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STUDIES ON THE GEOMORPHIC CHARACTERISTICS AND DEVELOPMENT OF SLOPES IN THE PERIGLACIAL ZONES OF SIKKIM AND DARJEELING HIMALAYAS

INTRODUCTION

This paper presents some observations and findings made during field studies on the geomorphic processes and the evolution of slopes in that part of the Eastern Himalayas which form the central segment of Sikkim bounded by the kingdom of Nepal on the one side and Tibet on the other.

By virtue of their isolated position in the high Himalayas and their location in a subtropical belt of the Indian subcontinent, these findings have some added importance. Moreover, these findings on slope formation in the periglacial and the outer periglacial zones of the Darjeeling and the Sikkim Himalayas are based on observations in the altitudinal range at 10,000 to 17,500 ft. and are derived from the same kind of lithology and geological structure of rocks that characterise these ridges. Although the general climatic regime is almost the same over the Darjeeling and the Sikkim Himalayas, the field studies cover two broad climatic--geomorphic zones of (a) an inner periglacial zone, under a sub--nival climate and (b) an outer or marginal periglacial zone under more humic conditions. These findings, therefore, throw some light on the modelling of high mountain slopes of the same lithological composition and geological structure but under varying conditions of summer and winter temperatures, thickness and duration of

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snow fall, intensity of ice formation and rainfall in the periglacial zones of the Eastern Himalayas.

It is, therefore, hoped that these observations and findings will fit in with the problem-themes number 2 and 3 of the joint IGU Symposium on Periglacial geomorphology and Evolution of slopes [1].

AREAL EXTENT AND LOCATION OF FIELD STUDIES

As mentioned above the area under study forms the central part of the kingdom of Sikkim flanked by the Singalila—Kanchenjungha range to the west (88°3′E) which forms the boundary ridge between Nepal and Western Sikkim. To the east the high ridge of the Dongkya range forms the boundary between the Chumbi valley of Tibet and the Eastern Sikkim (88°47′E). The northern limit may be taken at 27°45′N, just north of Kanchenjungha, while to the south 27°00′N latitude near the towns Darjeeling and Kalimpong may conveniently form the southernmost limit.

PHYSIOGRAPHIC SETTING

As may be imagined, the entire area of Central Sikkim is a rugged mountainous tract flanked by the two mighty boundary ridges of the Singalila—Kanchenjungha and the Dongkya Range and mainly drained by two river systems — that of Rangit and its tributaries fed by the glacial snowmelt and rain water of the Kanchenjungha—Singalila range to the west and north-west, and of the mighty Tista and its tributaries nourished by the snow of the Kanchenjungha massif (Talung glacier, Zemu glacier) to the northwest and by snow and rains from the Dongkya range to the east. In between these river valleys and tributary streams, the land is under various stages of dissection — under partly glacial, partly periglacial and the rest under fluvial morphologic processes. The river Tista, being the largest of all the fluvial agents receiving tributary waters from both the western and the eastern flanks of the Sikkim highlands has carved its valley floor in the heart of Sikkim far deeper than any other stream. The major part of the north to south flowing Tista has a valley floor below 2,500 ft. Though the main trunk of the Tista river shows no evidence of gla-

[1] See p. 5.

ciation, its upper tributaries like the Talung, the Zemu, the Lachen, and the Lachung had all their head water valleys glaciated during the last Ice age, as evidenced by their valley shapes and their morainic deposits.

The Rangit river has also its several head water streams entrenched into high mountain valleys which were once glaciated during the Pleistocene.

The lower reaches of all these tributaries like that of the master stream of the Tista below 10,000 ft. of altitude have however their valleys shaped mainly by fluvial processes, though also assisted by structural and geological ones. The lower reaches of the Rangit and the Tista in the area under study exhibit the typical features of a meandering river entrenched in a mountainous tract.

Obviously, the high lands and ridges in between these river- and stream-valleys are exposed to various morphological processes which ultimately model the form and shape of their slopes. Many parts of these high mountain slopes were definitely exposed to a fully nival/glacial climate and were under glacial morphologic conditions during the Pleistocene. At the same time the head water region of the Rangit river tributaries like the Ringbi, the Rathong, the Parek etc. and those of the Tista river namely the Talung, the Zemu etc. were also shaped by glacial sculpture by the advancing Pleistocene glaciers giving them a kind of antecedent slope character. In almost all such valleys, there is evidence of advancing glaciers followed by their recurrent retreats.

Even under the present-day post-glacial conditions, the high mountain slopes of the Sikkim Himalayas fall under four kinds of climatic-morphologic processes which have a profound influence on the development of their slopes. These may be enumerated as follows:

(a) High mountain ridges and crests subjected to present day glacial processes. In Sikkim they usually lie above the summer snow line at about 17,500 ft.

(b) Broad ridges and valleys having certain antecedent slope characteristics inherited from Pleistocene glacial sculpturing but subjected to present-day periglacial climate and periglacial morphologic processes. Usually, such ridges and slopes lie above 12,500 ft. of altitude in Sikkim, of course slightly varying from place to place, depending on the micro-climatic conditions.

(c) Just below and bordering on such periglacial slopes, lie the marginal or outer periglacial slopes of mountain ridges, where short winter snowfall and mild frost conditions alternate with spring thaw and higher summer rainfall and thus activate a different kind of morphological process influencing their slope development. They lie in a belt between altitudes of 12,500 ft. and 10,000 ft.

(d) Finally the lower reaches of these mountain slopes and valley sides below 10,000 ft. are now subjected to distinct fluvial processes, under mesothermal humid conditions of soil development, vegetation cover, inherent geologic structure and tectonic features.

In this paper the different kinds of morphologically active slope-formative processes along with the resultant slope profile features in the above mentioned zones are discussed, those under distinctly glacial sculpturing in the higher crest lines and those under fluvial processes in the lower valley-sides receiving lesser attention. It is the purpose of the present paper to focus attention on the modelling of slopes and on associated morphological processes under periglacial and extra periglacial zones of the Sikkim Himalayas as indicated under (b) and (c) above.

LITHOLOGY AND STRUCTURE

Interesting facts about the lithology and geologic structure of the area under study is that both, the Singalila—Kanchenjungha ridge and the Dongkya range to the west and east of the Sikkim territory fall in the same geological province having more or less the same lithology and geological structure. These two high ranges providing a basis for observations on periglacial processes of slope formation are formed of the well-known "Darjeeling gneiss" of the Eastern Himalayas, which covers the mountainous tract of eastern Nepal, the Kanchenjungha massif and the territory of Sikkim (fig. 1). The predominant rock types of the area is coarse grained gneiss and foliated granitic rock dipping more or less north- and northeastwards at varying angles of inclination. The high grade metamorphic rocks contain an abundance of sillimanite and kyanite and are followed to the south by a narrow enclosed belt of garnet and staurolite-bearing schists, which in turn are followed by chlorite and biotite-bearing phyllites in the heart of Sikkim, commonly known as the "Daling series".

