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Studies in the geomorphology of the mountain regions of the Upper Indus basin

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STUDIES IN THE GEOMORPHOLOGY OF THE MOUNTAIN REGIONS OF THE UPPER INDUS BASIN

by

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VOLUME 1

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ABSTRACT

The investigation primarily concerns contemporary geomorphological features and processes in the Upper Indus Basin. Past work, and theories of the denudation chronology of the region are described, and the broad climatic and geological setting. The bulk of the work examines characteristics of weathering, slopes and mass-movements, glacial and fluvial features in the Biafo Gyang area of the Central Karakoram. The nature and role of glacier surges and natural damming in the region are discussed. An effort is also made to support the central theme with background information and visual illustration not normally available, and a comprehensive regional bibliography is provided.

Weathering processes show an intimate interaction of chemical decay, salt weathering, frost action and primary mechanical failure of rock. A variety of forms is produced from tafoni to exfoliation structures, while weathering products are mainly angular with little clay fraction. This seems mainly due to rapid rates of removal which preclude advanced decay.

Slopes are steep, most of the Biafo Basin area exceeding 45° of angle. This, large upslope variations in climate and lack of vegetation promote vigorous mass-movements and varied slope deposits.

The Biafo Gyang Glacier is one of many enormous valley glaciers in the region, and is of the "Firn-Stream" type. The ablation zone has extensive covers of moraine and large flanking kame terraces. There is a short, vigorous melt season and marked resurgence of the glacier margins and terminus in winter.

Above the Biafo the Braldu River flows in a wide belt of valley train, but plunges into a deep gorge with huge terraces and rock walls below the glacier's entry. 80% of the Upper Indus rivers' discharge occurs in three months of the year and over 90% of the sediment transport. Extreme erosional events play an important role in the region, special significance attaching to the many natural dams and dam-burst floods. Overall, the orographic effect tends to express itself by promoting short-lived, high energy erosional events.

CONTENTS

Volume I

C O N T E N T S

Volume II

CHAPTER 1

THE REGIONAL SETTING AND SCOPE OF THE PRESENT STUDY

This study examines the geomorphology of a mountain region in South Central Asia, on the basis of field-work and published sources of information. The aim is both to add to our knowledge of regional geomorphology by describing a little-known area, and to try to place the geomorphic problems of the region in the context of contemporary thinking. In this first chapter the regional setting will be outlined, and the methodological approach of the study described.

1.1. Regional Setting: The Upper Indus Basin.

Immediately north of the Greater Himalaya lies a belt of mountain ranges and desert-like valleys generally known as the Semi-Arid Himalaya. This investigation concerns the north-west part of the belt where it comprises the Upper Indus Basin. Whenever "the region" is mentioned in the text, it refers to a region defined by the watershed of the Upper Indus above the entry of the Kabul River. (Fig. 1.1.)

Surrounding and within the Upper Indus Basin is a series of great mountain ranges and a complex of subsidiary drainage basins. Even today, the literature on the region shows a wide variation in nomenclature although much of it was thoroughly investigated in the Thirties (see. Karakoram Conference Report, 1938). Except where later exploration has revealed more appropriate local names, and in areas beyond the scope of the Report, this study employs the nomenclature adopted by the Karakoram Conference. The Royal Geographical Society's map, "The Karakoram" (1939) uses the recommended names, and indicates fairly well the geographical units established. As a whole, the region's mountains come within what Visser termed "The South-Central Asiatic Mountain System" (1935/38, vol. 1. p. 109). This forms a highly complicated set

