PARED-DOWN LANDSCAPES IN ANTARCTICA

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Abstract

The frigid-arid climate that now prevails in ice-free parts of Victoria Land, Antarctica, inhibits glacial erosion. If certain landscapes, more or less remote from the great troughs of outlet glaciers, have been glaciated in the past, as seems very probable, landforms that resulted from glaciation have been replaced by surfaces of different origin.

A widespread landscape glaciation was probably contemporaneous with the excavation of large cirques which still survive in mountain summit areas.

Replacement of glaciated landforms by others, in a general paring down of the land surface to forms of moderate relief, seems to have resulted from the process of gravity removal of debris from precipitous rock outcrops that were retreating because of disintegration by salt weathering and were eventually eliminated, in most cases, so that the landscape became a mosaic of smooth denudation slopes inclined at 33° to 35°.

In the Darwin Mountains ice-free area (80°S) an advanced stage of such denudation with respect to a base level some 400 m above the present level of surrounding glaciers has produced some pyramidal landforms. Just above the present ice level, however, narrow Richter denudation slopes that border weathering rock faces are at only a juvenile stage of development. Thus the ice level appears to have stood alternately at about its present position and 400 m higher in Pleistocene interglacials and glacial ages respectively. The higher ice levels must have been due to extensions of the ice sheet seaward caused by groundings of the shelf ice during low glacio-eustatic stands of sea level

INTRODUCTION

In many places the landscape of Victoria Land, Antarctica, consists largely of forms that are not classifiable in known categories and so have remained enigmatic. The geographer Griffith Taylor (1914) was aware that over considerable parts of the region none of the features of the surface could be explained as due to glacial sapping and erosion. Taylor was familiar with the theory of development of alpine forms. Though in making his report he seems sometimes to have overlooked the conclusions he had arrived at, he wrote with conviction: "The condditions . . . are now unfavourable for glacial erosion on a large scale . . . A mean annual temperature of 0°F., with a monthly range from 20°F. in December to —20°F. in August is quite unfavourable."

Taylor recorded numerous observations of extensive smoothly-sloping land surfaces that were too gently inclined to be of glacial origin — and indeed do not fit in with any theory of landscape development that was then or has since been in vogue — but he did not discuss the problem of how these surfaces originated. Fifty-six years later Wilson (*in* Cotton and Wilson, 1971) has described a process activated by salt weathering which explains the smoothly-sloping surfaces

This paper has been prepared for the press since the death of Sir Charles Cotton, and the necessary modifications could not be referred back to him. — Editor.

observed by Taylor. It not only furnishes a key to a reasonable explanation of commonly occurring landscape forms bounded by these smooth surfaces but is reinforced also by observation of processes now operating and of landforms now in the course of development. Such landforms may be peculiar to Antarctica, but they might be found in any region in which the commoner geomorphic processes had been inhibited for a long time by special climatic conditions. In the frigid-arid region of Antarctica all other processes, with the exception of trough-excavation by the largest glaciers, seem to be thus inhibited.

A juvenile stage of the cycle activated by salt weathering has been found by Wilson developing in numerous places where conditions of rock outcrop provide steep faces not only susceptible to the attack of salt weathering but so situated that the debris of disintegration can be evacuated by gravity and eventually by wind (after further disintegration while in transit down a gravity-controlled slope), though in rare cases the debris descending such slopes is delivered to and carried off by glaciers — e.g. in the case of the upper Canada Glacier, Taylor Valley, at or near the "snow line" (observed by A. T. Wilson, 1969 - 70).

Other than the abandoned glacier troughs of Wright Valley and several other large "dry" valleys in its vicinity (77° 20' to 77° 30' S) there is little or no evidence of glacial erosion in general views that show the landforms of ice-free parts of Victoria Land, except for the presence at high altitudes of apparently glacial cirques of great size and with precipitous walls of great height, such as those that diversify the summits of the Royal Society Range (Fig. 4, and Blank et al., 1963, geol. map). Besides these high-altitude cirques features that may be attributed to glaciation do not include cirques or uplands dissected by cirques, but are confined to oversteepened walls of some valleys occupied by outlet glaciers. Most of the extremely numerous glaciers, however, apart from the relatively few that drain from the polar ice sheet (outlet glaciers), seem to be rather shallow and have been regarded as shrunken and almost stagnant; they do not appear to be eroding the floors on which they lie. Such a conclusion is supported by the fact, recorded by various observers, that when, exceptionally, some melting takes place the melt-water is clear — not milky with rock flour — and other erosional debris that could be attributed to these glaciers is not found. Though active glacial corrosion no longer takes place under the small glaciers, hanging tributary valleys indicate considerable deepening of the valleys in the past. Most such deepening has been of ancient date, however, like the excavation of cirques at high altitudes which still survive.

Apart from the great troughs occupied by outlet glaciers, it appears that many of the valleys that now contain glaciers, more especially the smaller ones, are only the deepest parts — the very bottoms — of troughs that were excavated in a bygone episode of active glacial erosion, the upper walls of the troughs having since been removed by a non-glacial paring-down process that has been active over the surrounding land surface.

