smoothed surface. Most of the benches exhibit longitudinal slopes, the longer ones showing a greater departure from the horizontal ($< 5°$) than the shorter. It would appear that the shorter slopes are controlled, initially at least, by the very slight inclination of the quasi-horizontal jointing or pseudo-bedding in the dolerite.

DEBRIS-MANTLE

The dolerite ridge carries a thin, discontinuous debris cover. On the relatively flat summits and broadly convex upper parts of the slopes unmodified portions of the initial surface exhibit ice-smoothed, -grooved and -striated exposures of bare rock separated by very thin patches of red, shelly drift. Lower down the hillsides the pre-existing surface is more or less replaced by the currently-developing stairways with risers of bare rock and treads which carry, at most, thin skins ($<$20 cm) of moving gelifractate. The proportion of bare rock at the surface decreases towards the bottom of the slopes where continuous sheets of soliflual debris up to 50 cm in thickness extend across the broader terraces and obliquely down from one terrace to the next thereby breaking the longitudinal continuity of the intervening riser. Small, tor-like masses of dolerite project above the debris-mantled, rock-cut surfaces of the lowest and broadest terraces. They are of two kinds: one represents the more massive remnants of a former riser which has disappeared with the coalescence of two terraces; the other is the result of the vertical heaving of joint-bounded blocks by ground ice.

THE MORPHOLOGICAL EVOLUTION OF STEPPED HILLSLOPES

CURRENTLY-DEVELOPING FORMS

It is obvious from the fresh, unweathered appearance of the rock cliffs and the angular blocks at their bases that the small benches on the higher parts of the hillsides on Blomesletta are developing by the retreat of the vertical risers. It would appear that this is affected primarily by basal frost-sapping. Even in July the upper parts of most of the treads were moist underfoot while their lower frontal portions were quite dry. This suggests that the top of the saturated zone in the mollisol on the well--jointed dolerite is less accidented than is the ground surface. Consequently frost-shattering is likely to be particularly effective at the base of the riser where the saturated zone approaches sufficiently near to the surface to be affected by diurnal freeze and thaw, especially during Spring and Autumn. There it is that large gelifracts shed from the riser remain until sufficient fines have been produced for solifluction to occur. The soliflual debris then streams down the steepest slope of the tread; i.e., not directly across it as a broad sheet but either obliquely across or along it and down to the next bench. Thus the backs of lower steps are not overwhelmed all along their lengths by debris from above; rather does their independent retreat continue save at localized points where it is precluded by the concentrated soliflual stream.

The proportion of the surface that is covered with the thin layer of solifluction debris increases progressively in a downslope direction and breaks in the continuity of the risers become increasingly wide until on the lowest parts of the hillside the benches finally lose their individuality in an ever-broadening footslope. This is an almost wholly debris-covered, rock-cut, concave-upwards, solifluction slope of less than 6°, diversified by lines of „tors" which mark the positions of vanished risers. It grades imperceptibly into the flatter surface of the heavily-aggraded, strike vale.

Although it is clear that each individual step develops more or less independently as a solifluction slope of debris-removal by the retreat of its superjacent vertical free face, it is not known how effective the thin moving streams or spreads of soliflual material may be in degrading the terrace treads. It is conceivable that a certain amount of rock-robbing from the treads does occur through ablation of frost-heaved, joint-bounded blocks, particularly on the lower parts of the slope. But the ubiquity of rock-cliffs on the steeper parts of the hillsides suggests that downwearing is subordinate to backwearing, at least during the earlier stages of slope development.