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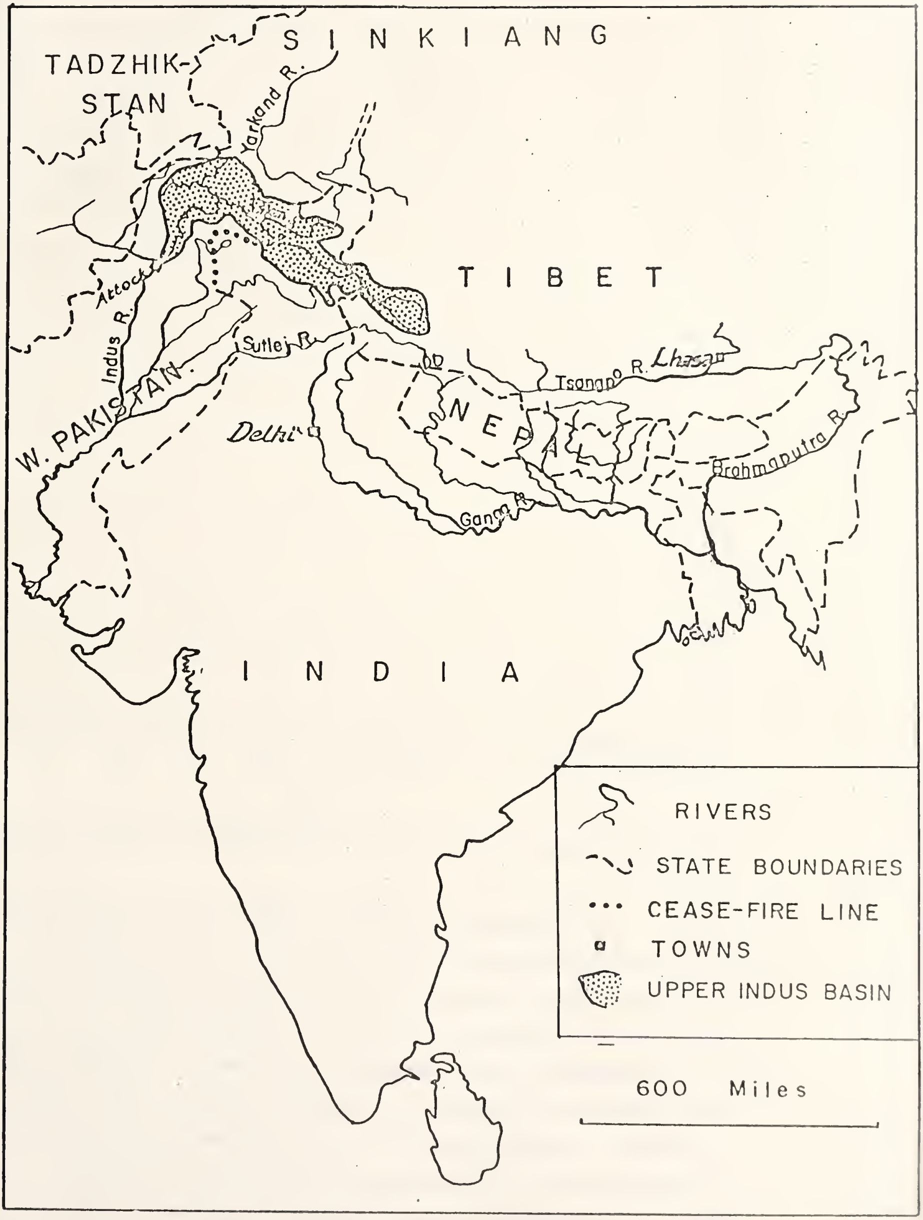

Fig.I.I. Map showing the location of the Upper Indus Basin in Southern Asia, and its relation to other major Himalayan rivers.