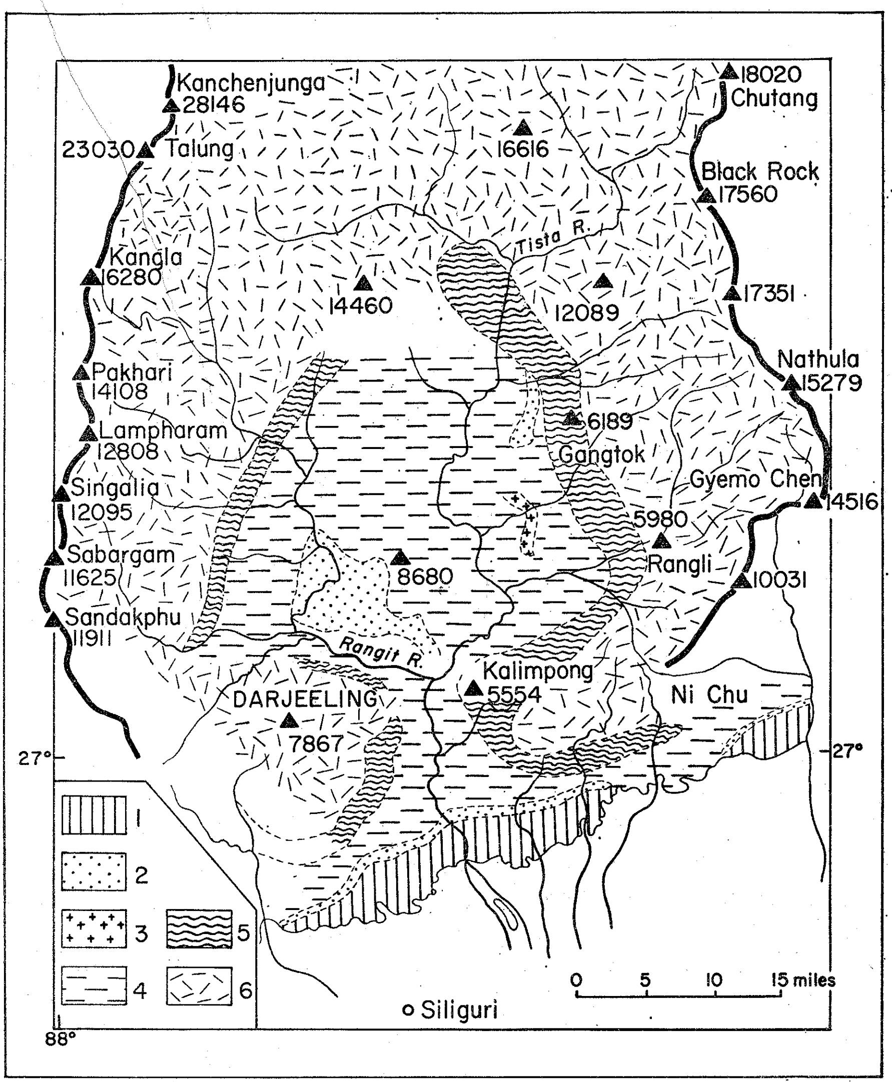

Fig. 1. Metamorphic zones is the Darjeeling—Sikkim region

1. Gondwana territory; 2. Lachist; 3. sheared granite; 4. Daling phyllite, chlorite & biotite zones; 5. Rangli schists, garnet & staurolite zones; 6. Darjeeling gneiss, kyanite & sillimanite

It may be mentioned here that the Darjeeling gneiss and the Daling schists form the entire mass of the Eastern Himalayan metamorphics and have been recognised by geologists as representing lower and upper facies of a great sedimentary-metamorphic succession (Auden, 1935; Ray, 1947). It has been thereby shown that from the Tista valley upwards to the Kanchenjungha range there is a progressively increasing metamorphism of a great ancient sedimentary formation with progressive preponderance of index of minerals, such as, chlorite, biotite, garnet, kyanite and sillimanite found in various metamorphic zones as one travels from south to north.

There is up to now no detailed work on lithology and geological structure available for the area under our study. It has been observed, however, that the gneissic rocks in the Singalila—Kanchenjungha ridge and the Dongkya range are rather coarse-grained gneisses with patches of foliated granites, akin to the "augen-gneiss" occurring frequently within them. The dip of the bandings and foliations is often N, NNE and NE and the angle of inclination varies from a few degrees to almost vertical, depending on local deformations, erosional exposures, topographic character etc. The present study on periglacial processes of slope development is confined to these coarse-grained gneisses and foliated granites of the higher metamorphics of Western and Eastern Sikkim.

GENERAL CLIMATIC CHARACTERISTICS

Next to lithological character and geological structure, the climatic characteristics are of importance in a study of the periglacial processes of slope formation. Unfortunately, no detailed information on climatic characteristics and seasonal rhythms of weather condidions of the area under study are available because of the absence of suitable weather stations in these isolated and far-flung areas of the Eastern Himalayas. The climatological stations at Darjeeling and Gangtok are too far-off from the area of study. Moreover, due to strict military control of the entire area of the Northern and Eastern Sikkim up to the Tibet border, such information as daily and seasonal fluctuations of temperature, amount and seasonality of rainfall, seasonal frost-rise and number of days with ground-frost etc., which are of utmost importance in a study of sub-nival climate and associated periglacial morphological processes (Troll, 1944) are not at all available for a scientific study. From direct field observations and information collected from various sources, it appears however that the periglacial zones of Western and Eastern Sikkim fall under the following two broad climatic belts with differing seasonal weather conditions depending however on altitude, topographic character, gradient of land, exposure to the sun etc. (Kar, 1963).

(a) The "inner periglacial zone" bounded by the summer snowline at 17,500—18,000 ft. in the upper side and the winter snowline at 12,500—13,000 ft. on the lower side.

(b) Below this zone and marginal to the above lie the "outer or marginal periglacial zone" bounded by the winter snowline at 12,500—13,000 ft. and 10,000 ft. of altitude on the lower side.

The general climatic characteristics and seasonal weather conditions of these two adjacent belts, though overlapping upon each other in some respects, are distinguished by the following climatic features which play an important part in the morphological processes.

(I) The inner periglacial zone above the winter snowline at about 12,500 ft. is a zone of winter snow cover, where snow may accumulate to a depth of 3—8 ft. during the passage of depressions in the winter months (Basu, 1947). The land is usually under a snow cover during the winter months from November to March, especially during the last 3 months of the winter and snow fall is intermittent during November after which the land surface remains buried under a snow cover which begins to melt in April. Thus 4—5 months of a year are seasonal periods of ground frost formation with temperatures below freezing point, when subsoil freezing takes place followed by thawing in the spring. Nocturnal freezing is, however, frequent during October and April. The summer months are usually snow free and moist with occasional rainfalls, though sporadic snow fall in summer is not altogether lacking. The average summer temperature is usually below 50° F (10° C), which is the limiting condition for forest. The timber- or tree-line stands at about 12,500—13,000 ft. of altitude in this part of the Himalayas and dwarf rhododendrons, lichens and junipers form the only vegetative species upto 13,000 ft. Only bare rock surfaces stand above this line of vegetation growth, exposed to the full impact of subaerial morphologic processes.

It can thus be easily imagined that recurrent ground frost during the winter months, the absence of an adequate vegetation cover on the bare gneissic rocks, and nocturnal freezing during the late autumn and early spring months usually give rise to intense frost-shattering in bare rock surfaces, severe frost-riving along joints and cleavage lines, scouring of craggy rock faces and ridge lines. Products of disintegration in the form of rock debris tend to slide down the mountain slopes over a frozen subsoil and give rise to solifluction deposits at the sides of mountains and hill slopes.