Absence of undoubted features attributable to glacial sapping except on high mountains may result from: (1) the unsuitability of the climate of the present day and of the immediate past for glacial sapping, which takes place only with the co-operation of melt-water (and this is not now produced at valley heads at any season at existing temperatures, which are round about — 20° C.); and, more especially, (2) the activity of processes associated with salt weathering; these working at the prevailing low temperatures, have pared the land surface down, thus destroying all former landscape forms, which had very probably been the

product of glaciation to a stage dominated by precipitous slopes; for these (hypothetical) landforms others have been substituted, though the replacement has taken a very long time.

THE PROCESS OF EROSION BY SALT WEATHERING AND GRAVITY REMOVAL

The non-glacial process which has been described by Wilson is, like that of pedimentation in semi-arid regions, as described by Howard (1942: p. 14), one of "weathering removal", though it differs both in the kind of weathering involved and in the mode of dispersal of the debris of weathering from those taking part in semi-arid pedimentation. In this case rocks are broken up by salt weathering, and the debris is removed at first (in the absence of running water) entirely by gravity down rather steep "Richter denudation slopes", so-called by Bakker and Le Heux (1952) in the case of a more or less analogous process; these are formed contemporaneously with the retreat of steep rock faces (Fig. 1).
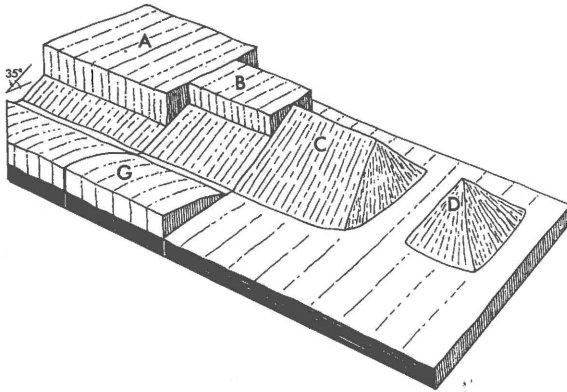

Figure 1. Development of Richter denudation slopes by weathering and removal of debris by gravity and wind in a frigid-arid climate. A, B: narrowing of a ridge; Richter slopes lead down from the foot of a weathering precipitous slope at an angle of 30° - 35°; C: Richter slopes intersect, forming a tent-roof ridge, which may end in a half pyramid; D: reduction of an isolated rock mass to a denudation pyramid; G: glacier.

As shown by Bakker and Le Heux (1952, Figs. 4 - 9), some forms that appear to be Richter denudation slopes (but *cf.* the *Haldenhang* of W. Penck, 1924; *cf.* Louis, 1960, Fig. 18) have developed in regions that are not rainless where precipices are wasting back as a result of ordinary weathering. One may explain these by the fact that the layer of debris in transit down the slopes is sufficiently coarse and thick to swallow water and prevent runoff, so that, as in the frigid-arid climate, debris is removed by gravity down at least the upper part of a bedrock slope with the inclination of a scree, which is formed instead of a pediment.

In Antarctica, where absence of running water is due not to super abundance of debris but to total absence of rain and the fact that the prevailing very low temperature prevents melting of snow or ice, the task of evacuation of debris is usually taken over eventually by wind, deflation becoming possible after granular disintegration has been effected by salt weathering during transportation of debris by gravity down the denudation slopes.

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Where, as is commonly the case, a moat separates a steep-sided shrunken glacier from a denudation slope (Fig. 1), the trough-floor on which the glacier lies seems to be the local base level that controls development of the slope. In the rarer case mentioned earlier, however, where there is no moat and some of the debris that descends the slope is delivered to and carried away by the glacier, the surface of the glacier must act as a base level.

Richter denudation slopes formed in the manner described above are stable forms and, unless affected by warping or dislocation, may be expected to survive as long as the present condition of refrigeration endures, being as it were preserved in cold storage. They are not subject, like the *Haldenhang* of Penck (1924), to replacement at the foot by gentler slopes; in consequence of such replacement the *Haldenhang* retreats parallel to itself, but a Richter slope retreats only extremely slowly.

The headward extension of these smooth, in some cases plane, denudation slopes of bedrock goes on progressively; they lead down at about 35° from the foot of precipitous weathering faces, which meanwhile retreat, in most cases dwindling in height, and if such retreat goes on long enough a weathering face is eliminated from the landscape.

The process of salt weathering and removal is a process of *paring down,* which, *given sufficient time,* can eventually replace a strongly accidented initial surface of considerable relief by a landscape of moderate though not usually low relief.

It is obvious that the process of Richter-slope formation activated by salt weathering cannot be initiated on a land surface of low relief, for weathering will soon cease if the debris of disintegration is not evacuated; the weathering faces must be steep and high.