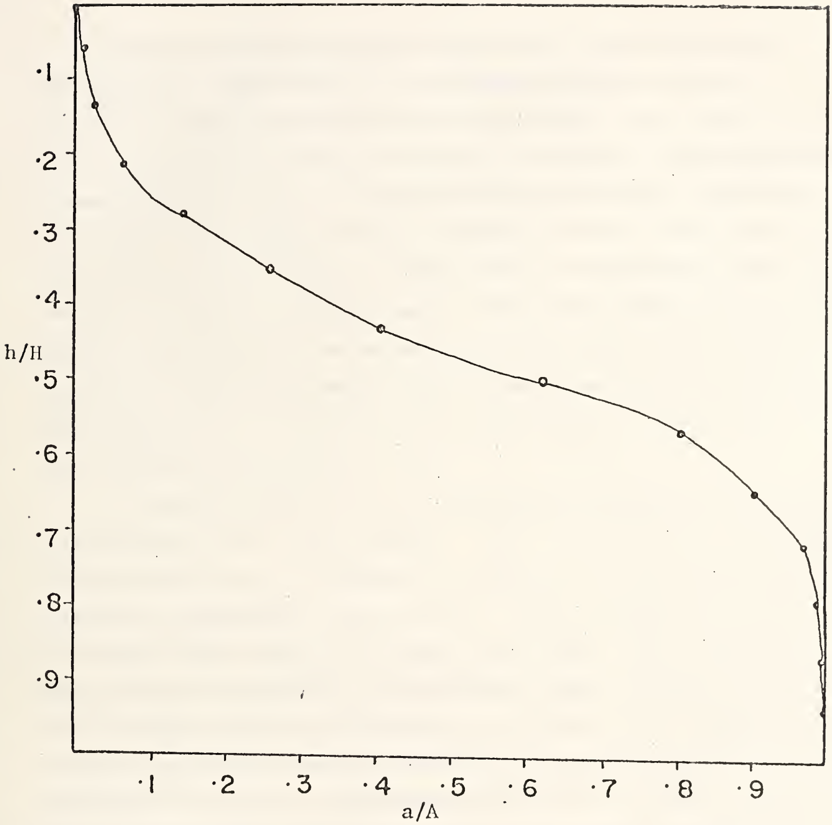

Fig. 1.2. Relative Area-Height Curve for the Upper Indus Basin.

of major and subsidiary ranges (Plate 1.1. Appendix 1).

Physiographically, the region is distinguished from the basins of interior drainage to the north, by drainage to and base level control by the Indian Ocean. It is distinguished from the areas to the south mainly by climate. The monsoon rarely intrudes into the Upper Indus Basin, and the climate is dominated by westerly air-streams bringing predominantly winter precipitation. Likewise, moisture availability and river flow reflect an entirely glacial regime, unlike the monsoon-reinforced glacial regime on the south side of the Himalaya.

The most obvious feature of all but a small fraction of the region is high relief. The maximum available relief is 27,300 ft. from the mouth of the Indus Gorge to the summit of K2, a straight-line distance of some 260 miles. More significant geomorphically, is the overall accidentation of the landscape. The Upper Indus Region consists largely of very steep slopes. It contains a greater array of high peaks and crest-lines than the Pamir, but smaller positive mass. The latter reflects the widespread dissection of the mountains by deep main valleys with relatively gentle thalwegs. Open valleys and low-angle slopes are confined to the edges of the Basin mainly along the rim of the Tibetan Plateau (Plate 1.2).

A general measure of the dissection is given by relative area-height curves (see Strahler 1952). The curve for the Upper Indus Basin (Fig. 1.2) appears to combine an upper part resembling Strahler's "Monadnock" Phase, with a lower "inequilibrium" or "Youthful" Phase (op. cit. Figs. 14 and 16). These terms are not apt since nearly all the landscape shows features of youth, and the zone below the 'monadnocks' and above the 'rejuvenated' valleys is itself severely dissected. What is reflected in the hypsometric curve is a landscape carved into a series of mountain blocks where high ridges with very steep slopes and small mass stand on broader plinths. The latter are also heavily dissected, but into thousands of minor valleys that include relatively gentle talus slopes, - i.e. 30-36°, - the combined interfluves still involving a considerable volume of rock. Between these mountain blocks ramify deeply incised main river valleys flanked by a second set of very steep slopes but with only a small per cent of the landscape mass removed. A most convincing illustration of the arrangement is the high level satellite photograph (see NASA 1967 p. 214).