(II) The outer periglacial zone lying between 12,500—13,000 ft. and 10,000 ft. of altitude is one of unstable snow cover. This zone is under frequent snow fall ranging from 1—5 ft. of snow during intermittent stormy spells in winter months from December to March and is snow-free during the rest of the year. Even in winter, the amount of snow cover and of ground frost phenomena is not uniformly intense and the summer months are usually rainy and moist. Chemical decomposition is stronger in the summer months and mechanical disintegration during the short period of ground frost in the winter months. In the spring the ground is saturated with snow melt-water which induces a distinct solifluct-ion-like mass movement of decomposed materials along the slopes.

On the background of such distinctive climatic characteristics and morphologically active processes in the two periglacial zones of the Sikkim and the Darjeeling Himalayas, though under equal lithologic conditions and rock structure it might be worth while now to examine the characteristics of hillside slopes and discuss their development in this part of the Himalayas.

CHARACTERISTICS OF HILLSIDES AND DEVELOPMENT OF SLOPES IN PERIGLACIAL ZONE

As mentioned above, in this part of the Eastern Himalayas, the summer snow line stands at about 17,500—17,000 ft. of altitude, and as such, the high mountain tracts of the eastern and western Sikkim including the Singalila—Kanchenjungha and the Dongkya ridge that stand above this line form a zone of glacial geomorphic activity under a truly nival climate. They were, in fact the play-ground of intense glacial activities during the last Pleistocene glacial age, evidence of which is still legible in the high ram-parts of serrated ridges, groups of horned peaks, widespread corrie basins nourishing glaciers even today, steeply excavated glacial troughs and amphitheatres, rock-cut glacial lakes dammed by threshold moraines and flanked by chains of lateral moraines. Such glacial zones under present-day nival climatic-morphologic conditions are outside the scope of the present investigation and have therefore been ommitted in the present paper.

It is the present-day sub-nival periglacial zone of high ranges of the Sikkim that form the basis of the author's field-observations and provide the materials of the present paper. The area in question lies below the summer snowline at 17,500—17,000 ft. of altitude and is confined to the Dongkya range of the Eastern Sikkim at the borderland of Tibet. Much of the observations are based on field work in the tract east of Gangtok, in the Changgu——Serabthang—Nathu La—Chola—Bidang Lake—Jelep La sector between lat. 27°30′ N and 27°15′ N and 88°40′ E and 89° E long. The same kind of sub-nival periglacial conditions prevails also in the Western Sikkim in the Singalila—Kanchenjungha ridge at the eastern border of Nepal and indeed below 17,500 ft. of altitude in the Kang La—Koktang—Lampheram—Singalila—Phalut area, in the headward region of the Rangit—Ringbi drainage system.

For the purpose of study of the characteristics and evolution of slopes the sub-nival periglacial zone of the Sikkim highland falls under the following physiographic-morphologic units:

(A) Areas of high ridge walls, deep glaciated troughs and steep slopes inherited from the largescale Pleistocene glacial activities. This is the area *par excellance* of relict slopes, of antecedent slope profiles with high degrees of inclination.

(B) Areas having hillsides and valley slopes which did not originate directly under past glacial action and showing moderate degrees of inclination of land surfaces. Much of the areas were not directly affected by glacial erosion in the past.

(C) The area of outer periglacial zone below the winter snowline, having both high and moderate degrees of slope inclination, but·under a somewhat different climatic regime of periodic winter snowfall and moist and snowfree summer conditions.

AREAS OF ANTECEDENT AND RELICT SLOPES UNDER PAST GLACIAL ACTION

The effects of present-day periglacial morphologic processes on the development of slopes in the high mountain regions of Sikkim can be easily realised when we observe the present-day winter and summer conditions in the steep rocky ridges, deep glacial amphitheatres, overhanging corrie basins and wide open glacial troughs of the Dongkya range in the Eastern Sikkim (pls. 1—4).

Early winter conditions in the Chola group of peaks with its ridgeline at 15,100—15,400 ft. of altitude reveal the overwhelming preponderance of physical weathering in both the summer and the winter season, the stamps of which are clearly impressed on the mountain walls and hillslopes of the area. On the high mountain ramparts, the peaks and ridges have lost many of their former smooth outlines and are subjected to various kinds of present-day frost weathering attacking the foliations, cleavages, joint lines and fractures of the granite-gneiss rock masses. The entire outline of the ridge has thus been sharpened and extremely jagged like the teeth of a saw. Deep frost-riving, frost splitting and basal sapping due to falling of angular and sharp-edged debris have given rise to certain kinds of horned peaks, which often take a shape reminiscent of rabbit ears, double-ridge formations, and steeply overlooking vertical cliffs, all discernible in photo 1. Below the ridge line, every geological texture and all the lines of weakness like joints and cleavages in the massive rocks have been attacked by snow and frost, giving rise to craggy rock faces and scaly rock surfaces with innumerable large and small clefts, furrows, chasms etc. Many of these small corrie-like basins still nourish ice-masses and snow-drifts in the winter months, and basal sapping and frost splitting tend to increase the slope and to sharpen the crest line. Avalanche chutes, snow drifts mixed with rock debris glide down these steep walls in the winter, wearing and tearing the already craggy rock walls. The effect of all these processes is a further steepening of the hillsides, extending from the valley bottom up to the craggy ridge line.

Vigorous mechanical weathering and rapid rock disintegration are thus tending to wear down the high mountain ranges with progressive steepening of the rock walls, and formation of debris slopes.

In face of these facts there is a very important difference in the morphologic processes of slope formation on the contrasting sunny and shaded sides of the great amphitheatre of the Cho La range (pl. 1). The contrasting morphologically active processes on the sunny and the shaded sides of moutain walls been thouroughly observed and investigated in the Alpine ranges and subtropical mountains of Anatolia (Spreitzer, 1960). In the glacially sculptured trough of the Cho La range, the righthand, north-facing wall is a shadow-side wall containing patches of snow accumulations and snow drifts in the early winter even when the wall is much steeper, while the lefthand, sunny, south-facing wall is devoid of snow even on its gentler slopes. The net result of this is that, while the shadow-side is constantly under the action of weathering agents, of snow avalanches, snow drifts, rock-splitting and debris chutes, all tending to maintain its inherited steep slopes and even over-steepening it by cliff formation, the opposite face with gentler slopes is under the influence of gravity creep and solifluction processes assisted by active frost-splitting and rock disintegration on the upper part. Further to the left, the exposed bare rocks below the areas of snow accumulation are also subjected to strong frost weathering and rock disintegration, leading to the formation of minor block fields, debris chutes and talus cones at the slope bases. In the main open glacial valley with a gentle declivity in the foreground, the present-day winter conditions stimulate a kind of Pleistocene glacial activity, and patches of snow, fed by avalanches and snow chutes from overlooking ramparts tend to move very slowly down the valley along with masses of debris, scree materials and other products of rock wastage. Due to changing frost conditions, in winter and spring, there is a distinct but slow solifluction movement over this gentle valley bottom.