HYPOTHETICAL GLACIATED INITIAL SURFACE

Though a complex of small tectonic blocks bounded by fresh steep fault scarps would afford slopes on which the development of numerous Richter slopes might be initiated, such an initial surface is out of the question because of the structure of Antarctica, with its vast extent of unbroken horizontal Beacon Sandstone with dolerite sills. It seems impossible, therefore, to avoid postulating a complex of strongly glaciated forms as the initial surface. Not only must the weathering faces have been steep and high, but they must have been numerous to account for the formation of denudation slopes inclined in various directions, not leading up to great heights, as long ramps inclined at 35° will do, but short enough to intersect with moderate relief.

The initial form of the land surface was probably therefore a glacially dissected, even "fretted", upland that had developed contemporaneously with the excavation of numerous valleys that now contain shrunken glaciers, and probably also with the large cirques that survive on high mountain summits.

The hypothetical episode that was characterised by active glacial erosion, especially by sapping, must belong to the distant past, for the very slow-acting non-glacial process that has obliterated the traces of glacial erosion over large areas has produced well-finished and stable surfaces that have taken a long time to develop.

SLOW DEVELOPMENT OF THE RICHTER-SLOPE LANDSCAPE

For long it has been a subject for discussion whether cracking of rocks ever takes place as a result of rapid heating and cooling (Washburn, 1969: pp. 32 - 3). Boulders on the moon do not seem, however, to be affected by it, nor by granular disintegration due to changing temperature, though they have been exposed for a very long time to changes of temperature more rapid than and far in excess of any that occur on the surface of the earth. So it appears that insolation cannot contribute appreciably to the wasting of precipitous Antarctic rock faces. In the absence of liquid water the processes of freeze-and-thaw and of disintegration due to chemical weathering are also negligible. In other climates salt weathering is at work, especially in coastal situations and in hot deserts, contributing along with other processes to the disintegration of rocks in bare outcrops, but in the frigid-arid ice-free parts of Antarctica it seems to work alone. Though the rate at which salt weathering disintegrates bare rocks in this region has not been measured, being unaided by other weathering processes it must almost certainly work so slowly that its action must be spread over a long period.

Landscapes so formed must be stable, being affected only by very shallow disintegration at the surface into fine debris that can be removed progressively by wind. Obviously, however, vigorous disintegration by salt weathering, with its erosional consequences, will become active again, generally under the control of a lower base level, on any new and steep faces that are formed, whether these be tectonic scarps or, in this region much more probably, valley-sides oversteepened by glacial trough-cutting. At a number of places this latter has probably taken place comparatively recently — for example, on steep slopes bordering the Miller Glacier (Fig. 5) and in those valleys, notably that of the Upper Taylor Glacier, on the oversteepened sides of which Wilson (*in* Cotton and Wilson, 1971, photo 2) has studied the juvenile stage of the development of Richter slopes. At those places large glaciers have comparatively recently been thicker than they are now, probably during an ice flood (*infra*), and have flowed vigorously down rather steep gradients. In such cases vertical glacial corrasion, which will steepen the valley-sides, must become possible if the temperature at the bottom of the glacier ice is raised to the melting point by conduction of the internal heat of the earth reinforced by heat mechanically generated in the glacier (see Appendix). Melt-water thus produced lubricates the sole of the moving stream of ice, contact of which with the rock floor makes corrasion possible.

LOCALITIES SELECTED AS EXAMPLES

The localities that will be referred to in the following pages have either been briefly, in some cases empirically, described in published works or are shown in photographs that have been used as illustrations. They are all in the relatively ice-free region that borders the western shore of the Ross Sea and Ice Shelf. In this meridional strip of country they are here located by their latitudes.

RICHTER SLOPES AT INLAND FORTS (77° 40′ S)
(Gunn and Warren, 1962, Fig. 24)

In the Inland Forts area of rather strong relief Gunn (*in* Gunn and Warren, 1962: p. 65), who has described the landscape as of "subaerial", as distinguished from glacial, origin has noted, besides buttes capped by sill dolerite, the presence