During the Pleistocene, the region was glaciated down to the mouth of the Upper Indus. Even now, the glaciated area is quite

considerable, though most of it is concentrated along the northern watershed. Here are found many large valley glaciers, seventeen of the ones draining to the Indus being larger than the Aletsch (see 11.1). The total glacial cover of the region is about 13 per cent, while that of the Indus flank of the Greater Karakoram is nearly 60 per cent.

An important feature of the regional climate is its vertical zoning. Throughout the Basin there is a juxtaposition of arid lower slopes, sub-humid to humid upper sub-nival zone, and a belt of relatively high precipitation at and above the snowline. The precipitation in the semi-arid and arid zones of the valleys is largely cold season and released by melting during the sharp rise of the annual temperature curve.

For field-work a relatively small area within the region had to be chosen, and the Biafo Glacial Basin and adjacent parts of the Upper Braldu Valley were decided upon. This is an area on the south flank of the Central Karakoram. The decision was based primarily on considerations of access and an interest in the large valley glaciers which constitute such an outstanding feature of the region. The Biafo is one of a whole array of glaciers which fan out from the Karakoram in this part. The Braldu River drains two other major glaciers, the Baltoro and Panmah before tapping the waters of the Biafo. The Biafo flows from Lat. 36° 09' to 35° 40' N, and attains a length of some 42 miles along the main ice-stream. The terminus lies at 10,2oo ft. and much of the watershed is over 18,ooo ft., reaching 23,9oo ft. at its highest point. The floor of the Braldu Valley and the flanks of the lower Biafo are semi-arid in character. Above 13,ooo ft. sub-humid and humid alpine slopes occur. Heavy snowfall is concentrated above 14,ooo-15,ooo ft., especially

towards the upper reaches of the Biafo (see, 5.3.ii).

While the Biafo observations were supplemented by reconnaissance in the rest of the Shigar-Braldu area and the Indus Valley below Skardu, and by information in the literature, they may lead to emphasis on features whose importance varies in other parts of the region. A broad regional homogeneity is given by the common hydrological regimes of constituent basins, repetitive upslope variations of climate and vegetation, uniformly high relief, and broad tectonic development. Nevertheless, there are variations which differentiate the Central Karakoram from other parts. The main variations are:-

a) A general increase in aridity and rise of the precipitation belts towards the centre and east of the Basin.

b) A parallel impoverishment of the sub-nival vegetation.

c) A grouping of most of the relatively subdued, open tributary basins in the east of the region (e.g. Chip Chap, Chang Chenmo, and uppermost Indus in the Kailas area).

d) A greater concentration of high peaks and crest-lines along the northern and north-western watershed, involving the Hindu Kush and Greater Karakoram Ranges. This is particularly significant in relation to the heavier precipitation, and larger glacial areas of the Karakoram.

While many of the features to be described are found in most parts of the region we shall tend to emphasize conditions of severe dissection more than would appear, say, on the Depsang Plateau; will give greater weight to contemporary glaciation than is apparent on, say, the Ladak Range; and will not be so concerned with very recent, deep fluvial dissection, or the

effects of a forested alpine zone as in the case of Nanga Parbat, and Haramosh areas. Nevertheless, it will also appear that the generally high relief, and sharp variations of climate with season and altitude throughout the basin, over-ride most of these differentials generating many typical geomorphic processes and forms.

Fortunately, the Biafo Gyang Basin is well mapped by Himalayan standards, and the 1939 Shipton Expedition which carried out the modern survey adopted the policy of the Karakoram Conference for local names (see Mott, 1950). The accuracy of the mapping is still not adequate for detailed geomorphological work but provides a better basis for the present study than will be found in most of the region (see Note 1.2. for P. G. Mott's assessment of the accuracy of the 1939 map). A general reference map based on the 1939 Survey is provided for identifying places referred to in the text (Plate A.1).