Further examples of similar morphologically active processes operating on the steep ridge walls of the Eastern Sikkim can be seen in pls. 2 and 3. In both these cases, the steep bare rock walls are under the spell of intense mechanical wearing by frost weathering with distinct processes of slope development. In the first, while the ridge wall overlooking the twin corrie basins has a sharp crest-line due to past glacial action from adjacent sides and present-day basal sapping due to frost activity (pl. 2 : X, A), the rock walls are subjected to current frost-riving and frost-splitting (as shown on the hillside under a cloud shadow). No doubt the geological structure and the grain-size also have some effect on the slope development in so far as strong vertical jointing and slightly dipping beds to the right have given rise to large and small clefts and the products of rock disintegration have formed talus cones (X, C, Y, C) and scree falls (Z, D), right below the denuded rock walls.

All these facts are also clearly evident in the denudation of the steep walls of a past glacial corrie-basin in the Dongkya range, east of the Nathu La pass (pl. 3: X,Y,Z). The sharply incised crest line stands high due to splitting of rocks along cracks and basal sapping from adjacent sides. Below the ridge crests, the bare rocks have been made craggy and the rocky furrows tend to split the walls along the major joints and to foliate the rocks (X C). These furrows give rise to debris chutes gliding down the steep slopes and constantly fed by rock wearing on the upper slopes. As a result the lower segments are under a thick mantle of scree, talus and rock debris, which give a gentler declivity to the slope. At the bottom of the walls, debris and talus cones are formed where the hill sides meet a flat ground (pl. 3: X D). To the right-hand side in photo (pl. 3), a precipitous vertical rock cliff has been formed owing to the strong effects of frost-riving, on a joint system and on foliation planes of gneissic rocks, whereby large blocks have been dislodged and toppled down, to be further disintegrated below. Just below the overhanging cliff, the disintegrated rock debris has formed a fairly steep slope, the declivity of which is broken by shallow-rooted herbs of several kinds, growing on moisture-containing soil and debris materials (see Y F). In all these cases, the vertical rocky cliff face is followed by a distinctly concave form of the slope profile, until it meets the flat ground below.

These features and forms are very conspicuous in the high mountains and hillslopes of the Jelep La ranges with altitudes of 14,350—15,400 ft. (pl. 4). The towering ranges have all been scoured into barren and craggy crests, with evidences of furrowing on bare rock-walls by frost action on joints and fractures, through which debris chutes glide down conveying rock fragments and particles down the slopes. Double crest building is already in progress (see Y B), with very craggy faces in all other hill tops. These craggy hill tops are followed below by a stretch of steep and almost vertical cliffs standing up as remnants of ancient glacially sculptured trough walls, as can be clearly seen on both flanks of the glacial valley. Still lower, there appear on both sides very smoothly concave slopes formed of a mass of rock debris and talus materials supplied from the zone of disintegration and rock splitting at the hill tops. The two concave profiles of opposing hill slopes nearly touch each other at the bottom, giving an almost perfect rounded shape to the entire valley. The active geomorphic processes operating at the hill tops and on the hill sides of these ranges have given rise to slope profiles of nearly perfect form, the origin of which will be discussed later (see sequel).

AREAS DEVOID OF ANTECEDENT SLOPES AND WITH MODERATE DEGREES OF INCLINATION

In the areas below the above mentioned belt of high mountain ranges and glacially sculptured landscape lying above 13,500—14,000 ft., there is a zone of broad hills and wide mountain valleys with moderate inclinations. Although some of the areas were clearly underwent glacial erosion, in Pleistocene times, when the snowline was much depressed giving rise to corrie basins and glacial troughs with steep walls that have persisted until now, much of the area has no relict type of slope which originated under past conditions, and has hillsides of moderate inclination. This zone is however under the action of a kind of morphologic processes, that is somewhat different from those operating in higher zone. While both the zones fall under the inner periglacial belt above 12,000—12,500 ft. of altitude above the winter snowline of the Sikkim Himalayas, the climatic conditions are somewhat different in so far as the higher zone of high mountain ridges and glacial troughs is subjected to intense ground-frost activity throughout the winter months and to diurnal ground frost in the summer aided by the absence of vegetation on the bare rock surfaces, the other zone, at a lower altitude, is under a less intense frost-action during the milder winter months and has more moisture and rains in the summer. The morphologic processes are here therefore characterised by frost-splitting, frost-riving and mechanical rock-breaking in the winter and solifluction flow in the spring and the summer.

Examples of such morphologic processes and of their effects on slope development are shown in plates 5—9. Towards higher altitudes of about 13,000 ft., the moderately sloping opposite sides of a shallow depression show the effect of hill side exposure on the morphology of slope development. While the secluded shadow side is under a thick mantle of soil debris under dwarf rhododendron bushes, the opposite side exposed to alternating radiation-frost formation-thawing has given rise to a well-defined block-field formation, with a mass of rock fragments and debris moving slowly down the hillside (pl. 5: X A, Z B). The effect of frost-splitting on the almost vertically jointed, coarsely foliated gneissic rocks is clearly seen in the middle of the picture, with evidence of repeated double-ridge formation, accompanied by talus accumulation at the foot of the ridges.

In the same area, the ridges and peaks are under frost-splitting and mechanical rock breaking that give rise to craggy ridge lines (pl. 6: X A), double-crest formation (pl. 6: Y A), rocky furrows under debris chutes, etc. On the same mountain side, the lower slopes are under a thick mantle of rock debris and talus accumulation with a moderate degree of slope, on which periodic solifluction movements take place (pl. 6: Y B). In another case, the fractures and joint planes of the rocks with moderate slopes are covered by a mass of angular rock fragments similar to the block fields of periglacial zones, moving slowly downslope (pl. 7), while the intervening areas under a mantle of shrubs tend to resist any downward movement of surficial debris. In this zone, one finds therefore strong mechanical breaking and splitting of rocks in the bare and exposed ridges, followed by chains of debris chutes and streams of block-fields slowly moving down the hill sides, beside a thick mantle of solifluction debris covering the intervening slope (fig. 2). The most striking feature of all these hillsides is that just below the zone of rock disintegration, the slope takes the form of a distinctly convex profile under a mantle of solifluction debris (pl. 6, fig. 2).

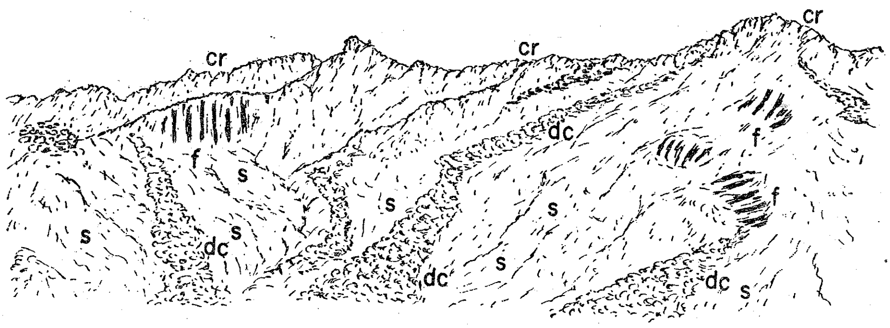

Fig. 2.
cr — craggy ridges, f — rocky furrows, s — solifluction, dc — debris chute

This shows clearly that in the climatic zone in question the hillsides below the ridges of active rock disintegration have invariably a convex slope profile due to the slow movement of solifluction materials. The fact remains equally true even in cases where steep slopes of Pleistocene glacial trough walls, where the bare craggy ridges suffering from mechanical denudation are followed in the lower parts by a mass of solifluction debris creeping slowly downslope, and thus giving rise to a series of convex bulges, in the otherwise concave profile of the slope (pl. 8, fig. 1). The climatic control of the slope building processes giving rise to distinct concavity and convexity of the slope profile on the hillside is thus clearly manifest in the mountainous tract of the Eastern Sikkim.