The effects of slowly-melting snow-beds (Lewis 1939) may, however, be relatively important during these early stages. Alternate freeze and thaw beneath an elongated snow-patch in the basal angle between the tread and riser encourages basal sapping of the back-slope and the continued fragmentation of the gelifracts shed from it. As silt-sized particles are produced, meltwater carries them farther down the tread and a relatively flat wash-slope of limited but variable width may then be seen between the narrow belt of coarse debris at the back of the tread and the position where soliflual movement supervenes. This zone of surface washing retreats with the slope elements above it and the area over which solifluction operates increases progressively. A melting snow-bank may thus encourage the parallel retreat of the face against which it is lying, particularly in the early stages of step development, but its presence is not necessary for the continued operation of the processes whereby the backwearing is effected.

Undoubtedly the steps originated in slight depressions in the initial, glacially-moulded slopes. These depressions, which through the presence of snow-beds or by virtue of their position relative to the saturated zone in the mollisol would be moister than their surroundings, would encourage the cryergic processes to begin their differential action. The disposition of the initial hollows was probably joint-controlled; in any event, during their subsequent conversion into, and development as, treads and risers divisional planes in the dolerite exercised an important control. And the morphological effects of structural control of one kind or another are still everywhere to be seen on the stepped hillsides. Even the inclination of their most evolved portions — the foot-slopes — is a function of structure, as is the disposition of the residual rock masses which rise above these foot-slopes.

RELICT FORMS

On the benched hillsides of Dartmoor the adjustment of surface forms to underlying structure is as striking as it is on comparably inclined slopes in semi-arid and periglacial landscapes. It arises where, in the absence of a continuous vegetation cover, the alternation of more „mobilisable" (Tricart 1950, p. 221) and less „mobilisable" rock outcrops promotes differential fragmentation and ablation. That the Dartmoor hillslopes are, in fact, relict periglacial forms, as Te Punga believed, is confirmed by the character and disposition of their debris mantle and by the morphological resemblances between them and the stepped slopes in Vest-Spitsbergen.

In both areas steps or benches occur on hillsides with mean slopes (8°—15°) that are less steep than direct gravity-controlled slopes but are steeper than the minimal slopes over which soliflual movement may occur. As on Blomesletta so on Dartmoor these moderately inclined hillsides have been broken up into a series of treads and risers; but the process would seem to have gone farther in the latter area where virtually no part of the pre-existing surface remains. Moreover, on Dartmoor the treads are broader and the backs higher. This may be a reflection of structure or of the fact that south-west England experienced several periglacial phases during the Pleistocene. If the amount of recent, post-periglacial slope modification is in any way indicative of the extent of inter-periglacial modification, then we may interpret the existing benched hillslopes as pure periglacial forms representing the cumulative effects of several periglacial phases. In any event most of the Dartmoor benches are more mature than the Blomesletta steps.

In one further respect the morphology of the benched hillslopes exhibits the ever-present influence of structural differences. Risers on dolerite in Vest-Spitsbergen and on equally massive basic intrusives on Dartmoor are vertical or nearly so, while those on the metasediments slope at between 15° and 22°. Insofar as the inclination of a basally-sapped cliff is related to the strength of the bedrock some variation in slope is to be expected. Subsequent differential downwearing of the relict free faces initially developed on rocks of different kinds may also be significant.

SUMMARY AND CONCLUSIONS

Of the several processes which have been collectively responsible during the last 10 000 years for converting moderately-inclined, glacially--smoothed, dolerite hillsides on Blomesletta into irregularly-stepped slopes, frost weathering — including frost-heaving, -thrusting and -shattering — and solifluction would appear to have been by far the most important. However, ablation of fine material by snow meltwater and of coarse material by free fall may have been significant contributory processes.

The differential action of both zonal and azonal processes which was occasioned by slight surface irregularities and has been subsequently encouraged by structural attributes, by the disposition of snow-beds and by the manner of disposal of surface water during the season of thaw has produced a series of individual free faces (risers) or waste-production slopes whose continued parallel retreat has, in turn, created an equal number of foot-slopes (treads) or waste-removal slopes. The inclination of the basally-sapped free faces depends ultimately on the strength of the bedrock and that of the foot-slopes is related to the calibre of the debris that moved over them. The removal of debris by solifluction along rather than — or as well as — across the foot-slopes normally keeps pace with its production, consequently intermediate debris-slopes or waste-accumulation slopes are rarely represented.