Finally, there are a number of conventions adopted in the text which need to be described:-

a) ALTITUDES: Reference to heights, slope lengths and other linear dimensions play an important part. To avoid ambiguity, all altitudes a.s.l. are quoted with the final zeros as small characters, (e.g. 23,5oo ft.). Height differences, slope lengths, etc., have final zeros as large characters, (e.g. 23,500 ft.). Altitudes are never accurate enough to give anything but a zero in the units column.

b) TECHNICAL TERMS: Wherever it is necessary to redefine, or stress the technical usage of a particular geomorphic term, the term will be underlined when it first appears in the given section of the text.

c) NOTES: Notes are used to deal with matters not

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directly required in the flow of argument, but which may be useful ancillary evidence, or clear up possible ambiguities or minor points of disagreement with other studies.

1.2 Scope of the Present Investigation

While certain aspects of the geophysics and geology of the region have received relatively modern treatment, the primary interest of the present study, - contemporary landscape features and erosional processes - has had no systematic investigation in the Semi-Arid Himalaya. The approach has been therefore to use an essentially "exploratory" design (Selltiz et.al. 1959 Ch.II),working systematically through phenomena which come under the normal sub-divisions employed by geomorphologists - i.e. weathering, mass-movements, glacial features. At the same time, an effort has been made to be sensitive to the special characteristics of the area, such as the importance of large areas of rock-wall, the role of high energy processes, and rare catastrophic erosional events.

The most difficult technical problem has been to maintain an appropriate sense of scale. In exploratory scientific work everything is potentially significant, but scale either of action or of size ought to be an indication of actual significance. However, in the Himalaya, neither the available information nor geomorphological concepts allow one to progress far while dealing with the major mountain and valley features. Relatively minor, superficial features often provide a much better basis for establishing the processes and environmental controls at work. On the other hand, lack of information taken for granted elsewhere, can lead to overemphasis of some minute item simply because it is better documented or accessible. Logically, exploratory systematic studies cannot specify how to solve these problems. In this study, decisions

about the relevance of a given topic have been made by considering two questions:-

a) Is it apparent from studies elsewhere that this phenomenon can play an important role in the landscape?

b) Is the phenomenon one which plays an important part in contemporary geomorphological thought, making its characteristics in this region worth noting, even if it has a small role in the local landscape?

The usefulness of systematic studies of a little-known region depends to an important degree on their relation to existing work and thought as well as their content of local information. Descriptive material should communicate as accurately as possible the features observed (see Johnson 1940 p.355). In the present work most features described are also illustrated photographically, and ambiguous terminology has been revised and defined. Also, an effort has been made to cite relevant literature from other, usually better known regions.

In relation to the Upper Indus Region it was felt that the study should provide a good background to the region and existing work on it. The available literature that would give the reader regional background is far too general, while most of the publications specific to the area are either very dated, or hard to acquire. An extensive bibliography on the region is given at the end, and most of this literature has been scoured for geomorphic data. The results of this appear mainly in citations of works where further descriptions of particular features can be found.

1.3. Acknowledgements

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CHAPTER 2

HISTORY OF PREVIOUS STUDY

2.1. Geographical Knowledge in the Nineteenth Century: A brief survey.

The "Mission to Caubul" under Mountstuart Elphinstone really began the modern unravelling of the region's geography, and brought names such as "Mooz Taugh", and "Karra-koorrum" to the attention of European scholars (Elphinstone 1815) (Note 2.7). Maps appearing between 1790 and 1820 often show the Upper Indus quite well but link it ultimately with either the Sutlej, Ganges or Fergana valleys (see Hedin 1917-22 v.7). Mir Izzet Ullah, sent on reconnaissance in 1812, gave the first accurate account of the Khumdan Glaciers, whose "Shyok Dams" were to be the region's main source of publicity (1842-43 p.283). Carl Ritter's "Erdkunde" contains probably the best description of the relief to that date and he hinted at the existence of unknown, large glacier areas (1837 Bd.5). These, however, do not appear on Arrowsmith's map of 1841, which represents the state of knowledge in the West when serious exploration began.