AREA OF THE OUTER PERIGLACIAL ZONE WITH HIGH AND MODERATE INCLINATION OF SLOPES

As mentioned above the mountain slopes of the Eastern Sikkim between 12,500—10,000 ft. of altitude at the outer margin of the winter snowline constitute the outer periglacial zone. The climatic environment and the associated morphologically active slope-building processes are somewhat different in this zone, in so far as milder winter frost phenomena and spring thawing is followed by moist and rainy summers and autumns; as a result the mantle of disintegrated rocks and decomposed debris is saturated with moisture and thus converted into a kind of plastic body slowly moving downward in the form of solifluction flow, soil creep, etc.

A distinctive feature of slope development in this region is the very pronounced convex profile of the mountain sides, which is only broken by numerous „terracettes" originating by gravity creep at the base of steep slopes (pl. 9). It also appears, from field evidence in the Sandakphu-Singalila range in the Western Sikkim, that mechanical disintegration of gneissic rocks by winter frost action is followed by chemical decomposition (due to saturation with water, hydrolysis, kaolinisation etc.) and the entire mantle of such semi-decomposed debris materials acts as a plastic body which slowly moves down over a frozen or half-frozen subsoil giving rise to rounded outlines of the hillsides, even when the granitic-gneissic rocks are dipping high and almost vertically (pl. 10). Wherever these debris mantles slide down over a steep slope owing to gravity, they often give rise to a series of natural "terracettes"; even then they impart an overall rounded or convex shape to the hillsides (pl. 11). In these hills, while the lithology and structure of rocks (degree of foliation, jointing, amount of dipping etc.) influence the mechanical breaking up of rocks due to radiation and frost-phenomena, they have little influence on the overall development of hillsides, whereas the climatic control influencing solifluction flow and soil creep becomes the determining factor. All these facts are abundantly made clear in the overall development of hillsides, as observed in the hill ranges of the Sandakphu—Phalut area in the Western Sikkim (pl. 12). The moderate to steeply dipping gneissic rocks forming the main mountain ridges, have developed rounded outlines and convex slope profiles, with slopes grading from 25° to 50°. Whether steep or gentle, the smooth rounded outlines of these hills covered by a thick debris mantle stand in contrast to the young and recent gullies and streams entrenched into it (pl. 12). The side-walls of these gullies and stream trenches even show convexity, indicating that solifluction flow and mass wasting are stronger than linear fluvial erosion — a phenomenon that becomes still more pronounced in the lower reaches (below 10,000 ft. of altitude), where the river and stream valleys take more and more concave or at least V-shaped profiles.

SUMMARY OF OBSERVATIONS ON MORPHOLOGICAL PROCESSES AND SLOPE DEVELOPMENT IN THE SIKKIM HIMALAYAS

The observations recorded above reveal certain general principles or natural laws under which the mountain- and hillsides have developed in the periglacial regions of the Sikkim Himalayas during post-glacial times. The following important factors seem to have played a part in the evolution of the periglacial slopes of the region:

(a) altitudinal position, ranging from that of outer periglacial belt (10,000—12,500 ft.), to that of inner periglacial belt (above 12,500 ft.);

(b) climatic environment ranging from mild winter frost action, and moist summer conditions in the lower zones to severe winter frost phenomena, vigorous mechanical rock breaking and reduced chemical decomposition in the higher ones;

(c) micro-climatic factors such as exposure of slopes, shadow and lee-side of hills, abundance of snow patches and avalanches in winter and spring;

(d) lithology and geological structure, such as coarseness of foliation in granitic and gneissic rocks, degree of jointing, dip and inclination of beddings etc.;

(e) ecological-biotic factors such as nature of vegetation in the form of tree cover, herbs, shallow-rooted shrubs, etc.;

(f) periglacial slope building processes resulting from the interaction of geological character, degree of slope inherited, climatic control and micro-climatic features, the agency of avalanches, snow, meltwater and rains.

Considering the high altitudinal range of the periglacial phenomena observed in the Sikkim Himalayas, altitude appears to have an important influence on the periglacial processes of slope development through the medium of climatic control and microclimatic features. Such being the case, the lithology and geological structure have in general no determining influence on the development of slopes but act indirectly under the action of climatic control and micro-climatic features. In the entire region, the degree of inherited slope inclination has also no direct influence but is modified by periglacial climatic-morphologic processes. Biotic factors such as occurrence of plants and shrubs also have a contributory role to play in some minor degree. It is the climatic control expressed through the agency of avalanches, snow, frost, meltwater and rains acting on the lithological grains and the evolution of slopes in the periglacial region.

In order to elucidate these points, one ought to remember that in this part of the Sikkim Himalayas, the high mountain ridges, crest lines and steep rock walls above 13,500 ft. are subjected to most intensive frost weathering and to vigorous rock disintegration leading to features like double-crests, serrated ridges, rocky furrows, debris chutes, recession of rock walls etc., all due to severity of radiation, and lack of an insulating vegetative cover. The influence of micro-relief (geological grains, factures, joints etc.) and micro-climate (exposed to or lee-side from sun and wind) have also a minor role to play, leading to asymmetry of valley sides, formation of rock-streams and solifluction etc. (pls. 1—5). The severity of frost action on bare rocks and its influence on geological structure is the determining factor in the evolution of slopes in this zone. So for example, where the jointing and bedding is favourable frost disintegration has given rise to vertical cliffs with rockfall and talus accumulation at their bases which again gradually merge into solifluction debris below (pl. 3). The slopes take here a highly concave profile (fig 3: C D). Owing to the predominance of mechanical weathering and the abundance of rock debris in this high mountain zone subjected to vigorous frost action, this zone seems to correspond to the "blockfield zone" and "tundra zone" of high latitude regions of Scandinavia (B ü d e l, 1948; R a p p, 1960).

With diminishing altitude and decreasing severity of radiation and of frost phenomena in the winter, along with increasing snowmelt and summer precipitation, the morphologic processes of soli-