By virtue of their morphology and the nature and disposition of their debris mantle, the benched slopes on Dartmoor are interpreted as relict examples of more mature, stepped hillsides fashioned by cryergic processes during successive Pleistocene periglacial phases. This interpretation also accounts most satisfactorily for their marked adjustment to structure.

The demonstration that these landforms are periglacial features not only supports the already widely-accepted conclusion that many parts of Southern England exhibit relict periglacial landscapes. It also suggests that in some areas cryergic processes created rather that smoothed out irregularities of slope. The mature or equilibrium slope of cryoturbation (geliturbation) is indeed smooth and compounded of accordant elements the inclination of each of which represents the slope limit (Tricart 1952, p. 232—233) appropriate to the calibre of the debris that is moved across it. But the achievement of cryoplanation on certain moderately-inclined, initial slopes is effected *via* the production of altiplanation steps and benches. These are characteristic of those parts of Southern England of which, for one reason or another, the complete periglacial metamorphosis was never realized.

ACKNOWLEDGEMENTS

This paper is based in part on observations made while the writer was a member of the Birmingham and Exeter Universities 1958 Spitsbergen Expedition. Grateful acknowledgement is made of the financial assistance that was provided by the Univerisities of Birmingham and Exeter and by the Royal Geographical Society to make the expedition possible. The author's thanks are also due to A. Horton for his valuable help in Vest-Spitsbergen.

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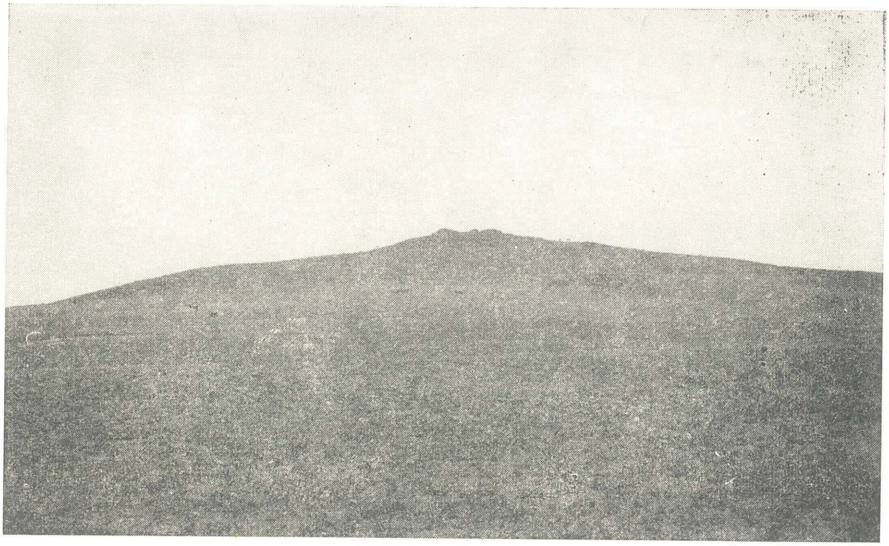

Pl. 1. Longitudinally sloping benches on Cox Tor

Pl. 2. A gently sloping terrace tread, with turf-covered mounds, backed by a steep riser with free—faces and *ravins de gélivation*, on the metadolerite of Cox Tor

Pl. 3. View downslope across a broad bench on Peek Hill showing a „tor" in metasediments on the steep backslope and one in granite on the slope below the bench

Pl. 4. Section in debris on the front of a bench on Southerly Down showing sorting in the congelifluction material

Pl. 5. Braided streamlets flowing obliquely across a terrace tread on Cox Tor

Pl. 6. Stepped hillside on dolerite, Blomesletta, Vest-Spitsbergen