The general geography and more striking natural features soon became known after the 1830's. Strachey, Cunningham, Thomson, the Schlagintweits and a few travellers like Vigne, demonstrated the size of the mountains, rivers and glaciers, and gave some information on climate, snowlines and major natural events (Vigne 1842; Thomson 1852; Strachey 1853; Cunningham 1854; Schlagintweit 1861-66). From the middle of the century onwards, keen observers visited the high valleys bringing back a wealth of descriptive material, drawings, rock samples and sketch-maps. The Schlagintweits, Godwin Austen, and Conway visited and described the Biafo

Glacier, the latter travelling the length of it, from the Hispar Pass down (Austen 1863 & 1864; Conway 1894; McCormick 1895; Eckenstein 1896).

Meanwhile, political and trading interests of the British brought missionaries, civil and military personnel into Ladak, Baltistan, Gilgit, and later Hunza, and some of them recorded valuable information (e.g. Drew 1875; Biddulph 1880; Woodthorpe 1885-1886; Dunmore 1893; Curzon 1896; Durand 1900; Franke 1907). The Survey of India extended its gravimetric surveys and major triangulation system to the Karakoram and surrounding ranges (Schlagintweit 1856 & 1857; Montgomerie 1869; Tanner 1891). Reconnaissance surveys of the geology and glaciers were begun in a limited way, (Lydekker 1880, 1881a & b, 1883; Godwin Austen 1864, 1866 & 1884; Hayden 1907). In 1868 a once-daily reading of river stage was begun at Attock, where the Indus leaves its mountain course.

The main attributes of the landscape stressed (or denied) by these early observers included; the probability of climatic change towards aridity; the formerly greater glaciation; the problem of immense amounts of alluvium in the main valleys; the contrast of arid valleys and humid mountain tops, and the strong seasonality in temperature, precipitation and river flow. Catastrophic glacier dam-bursts received much attention, as did the large mud-flows. But the main contribution was sorting out a difficult topography.

2.1.ii. The Twentieth Century.

The Workmans took an interest in the Biafo area in 1899, and brought back the first photographic coverage. While his lady was displaying "Votes for Women" on minor Biafo peaks Dr. Hunter Workman examined detailed glacial

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forms (Workman 1899, 1908, 1910, 1914, etc.). In addition to a host of travellers' and mountaineers' reports, there were, before the Second World War some large and well-equipped scientific expeditions, several stretching out field-work over a number of years. Of particular note are three Italian expeditions in 1909, 1913-14, 1929, 1930, and 1939, the Netherlands' expeditions of 1922, 1925, 1929-30 and 1935; German work, especially on Nanga Parbat and the Eastern Karakoram; and certain individual projects such as the Yale expedition to Ladak (Abruzzi 1910a & b, & 1912; de Filippi 1912, 1919, & 1922-32; Dainelli 1924a, 1932c, & 1933; Desio 1930a & b, 1936 etc.; Spoleto 1930 & 1936;/ Visser 1928a, b & c, 1932, 1933, etc.; Bleeker 1936;/ Finsterwalder et.al. 1935 & 1938; Trinkler and de Terra 1932; Misch 1936a & b, & 1949; Troll 1938;/ Memoirs Connecticut Academy of Arts and Sciences 1934; Hutchinson 1936 & 1939; de Terra 1933, 1934, etc.). In the eastern reaches of the Upper Indus Basin Hedin's Tibetan expeditions added valuable topographical, geological and other information (Hedin 1903, 1910, 1917-1922 etc.).