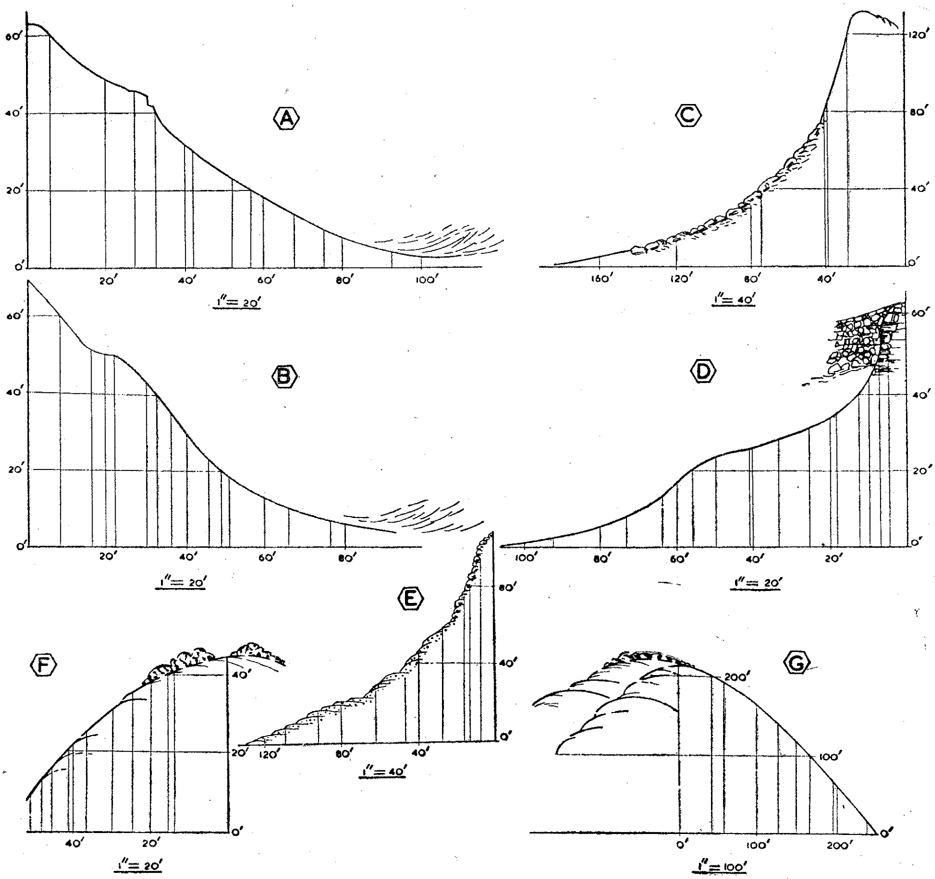

Fig. 3.
Explanations in the text

fluction, debris chute, rock stream tend to take the upper hand irrespective of geological structure and inherited slope, forming a thick mantle on all hillsides, being hindered only by stunted trees, shrubs and stubborn bushes (pls. 6—8, fig. 2). Though the ridges and crests are still under strong mechanical denudation, this zone, lying slightly above and below the "tree-line" affords abundant evidence of mass wasting over the mountain slopes. The hill slopes now tend to assume convex forms, being strongly influenced by morphologic processes giving rise to solifluction, rock stream etc., all under the action of climatic control rather than of any other factor. This zone can be paralleled with the "forest zone" of periglacial regions in high latitude countries (Büdel, 1948; Rapp, 1960). Further below, the much milder winter conditions associated with less severe frost-shattering and freezing of subsoil under a heavy debris cover alternating with moist and rainy summers give rise to solifluction flow and debris creep over the hillsides outstripping by far any other denudational activity and irrespective of inherited slope, geological structure or any other factor. Mechanical rock-breaking is less effective while periodic chemical decomposition is more pronounced. Under these circumstances, the plastic debris mantle saturated with snow-melt- and rain water has given rise in the processes of slow downhill movement to very rounded ridges and distinctly convex slope profiles (pls. 9—12, fig. 3: F G). This outer periglacial zone again stands in contrast to still lower mountain sides which are under the influence of distinct fluvial processes, with concave hill slope profiles.

The above discussion and field evidence have demonstrated that the slope profiles in the mountainous terrain of the periglacial zone in the Eastern Himalayas have been produced by well-defined morphologic processes operating through the agency of frost, snow, melt-water and rains under the control of climate and micro--climate, acting on the lithological texture and the geologic structure of the terrain. As such, hill slope profiles are of "diagnostic value" in the study of periglacial processes and the various forms of slope profiles, ranging from concave to convex give evidence of different kinds of morphological processes and slope-building agencies.

MECHANISM OF SLOPE-BUILDING PROCESSES AND FORMS OF SLOPE PROFILE

An analysis of the various forms of slope profiles in the three morphologic-climatic periglacial zones of the Sikkim Himalayas, along with a study of the mechanism of different slope-building processes, give the following results.

In the higher altitudes, with rigorous mechanical weathering of rocks under severe frost activity, the hill-side profiles tend to have their "crest slope" [2] developed as cliffs or vertical precipices

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[2] Savigear has defined the „crest-slope" as the upper one, the „mid-slope" as the central one and „foot-slope" as the basal segment of a typical hillside (Savigear, 1956).

owing to dislogment of rock fragments along the joints and bedding planes produced by frost-riving, ice-wedge formation etc. (fig. 3: C D). These vertical cliffs or free rock faces ranging in inclination from 90° to 75°, overlook a mass of rock debris, talus accumulations etc., supplied from the cliff face and forming the "mid-slope" with 55°—20° of inclination. This is followed by a gentler slope of solifluction materials inclined at an angle below 20°, until it merges into an almost flat slope-wash (foot-slope) (fig. 3: C D; pls. 3, 4). These slope elements are very nearly conform to the four zones in a typical Spitsbergen slope (rock zone, talus cone, solifluction, and slope-wash) as described by Jahn (1960) from high latitude areas of Scandinavia.

Even under conditions of inherited slopes of a past glacial trough, periglacial processes seem to modify the steep slopes by a superimposition of the above mentioned debris cone and solifluction slope with a lesser degree of inclination (fig. 3: A B; pl. 4). Where local ecological conditions, such as plant and shrub roots or increasing moisture content of the subsoil interfere, the mid--slope element is broken into two parts by a convex bulge (fig. 3: D; pl. 3); otherwise the entire profile tends to form smooth concave curves.

It thus appears that in the formation of vertical cliffs and precipices in the crest-slope zone, the severity of atmospheric radiation (seasonal and diurnal) plays a prominent part, whereby the rock at the crest acting as an "elastic solid" gives rise to "tensional fractures" or "shear rupture" usually along the joints and bedding planes of rocks, due to recurrent stresses induced by the freezing and thawing cycle, which again gives rise to ice wedges, ice-crystal etc. developing along such fractures, joints and bedding planes. The phenomena of frost-riving, frost-shattering, basal sapping etc. thus come into being, leading to periodic failures in the stability of loosened blocks or cubes of rock fragments.

The development of cliff face in the crest zone is invariably associated with a development of debris slope or talus cone, whose angle of repose depends on the height of the cliff-face, the amount of unconsolidated materials eroded from above, the degree of original inclination of the hillside, and the nature of the gravitational stresses tending to remove the talus and debris materials downwards. In the mechanism of talus cone or debris slope formation, any disturbance in the equilibrium of forces, of the "driving moment", of the loose materials in the upper portion and the