of forms he has called "pediments"; these either fringe buttes or have become more extensive and "intersecting". They are, however, not true pediments, as they are described as much steeper, having the inclination of screes. "In the absence of rain and sheetfloods", they are shaped by "gravity and wind"; they are thus Richter denudation slopes. As they have been developed at the expense of escarpments of dwindling buttes, these escarpments must have been retreating under the attack of salt weathering.
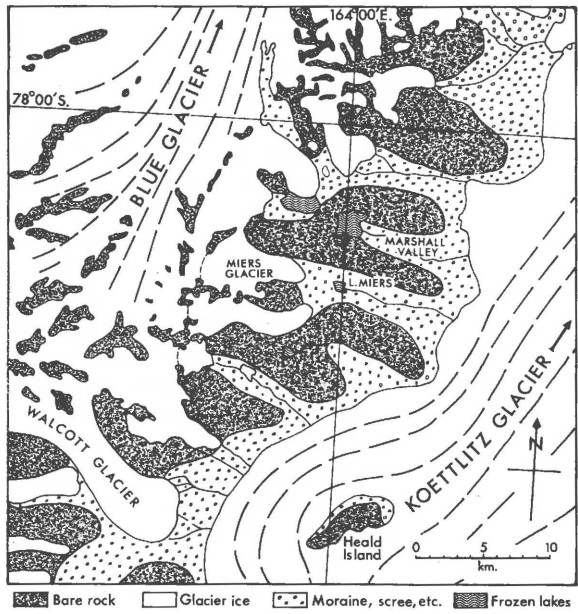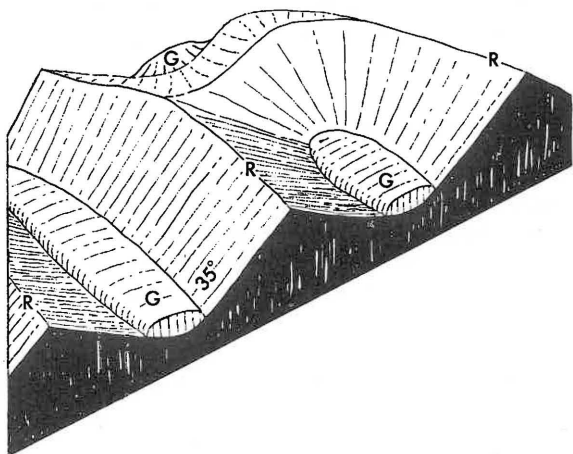

Figure 2. The Foothills Bench.

Figure 3. Theory of origin of Foothills landforms as a complex of Richter slopes intersecting in tent-shaped ridges, R, R, R: G, G, glaciers. The form of the surface has been drawn with the help of the description by Taylor (1914).

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Figure 4. The Foothills Bench between Royal Society Range, background, and the lower Koettlitz Glacier, foreground. Residual of rock between Miers and Marshall Glaciers, right of centre. Photo by U.S. Navy, by courtesy of Guyon Warren.

THE SURFACE OF THE FOOTHILLS BENCH (78° S.)

On the tract of ice-free land surface between the glaciers that drain from the high Royal Society Range and the floating part of the lower Koettlitz Glacier (Figs. 2, 4) there is a more advanced development of Richter slopes than at Inland Forts, probably because less resistant metamorphic rocks form the terrain instead of the Beacon Sandstone with dolerite sills.

Topographic Form of the Bench

This bench is regarded by geologists as a block that has been downfaulted relatively to the high-mountain area (Royal Society Range) behind it. Its margin, bordering the Koettlitz Glacier, is apparently a coastal cliff that has not been modified to any extent by glacial erosion but has been plastered with morainic debris when the ice of the Koettlitz and other large glaciers was at a high level during the last glacial age of the Pleistocene (Blank *et al*, 1963) and perhaps on earlier similar occasions.

On the bench, at altitudes round about 1000 m, smooth rock surfaces "all thinly covered with debris", as Taylor noted, slope up at a constant angle of 33°, as measured by Taylor (1914: p. 559) at a number of places, from the heads and sides of small glaciers in parallel valleys that dissect the margin of the bench. These surfaces are obviously Richter slopes that survive after precipitous weathering-back slopes at the foot of which they have been formed have retreated so far that they have been eliminated from the landscape. Adjacent Richter slopes that lead up for the hollows occupied by different glaciers must intersect at blunt angles, thus explaining Taylor's observation of a "sharp crest" between two of these 33° slopes (Taylor, 1914: p. 559). An extensive mosaic of these slopes (Fig. 3) has been developed at the expense of former stronger relief of some kind: The present moderate relief that gives this earth block its rather flat-topped or bench form (Fig. 4) has apparently been shaped in this way *on* the bench

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rather than dating from a period anterior to the emplacement of a faulted block that forms it, as Taylor (1914: p. 572) believed. If this is the case, a few, but only a few, generally small residuals have survived of the rocks over which a former land surface spread out at a higher level; these break the smoothness of some of the ridges defined by Richter slopes. One rather conspicuous residual, which is described below, is undergoing reduction to a pyramid of denudation.

Large Residual Standing above the Richter-slope Complex

Among the few surviving relics of the rock terrain of unknown thickness that has been removed from the Foothills Bench by the paring-down process one is a landform of considerable size. With precipitous slopes on all sides, this large knob outwardly resembles a small stock or large neck in a "normally" eroded landscape, but such an interpretation of it is not supported by the geological map of Blank *et al.* (1963). It stands between the Miers and Marshall glaciers (Figs. 2, 4) and appears to be about 100 m high. That the precipitous cliffs of the residual are still undergoing disintegration by salt weathering is evidenced by a slope covered with coarse debris that leads down from its base towards the Miers Glacier (Fig. 4).