The Geological Survey of India instituted some surveys of geology, glaciers and glacier snout positions in the region (Hayden 1917; Douville 1926; Mason 1930, 1933, etc.; Wadia 1931, 1933, 1937 etc.; Auden 1935a & b). An early warning system and periodic observation of threatening glaciers were begun (Mason 1930a). The Survey of India extended its major triangulation across the Greater Karakoram to link with the Russian system (Mason 1914). Both Departments seconded men to expeditions going to the high glacial basins (Wood 1922; Mason 1927a & b; Auden 1938; Shipton et.al. 1938; Spender et.al. 1938). The excellent map of the Biafo-Hispar Glacial Regions by Shipton's 1939 expedition was a product of this co-operation (Mott 1950).

Since the war mountaineering has dominated the scene, but there have been some valuable scientific studies. The Italians continue their work, concentrating on the Baltoro area but also looking as far afield as the Hindu Kush connections (see. Desio 1954a, etc; Desio et.al. 1961; Marussi 1964; Zanettin 1964; Desio 1963a, etc.; Desio et. al. 1964). German expeditions to the Western Karakoram, Chogo Lungma and Nanga Parbat have greatly advanced glaciological and geological knowledge (Kick 1956 & 1964; Pillewizer 1956 & 1957; Schneider 1956a & b, 1957 etc.; Finsterwalder 1960; Paffen et.al. 1956; see also, Gattinger 1961). Japanese scholars have also contributed a variety of studies, including a geological traverse of the Biafo Basin (ed. Matsushita and Huzita 1965; Matsushita 1956; and Matsushita and Huzita 1966). Finally, there is increasing study of the hydrology and associated conditions of the region in connection with Indus water resource development (e.g. Harza 1963).

2.1.iii. Summary of Geomorphological Knowledge to Date.

On the whole, geomorphological observations have been incidental to work in other fields, especially geology, geophysics, hydrology and meteorology; or general exploratory accounts. Expressly geomorphological study deals mainly with topography in relation to structure (e.g. Desio 1936). There are many useful descriptions of particular forms and processes throughout the region, often reinforced with good photographic coverage. The information is, however unsystematic, being the outcome of chance encounters rather than a definite research design (see for a digest of material, Spate 1964, p. 354). The less obviously *ad hoc* work on landforms deals with four main topics:-

a) General topographical description tracing the arrangement of mountain ranges and valleys (Neve 1910; Hedin 1917-1922).

b) Description and classification of glaciers and their superficial features. The work relates primarily to the very large glaciers or those which have dammed rivers or advanced rapidly.

c) Erosion and sedimentation associated with Pleistocene events.

d) Long-term landscape development, equating certain present-day forms with erosional phases going back to the early Tertiary, but relying heavily upon geological and tectonic evidence from surrounding regions.

The parts of this material which reinforce the present work will be drawn upon in the relevant chapters. However, it will be useful to outline what is known of the denudation chronology, in an introductory chapter. One must be aware of the extent to which the contemporary landscape expresses the legacy of past conditions, especially if they differed radically from the present.

CHAPTER 3

PREVIOUS WORK ON LANDSCAPE DEVELOPMENT IN THE REGION: A RESUME and CRITIQUE

Some reconstruction of tectonic evolution and related sedimentation will be treated first. The topic is germane to the problem of landscape development, particularly in view of the recent large uplifts, and may be dealt with here rather than in a general section on the geology.

3.1. Tectonic Events.

Geosynclinal sedimation continued in the region until the mid-Cretaceous. Since then three main periods of orogeny have occurred. Their actual dating is difficult since most of the evidence is found outside the region. Moreover, such information suggests that orogenic movements began in the north - perhaps in the vicinity of the Greater Karakoram - and moved progressively southwards (Gansser 1964. p.37). Hence, orogenesis in the Upper Indus Region seems both to antedate, and continue during that of the better-known southerly ranges. A similar erosional difference may apply.

The three main phases of the Alpine Orogeny have been placed as:

a) Late Cretaceous-Eocene;

b) Oligo-Miocene;

c) Plio-Pleistocene.

Also, for the last, de Terra recognised three sub-stages in the Upper Indus Region: late Pliocene, mid-Pleistocene and immediate post-Pleistocene (1934. p.41). This is supported by evidence from the Karewas of Kashmir on the Siwaliks of the sub-Himalaya.