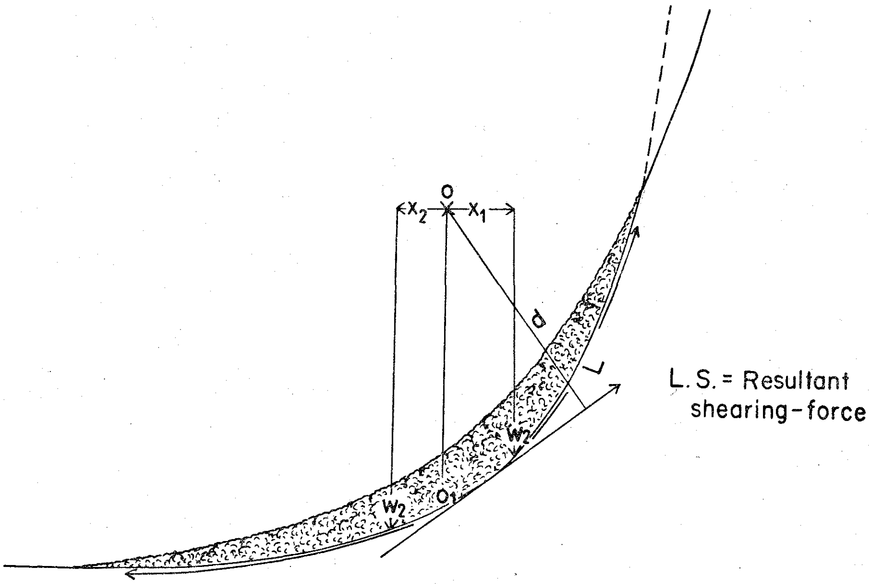

Fig. 4.
Explanations in the text

"resisting moment" of the materials below leads to sliding of scree materials until the equilibrium is restored again by readjustment [3]. This will obviously give rise to an essentially non-rectilinear concave profile, with the steep crest slope on the upper side and a gradually decreasing declivity of talus and scree surface, which finally merges with a flat base. The entire slope has under these conditions an upper "degrading or receding slope" and towards its

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[3] The equilibrium of forces maintaining a concave slope on a mass of unconsolidated talus materials and subjected to gravitational stresses of sliding can be expressed as follows (fig. 4).

Resisting Moment = Driving Moment

$$w_2 x_2 + s.l.d. = w_1 x_1, \text{ where:}$$

0 0′ is a vertical line through any point 0, such that the weight of the portions of the talus materials to the right of the vertical is w_1 tending to produce failure under gravity, and the weight of the materials to the left is w_2 tending to resist it,

x_1 x_2 are respectively the perpendicular distances of 0 from the lines of action of w_1 and w_2

s is the resultant shearing force (resistance) of the talus materials per unit of length of the curve on which the debris lie (original glacial trough)

l is the total length of the above curve,

d is the length of the perpendicular from 0 on the line of action of the resultant shearing force (adapted from Leopold, Wolman, Miller, 1964).

base a "slope of accumulation or accretion". Scheidegger (1950) in his study of the model of slope building under erosion and accumulation has shown that "accumulative slopes should be essentially concave and flatten out with time". Later on, improving on the linear equation models of slope development propounded by Lehmann (1933), and Bakker and Le Heux (1947, 1952), Scheidegger (1950) developed a non-linear hyperbolic partial differential equation of slope development by taking into account the rate of denudation-effect on the crest and that of aggradation at the foot of the slope, and found that with the passage of time an original rectilinear slope edge recedes backwards by the wearing off of the cliff with a gradual extension of the foot-slope away from the cliff, owing to which the slope assumes a concave overall appearance (Scheidegger, 1961).

In the still lower altitudes, where block-stream, debris chute and solifluction debris are the prominent features, a different kind of mechanism of slope formation operates. In the case of block-stream covered slopes, shear stresses set up by interstitial ice-crystal growth leads to rupture between grains, cleavage pieces or joints, producing rock fragments which are subjected to slow creep or slide by the repetition of the process. There is no definite cliff-face development and the heaps of rock-fragments tend to form a slightly convex debris surface. In the case of debris chutes the same statement holds good, except that they are confined to linear alignments.

A remarkable change in the mechanism of slope formation and in the form of slope profile comes again with an increasing degree of snow-melt- and rain water, etc. along with a decrease in the severity of frost phenomena with lowering altitudes. This is manifest even in the steep hillsides of a past glacial trough subjected to solifluction flow, where the solifluction debris moving down the steep glacial trough-wall produced a series of minor convex bulges in an otherwise concave profile. Here, the small aggregates or particles within the plastic debris material have a tendency to slide over or to over-flow the next below. This process is akin to laminar flow, where the velocity of thin sheets of plastic debris above is always higher than that of the materials immediately below, thus giving rise to a series of convex bulges in the form of small lobes or tongues of debris materials (pl. 8, fig. 3: F).

This process is more pronounced in still lesser altitudes of the

Table I

1	2	3	4	5	6	7	8	9
Periglacial zones	Climatic control	Nature of slopes	Type of rock materials and nature of vegetation	Properties of materials	Type of failures	Geomorphic process Types of movements, flows, etc.	Forms of slope profiles	Inclination of slope; values of C and f
(A) INNER PERIGLACIAL (a) Higher zone Alt. above 13,500 ft.	Extreme radiation (seasonal-diurnal); severity of frost phenomena; less snow and fines; mechanical disintegration predominant	Steep hill sides; glacially carved valley walls	Granite-gneiss crystaline; dip high to moderate; bare rocks above tree line	Rigid elastic solids; strain stress, according to Hookes law	a. Tension fractures, ruptures along joints, beddings, foliation planes b. Gravitational stresses, instabilities, etc. on loose rock-fragments	a. Rockfall, rock slump, rock slides b. Talus and debris slide	a. Vertical cliffs with free faces b. Slope of accumulation, forming parabolic concave profile	a. Almost vertical — 75°—90° C = 67—1.02; f = 0.61—1.11 b. Steepness decreases from 75°—25° until flattened out
(b) Lower zone Alt. above 12,500 ft.	Less intense radiation (seasonal-diurnal); less severe frost phenomena; more snow-melt and rains; mechanical disintegration still strong	Steep to moderately steep hillsides; glacial valley walls	— do — Stunted trees and shallow rooted shrubs	a. Elastic solids b. Plastic solids	a. Shear stress by interstitial ice crystals; rupture between grains, cleavage, joints b. Slight tendency to laminar flow	a. Frost disintegration; block streams, debris chutes b. Solifluction	a. Slopes of accumulation forming concave profile b. Convex bulges on concave slopes	Steepness decreases from 55°—25° with minor breaks and bulges C = 1.04; f = 0.96
(B) OUTER PERIGLACIAL Alt. above 10,000 ft.	Milder winter frost phenomena; summer rains and ground moisture; seasonal chemical decomposition	Steep to moderately steep hillsides	— do — Conifers in sheltered valleys; shrubs on exposed slopes	Debris mantle behaving as plastic solid, ac. to Binghams law	Plastic flow, with shear between grains and particles, when stress exceeds yield value; flow mainly laminar	Solifluction, soil creep, mass wasting, etc.	Parabolic convex	Steepness increasing from 25°—30° to 45°—50° C = 12.84—0.04; f = 0.57—1.73

outer-periglacial zone, where the great mass of decomposed rock debris saturated with snow-melt- or rain water tend to glide over a still frozen or hardened subsoil, giving rise to a perfectly convex slope profile. The debris mantle acts now as a semi-viscous or viscous-solid subjected to plastic flowage under gravitational stresses, producing shear between grains, or small aggregates of particles, such that the rate of shear is proportional to the stresses applied, after a yield value is exceeded (Leopold, Wolman, Miller, 1964). In this mechanism of laminar flow, there is again a clear tendency for each thin sheet of plastic materials to overflow the one just below, producing thereby bulges or an overall convex slope on the hillsides (pl. 10—12, fig. 3: F. G). In both the cases of talus slope formation in the higher zone and of solifluction or plastic debris slope in the lesser altitudes, the degree of initial slope, lithology of rock particles and geological structure of bedrock etc. are the same, but the different mechanism of the slide movement and the plastic flowage produces different kinds of slope profiles, ranging from concave to convex and, thereby clearly indicating that the simple addition of water may alter the mode of failure (stress/strain relationship) and of movement (Leopold, Wolman, Miller, 1964).