Inactivity of Small Glaciers on the Bench

The now-isolated masses of glacier ice on the Foothills Bench, which are dismembered remnants of former distributaries of glaciers descending from the Royal Society Range, are quite inert. Temperatures are for most of the year below — 20° C., judging from the summary of meteorological information at Scott Base, McMurdo Sound, given by Gunn and Warren (1962, Table 1, p. 15) so that these small glaciers cannot yield the melt-water required for either sapping or corrasion, ablation being entirely by sublimation. The theory of development of landforms around the sides and heads of such glaciers that has been formulated above is the reverse of "biscuit-cutting" by cirque glaciers, and the development of the pared-down surface of the bench must have taken place since rather than before any glacial erosion. The presence, however, of scattered small glaciers is liable to deceive a casual observer, especially when they are seen from a distance (Fig. 4), suggesting that they are, or have formerly been, at work digging themselves in ("biscuit-cutting"), as Taylor (1914: p. 559) seems to have assumed, though the fact (which he recorded) that declivities are only 33° on the hard-rock slopes that lead down to the supposed cirque-cutting glaciers negates such a theory of the origin of existing landforms.

SOUTHWEST BANK OF THE MILLER GLACIER (77° 45' S.)

The shaping of the landforms on the Foothills Bench, as described above, by development of a mosaic of Richter slopes is not exceptional; similar development explains a surface underlain mainly by metamorphic rocks southwest of the Miller Glacier. The surface, which is partly ice-free and partly covered by obviously shrunken glaciers, is shown in an oblique photograph by the U.S. Navy (Gunn and Warren, 1962, Fig. 20) (see Fig. 5). These glaciers are not contained in troughs, but lie in open hollows in which the land slopes up from the ice margin in most cases with declivities that apparently do not exceed 35°. The ridges between the glacier-filled hollows are tent-shaped, or ridge-roof-shaped, and are even in some cases broken up into pyramids of denudation, showing that nearly all the landforms that are visible have been developed by intersection of Richter slopes.

Figure 5. View looking across the Miller Glacier, showing shallow valleys of nearly-stagnant glaciers on the southwest side. The ridges between these have apparently been pared down and re-shaped by the process of salt weathering and removal. The side walls of the valley occupied by the main (Miller) glacier have been steepened by glacial erosion (in an ice flood). Photo by U.S. Navy.
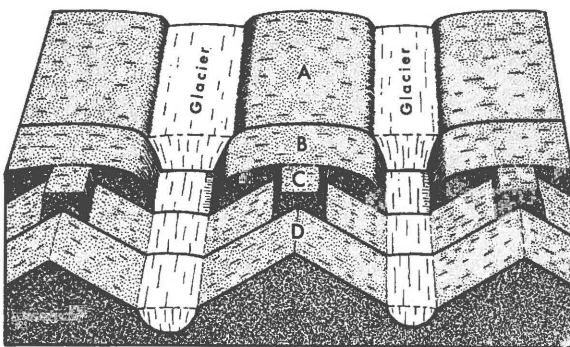

Figure 6. Hypothetical history of the land surface southwest of the Miller Glacier (*cf.* Fig. 5). A: deep glaciers excavate troughs; B: owing to oncoming of frigid-dry conditions the glaciers shrink, occupying now only the bottoms of the trough which they protect; C: the process of salt weathering and removal of debris causes the walls of the troughs to recede; D: continuation of the process has eventually pared down the land surface to the form of a system of tent-shaped ridges made by intersection of Richter slopes.

In explanation of the history of the landscape it may be assumed that the glaciers were in the distant past contained in steep-sided troughs which they, when full-bodied and active, had excavated by vertical glacial corrasion (Fig. 6A); that with the oncoming of the frigid-arid climate now prevailing the glaciers shrank to a small thickness, so that each lay in the bottom of a trough (Fig. 6B), which henceforward it protected instead of eroding; that the process of salt weathering and removal of debris by gravity and wind next caused the trough walls to recede (Fig. 6C); and that eventually, when Richter slopes intersected, the surface had been pared down to its present condition (Fig. 6D).

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THE KUKRI HILLS (77° 45′ S.)

Another example of such a landscape, in the Kukri Hills, may be recognised from the description given by Taylor (1914), who has reported the top of that range to be "approximately level, but crossed by narrow ridges" running "at right angles to the main glaciers". These ridges, between small glaciers on the top of the range, seem to have been shaped by intersection of Richter slopes which lead down towards the small glaciers; they are not sufficiently steep-sided to have been cut by intersecting cirque or trough walls, as Taylor apparently supposed was the only possible explanation of them. There are, moreover, some small but steep-sided unconsumed residuals standing up conspicuously above the smooth Richter-slope-made ridges that form the "approximately level" plateau of the range top (as Taylor described it). These residuals are seen in an oblique aerial photograph by the U.S. Navy that is used as an illustration by Gunn and Warren (1962, Fig. 9).

SIDE WALLS OF THE VALLEYS OF FERRAR AND TAYLOR GLACIERS

In some cases the valleys of large trunk glaciers, as well as those of minor glaciers, have side walls of rather gentle declivity that do not suggest recent over-steepening by trough-cutting erosion, but appear rather to be Richter slopes that have replaced the originally steep walls of troughs. Taylor (1914) remarked as follows on such side walls consistantly inclined at a small angle: "The [side] slopes [of the valleys] of the Ferrar and Taylor Glaciers . . . have a remarkably uniform angle of about 33° . . . This is due . . . to the action of King Frost. It is in fact near the 'angle of slope' of loosened debris and it is a sort of 'basal surface' [i.e. a Richter slope], for the debris is to some extent preservative where it covers a slope" (Taylor, 1914: pp. 464 - 5). On another page he remarked on a constant angle, estimated by him at about 35°, which is almost universal "in these steep-walled [sic] valleys" (Taylor, 1914: p. 381). This amounts practically to an expression of opinion that any steeper walls due to former glacial trough-deepening had been eliminated from the area he was writing about (the valley occupied by the Ferrar Glacier) either by "King Frost" or some agency unknown to him. At another place (1914: p. 465) he referred to these valley-sides as "33° walls".

In Taylor's account of the development of some forms he classed as "cwms", or cirques, he remarked on the "uniformity of the angle of slope, from 30° to 35°" as an indication that gravity had much to do with determining the shape of the landform, for that was "near the 'angle of repose' for talus" (Taylor, 1914: p. 465).

Taylor's description, as quoted earlier, does not apply to all parts of the side walls of the valley of the Taylor Glacier. The valley of the Upper Taylor Glacier has apparently been deepened by corrasion during an ice flood (infra), and this part has high, precipitous walls, which, having been long enough in existence, however, have receded as a result of the salt weathering process and are flanked in many places by juvenile Richter slopes (Wilson, in Cotton and Wilson, 1971, photo 2).

THE DARWIN MOUNTAINS

A High-level Landscape

Pyramids of denudation, accompanied by small, residual sill dolerite-capped mesas, in the Darwin Mountains frigid-arid ice-free area (at nearly 80° S.) have been developed with respect to a base level some 400 m higher than the present level of the ice of the Darwin Glacier and its distributaries (about 1300 m), which furnishes another local base level for a salt-weathering-and-removal cycle of erosion now in progress (Figs. 7, 8).

The pyramids and related forms appear to rise from a basal platform at the level of, and perhaps in some way related to, a nearly-level land surface forming a conspicuous bench some 400 m above the surrounding glaciers. Though probably veneered with superficial deposits, this bench has the appearance of being structural, being at the top of the resistant Hatherton Sandstone of the horizontally-bedded Beacon Group (Haskell *et al.*, 1965). Whether it be a structural surface or one planed by cyclic erosion, however, its hypothetical stripping or planation, either of which implies the work of running water, must have taken place before the frigid-arid conditions of climate set in. Unless this is the origin of the plane horizontal surface of the bench and it is dated very far back, perhaps in a pre-glacierisation period of rain-and-river erosion (*infra*), it would seem necessary to explain it by invoking the crude and questionable theory of regional planation under a thick and fast-moving ice sheet, which was advocated by James Park (1925: pp. 51 - 2) and has been appealed to more recently by Grindley (1967).

Hypothesis of Alternate High and Low Ice Levels

The development of Richter slopes bordering glaciers at their present level is in only a very early stage, but at the higher level the denudation pyramids are isolated forms, fully 200 m high — for example, The Sphinx and another close to it, as figured by Wilson (*in* Cotton and Wilson, 1971, photo 3), and, in line with these, a short length of tent-roof ridge with half pyramid terminations forming an elongated peak called The Camel (Fig. 8, left). These have apparently all been isolated from a single elongated mesa continuous with the surviving one that has been called the Colloseum Ridge (Haskell *et al.*, 1965, geol. map of Darwin Mountains). The peaks have reached the pyramidal penultimate stage of development termed "mature" by Wilson. As pyramids may be expected to become lower and dwindle in size only very slowly (Wilson, *in* Cotton and Wilson, 1971), it would seem that the cycle in which this group of pyramids developed had run almost its full course — though individual pyramids are of almost mountainous dimensions — and that the pyramids are senile rather than merely mature forms. The stage here exemplified, being a product of evidently very long continued development, seems, notwithstanding the rather steeply inclined flanks of the pyramids and their strong relief, to be the penultimate stage of this cycle, just as the peneplain is in the Davisian theory of the "normal" cycle. It is difficult, indeed, to imagine any further development other than very slow dwindling in size of the pyramids without change of form, together with some loss of relief that would result if the spaces between them were built up by accumulation of aeolian deposits.

The old-age development of the landscape with pyramids, together with the fact that the development of Richter slopes adjacent to the existing glaciers (either they or the floors on which they lie being local base levels for such slopes) is

as yet not far advanced, suggests a theory of two cycles of salt weathering erosional development, the former cycle having been interrupted by a lowering of the local base level by about 400 m. This seems, however, to be an over-simplification, for probably there have been movements of the glacier-ice level alternately down and up, the higher levels corresponding to the Pleistocene glacial ages and the low levels, including that of the present day, to interglacial episodes (*infra*). Though the cycle that culminated here in pyramid development appears to have been initiated under the control of an early high ice level as base level, the extension of its Richter slopes would continue after that unaffected by later changes of ice level.