QUANTITATIVE MEASUREMENTS OF SLOPE PROFILES

In order to give a meaningful interpretation of the slope profiles occurring in the separate altitudinal zones of the Sikkim Himalayas, a quantitative measurement of the slope profiles was undertaken (fig. 3: A—G).

An analysis of the angle of inclination of the various slope segments in the high altitudes of the inner periglacial zone shows that the declivity of the slopes is highest in the upper segment (in the cliff face i.e. 75°—90° steep), gradually decreasing in value until it merges into the flat slope base (fig. 3: A—D). This is typically representative of a parabolic concave curve developed by talus and scree accumulation in high altitudinal zones. Even in steep glacial slopes at lesser altitudes with an occurrence of plastic solifluction materials, the concavity of the general slope persists, though interfered with by minor bulges or tongues of plastic debris (fig. 3: E). The reverse is however true in the convex and rounded hillsides of the outer periglacial zone, where the angle of inclination is lowest in the upper segments (25°—30°) and gradually increases in value downwards (45°—50°). These therefore represent typically parabolic convex slope profiles.

These profiles were again studied quantitatively by considering them as smooth mathematical curves defined by an equation and then comparing the constant values of these equations. This was done by measuring (a) the slope gradient, H, measured as the vertical distance from the ridge-crest to a point on the slope, and (b) the horizontal distance, L, measured from the ridge-crest to the point in question, with the origin at the crest of the slope, in the equation, $H = C \cdot L^f$, where C and f are constants. Here C is a measure of steepness and f is a measure of curvature or of the rate of slope change (Hack & Goodlett, 1960). A comparative study of the constants derived from the above equation of the slopes indicates that in the profile A—E in figure 3 the value of the curvature f ranging from 0.61 to 1.11 stands in inverse relation to the value of C ranging from 6.67 to 1.02. In the profiles F and G, the value of f ranges from 0.57 to 1.73 standing in inverse relation to the value of C falling between 12.83—0.04.

A comparative study of the nature and properties of the materials, of the type of strains produced, of the nature of the geomorphic processes involved, with the resultant forms of slope profile is presented in Table I.

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Pl. 1. Early-winter conditions in a part of the Eastern Sikkim range at analtitude of about 15,000 ft.

In the foreground, a glaciated cirque basin with avalanches and snow drifts. Note steeper walls in shadow side (Z_1C) and gentler slope on the exposed sunny sides (YD). Mechanical weathering, frost-splitting made ridge line craggy (YA, ZA), rock surfaces scaly (XB), with clefts and furrows (YB), and debris chutes (XD)

Pl. 2. Frost action on mountain walls at about 14,500—15,000 ft. showing sharp crests due to nivation, basal sapping etc. from adjacent sides (XA), rocky furrows, clefts due to jointing (YB), debris, talus chutes (XC, YC) and scree falls (ZD)

Pl. 3. Morphologically active processes in high mountain walls at about 16,000 ft. showing sharply incised crest-lines (XYZ), arising out of *Bergschrund-korrasion* and *Gratbildung*

Note rocky furrows along joint and fractures (XC), scree and talus (YC), and talus cones (XD). The almost vertical precipice due to block disintegration to the right (ZA), followed by concave talus slopes (ZB) and convex bulge due to shallow rooted herbs, plants etc. (YF) are visible

Pl. 4. Ideal slope building due to periglacial processes superimposed on a glacially sculptured valley at the NE border of Sikkim at about 14,500—15,000 ft.

Note the bare ridges in the background being split, riven and attacked by frost action with formation of double horns (YB, XB), and giving rise to perfect concave scree and talus slopes, superimposed on steeperglacial valley slopes (XC). Remnants of steep shoulder of an older glacial trough seen at XA, XB

Pl. 5. Periglacial processes at about 13,000 ft. having not antecedent glacial slopes and showing development of block-fields on the exposed side (XA), and solifluction covered gentle slope on the opposite side

Note the effect of vertical jointing on rock splitting and formation of double horns (ZC, YC, and talus accumulation below (ZA, YA)

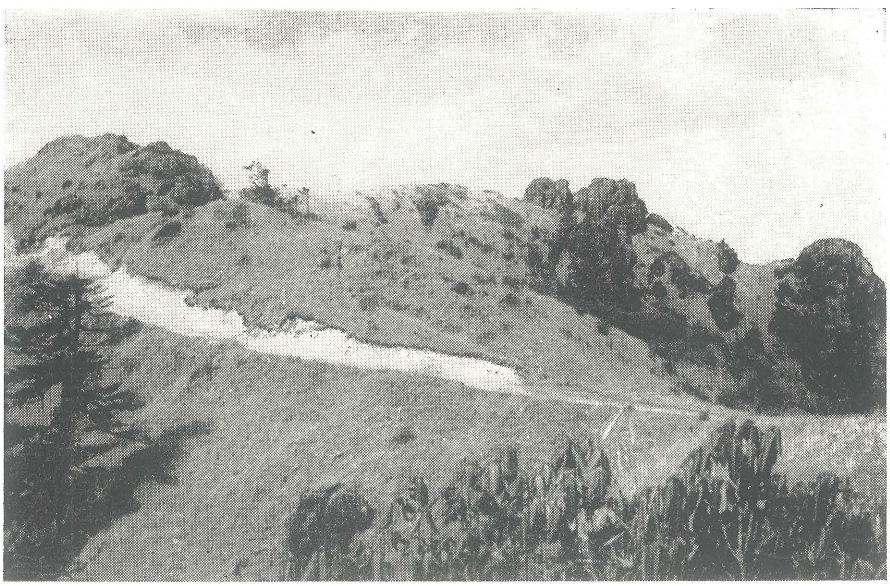
Pl. 6. Periglacial slope frmation on a mountain side at about 13,000 ft. indicating strong rock disintegration, frost-splitting, enlargement of jointing and cracks (XA, YA), and distinct formation of double-peaks, with concave slopes. This is attended with a thick accumulation of solifluction debris with a distinct convex slope (XB, YB)

Pl. 7. Effect of rock jointing, fractures, cleavages interspersed with vegetation growth on the formation of talus and scree materials at about 12,500 ft.

Pl. 8. Composite hill slopes on the walls of a Pleistocene glacial trough at about 12,500 ft.

Note the steep, cragy and frost-splitted rocky ridges above, followed by gentler slopes with convex bulges of solifluction materials. Early winter snow on valley bottom and on hill slopes

Pl. 9. Overall convex slopes with "terracettes" developed on thick mantle of slope materials im marginal periglacial zone at about 11,000 ft.



Pl. 10. Slope building processes at about 11,500 ft. in NW frontier of Darjeeling district in the marginal periglacial zones

Steeply dipping gneissic rocks under mechanical wearing and splitting in winter are giving rise to a thick mantle of slope deposits under periodic chemical decomposition due to hydrolysis, kaolinisation, etc. Note convex slopes below areas of steeply dipping gneissic rocks

Pl. 11. "Terracettes" formed due to gravity creep on thick, semi-decomposed mantle in the same area as in pl. 10

Pl. 12. Typical convex slope formation in marginal peri glacial zone near NW border of Darjeeling district between 11,500—12,00 ft. due to the effect of semi-viscous and semi-decomposed man the moving downslope