The more advanced stage of development of the Richter slope cycle at the higher, as compared with that at the lower (or existing), ice level suggests that the higher level has been occupied for considerably longer periods than the lower one so as to produce a perhaps misleading appearance as though a postmature or senile upper land surface (with denudation pyramids) is undergoing rejuvenation by development in another cycle of slope formation, though the stage that this later cycle has attained is only that of partial replacement of salt weathering precipitous slopes by narrow Richter slopes at their foot (Figs. 7, 8). The true explanation of the juvenility of the landscape at the low level may be different, however; it may result from inconstancy and fluctuation of the lower ice level and hence of the lower local base level of erosion. Alternatively, when the ice level has been high some glacier-trough excavation by adjacent glaciers may have been going on that would destroy early-formed low-level Richter slopes, so that the process of formation of these must begin anew.
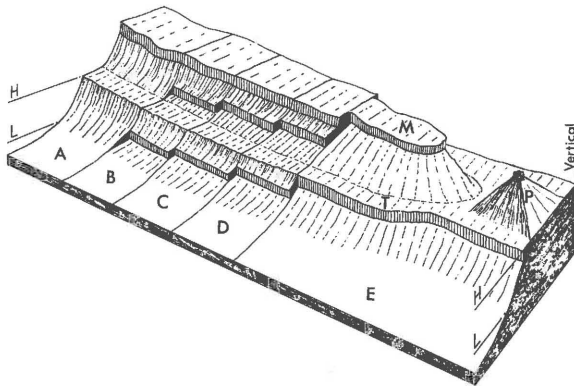

Figure 7. Hypothetical Pleistocene history of the Darwin Mountains, adopting the theory of alternating high and low ice levels. A: inherited initial form of the land surface (the mesa, which is capped by sill dolerite, may be a pre-glacierisation feature); E: forms of the present-day landscape; B, C, D: three (among many) intermediate stages between A and E; HH: high glacier-ice level; LL: low glacier-ice level (as at present). Oscillation of ice level between HH and LL (perhaps throughout the Pleistocene) is assumed. The ice when at the high level is assumed to have been largely protective of the low level features. Denudation pyramids (P), mesas (M), and a bench that resembles a structural terrace (T) are the principal elements of the upland lanscape. The bench T is possibly inherited from pre-glacierisation times. Some features resembling cirques, e.g. Misthound Cirque (Haskell *et al.*, 1965) may have been formed in an ancient episode of active glaciation or may have originated as embayments in the retreating escarpments of mesas.
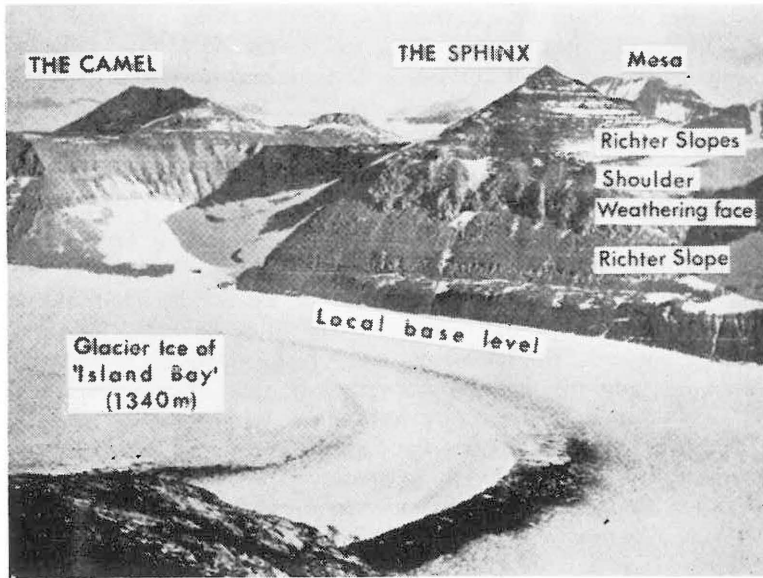
Figure 8. Features of the Darwin Mountains. Key to photograph (Haskell *et al.*, 1965, photo 5).

FLUCTUATING ICE LEVEL (ICE FLOODS)

In Victoria Land marginal Antarctica has been inundated with excess of ice from time to time, as is shown by evidence of very high ice levels. Taylor (1914: p. 574) used the expression "ice flood", a designation introduced by Andrews (1906) for the glacial period, to signify a supposedly single episode in which glacial erosion had been more active than at present. Though in that sense misleading, and better discarded, it may be used now for any one of perhaps many ice inundations that have occurred, as is shown by discoveries of morainic debris and till deposits at high altitudes (Péwé, 1960; Grindley, 1967). It has not been shown that temperatures were different at times of such high ice levels from those now prevailing, but it is highly probable that ice floods in Antarctica were synchronous with world-wide glaciations in the glacial ages of the Pleistocene.

The question of ice levels much higher at times in the past than at present has been discussed by Grindley (1967). Of the two most plausible suggested causes of these which Grindley cites, namely vertical movements of the underlying land and eustatic effects (Voronov, 1960; Hollin, 1962) only the latter seem capable of producing oscillation between positions of ice level several hundred metres apart (*cf.* Grindley, 1967: p. 575). Grounding of shelf ice as a result of glacio-eustatic lowering of sea level in Pleistocene glacial ages has caused seaward extension of parts of the Antarctic ice sheet, and as a consequence build-up of ice, raising the level of those parts of the ice sheet, has been required to maintain the seaward flow (Weertman, 1964). This must have raised the ice level hundreds of metres, making it especially high at a moderate distance inland (Grindley, 1967, Fig. 12). Such raising would naturally be followed by lowering of the ice level — return to the former condition, approximately that of the present day — in interglacial episodes.

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Oscillation of the ice level between glacial-age high and interglacial low positions seems to be the most probable cause of the successive "glaciations" in Antarctica described by Péwé (1960). Differences, however, in the levels at which high stranded moraines and till deposits occur — especially differences from one glacial age to another — may possibly be correctly accounted for, at least in part, by postulating vertical movements of the underlying crust (*cf.* Grindley, 1967: pp. 561 - 2), especially where rather ancient events are concerned.

It may be asked how the hypothesis of paring-down of large areas of land surface by development and extension of Richter slopes, if this has been spread over a long period, is affected by recognition of ice floods. The answer to this question may be that ice would inundate some areas in which the process had been operating, but that, the ice sheets temporarily flooding over these being of no great thickness and the temperature very low, their effect would generally be protective, even though glacial corrasion might be deepening adjacent glacier troughs. The effect of a protective covering of ice would be merely to put an end for a time to the salt-weathering-and-removal process, which would, however, be renewed after the recession of each ice flood. After the next lowering of the ice level shallow and nearly stagnant glaciers, like those of the present day, would remain in the old glacial hollows, the size of the glaciers being determined by equilibrium between alimentation and ablation by sublimation.

DATE OF ONCOMING OF THE FRIGID-ARID CLIMATE

Survival of Valley-head Cirques at High Altitudes

A glance at the Royal Society Range (78° S.), 3000 m to 4000 m high, which, as shown in Figure 4, overlooks the Foothills Bench, reveals an alpine landscape in which numerous valley-head cirques up to 5 km wide (Blank *et al*, 1963, geol. map) are developed, their walls towering at least 1000 m above the heads of glaciers that accumulate in them. It seems beyond the bounds of possibility that the formation of such features by sapping should be in progress at present, however. Taylor (1914: p. 369) has remarked: "Cirques are better developed in the Royal Society Range than anywhere in the world, and this raises the interesting question as to how long ago the conditions for cirque-cutting were more favourable than at present". Taylor (1914: p. 564) has referred at another place to "a previous glaciation . . . resembling that of warmer regions".

Because of the formation of desert varnish salt weathering is less active above than below the Antarctic "snowline" (separating a higher-level zone in which glaciers grow in size by alimentation from a lower-level zone in which they dwindle as a result of ablation by sublimation), and it is possible that in some areas at high altitudes salt-weathering does not operate at all. If this process of weathering, as well as all others, were inhibited, survival of landforms for an indefinite period — survival even of the near-vertical slopes around the cirques of the Royal Society Range — would be explained. At the foot of these slopes the ground is protected by glaciers, so that Richter slopes that might work back headward from lower levels could not encroach on the cirque-wall precipices. Some glaciated high-mountain summit features may therefore be practically everlasting, provided that the present frigid conditions are unchanged.

A Less Cold Episode in the Pleistocene?

There does not seem to be any evidence of much warmer world-wide climates in any of the interglacial episodes of the latter part of the Pleistocene. Because,

however, of the presumable slowness of the process of non-glacial landscape development now operating and the extent to which formerly-existing landscapes have been pared down or destroyed by it, together with the (assumed) immunity from destruction and possibly very long survival of glacial cirques at high altitudes, the last date at which the temperature was high enough for active cirque-cutting and the excavation of troughs by glaciers that have since shrunk to small dimensions must be rather ancient.

CLIMATIC HISTORY

The following are suggested stages of the later climatic history of the region:

(1) Pliocene cooling climate, accompanied by rain-and-river erosion.

(2) Late-Pliocene (?) to earliest Pleistocene glacierisations (> 3 million years ago?) accompanied by an unknown amount of glacial erosion.

(3) Early to middle Pleistocene oncoming of frigid-arid conditions, probably accompanied by destruction of some glaciated landforms by an early cycle of Richter-slope development.

(4) Late-Pleistocene - Holocene frigid-arid climate, with Richter-slope development.

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