The net uplift of the Karakoram since the early Tertiary has been placed at about 40,000 ft. (Gansser, op. cit.; quoting Schneider). Perhaps a quarter of this occurred in the Pleistocene and Recent Periods. But the proportion of folding and uplift attributed to different phases in various parts of the mountains is very conjectural.

Nevertheless, large and recent differential movement creates important problems in the tracing of erosional development. Throws of 10.000 ft. along Pleistocene Faults, for example, require great caution in the interpretation of erosion surfaces at apparently separate levels (Gee, in Gill 1952, p.416).

Although the Karakoram forms part of the overall Himalayan orogenesis, there are some clear tectonic divisions within the Upper Indus Basin. In the north is the Karakoram system, a two-sided orogene apparently more stable to the north where it meets the Hercynian massif of Kun Lun. Its southern margin is a downwarped eugeosynclinal belt which, until the late Eocene, supported a marine gulf where thick flysch was laid down following the Cretaceous-Eocene uplift. Gansser believes vast quantities of Tethys sediments subsided into the crust here, in contrast to the uplift and lateral translation taking place to the north and south (Gansser 1964 pp. 75-79, and 253-254). The Eocene marine deposits of the belt now lie at 15,ooo -20,ooo ft. a.s.l. (Wadia 1964 p. 851). Immediately south is the Tethys Himalaya, the geosynclinal part of the Greater Himalaya, which has suffered repeated buckling and uplift. Southwards again is the crystalline thrust zone, where strata have overthrust the Indian Foreland and one another by more than 100 miles. Finally, the North-Western Syntaxis introduces north-south structures and related intrusions cutting right across the trend of the Himalaya (Wadia 1931; Misch in Finsterwalder et. al. 1935, Zanettin, 1964).

All these tectonic elements show a measure of independence and of interaction within the overall orogenic process. With the resulting differentials of uplift and lateral movement any surviving erosion surface of late Tertiary age, could exist over a range of altitude of 20,ooo ft. The complexity of local developments makes it unlikely that any such surface would simply be warped into a dome-like form across the mountains.

3.2. Depositional Evidence.

The depositional evidence of landscape history lies mainly in the Indus trough, Kashmir, and the sub-Himalaya. The Indus flysch of Ladak represents erosion following the first Alpine orogeny. The

marine, and deltaic facies are said to suggest a net diminution of erosional energy over the period of deposition. Strong folding and thrusting of the Flysch occurred before a Pleistocene conglomerate was deposited, unconformably, above it (de Terra 1935; Sahni et. al. 1962). This seems to record the sequence of events of the second orogeny and subsequent erosion.

Farther west, in the Indus Gorge under Nanga Parbat, Misch described steeply folded, barely consolidated sandstones, apparently of early Pleistocene age (Misch op. cit. and 1936). Gansser notes that:-

> "The sandstones contain only small pebbles, and the large boulders typical of the younger Indus gravels are not present. This may indicate that during the deposition of the young Jalipur sandstones the relief was considerably lower..." (1964 p. 62)

These small pieces of evidence suggest two major phases of denudation before the Pleistocene uplift and glaciation. But for more substantial evidence, we must look at the sub-Himalayan deposits.

A close relationship between Himalayan erosion and Nimradic (sub-Himalayan) deposition begins in the North-West after the Miocene. Late-Cretaceous-Eocene uplift is recorded by the absence of middle and late Eocene and all Oligicene deposits from the transitional Salt Range, but there was little deformation. Furthermore, although Miocene freshwater deposition was considerable in the area, the material (Murree Beds) derives from Indian Shield rocks not the Alpide belt (Wadia 1961, p. 353). The succeeding unconformable Siwaliks of the Plio-Pleistocene show increasing involvement in Himalayan events and tell us something about them. The volume of erosion is suggested by the 22,000 ft. of Siwalik beds in parts of the Potwar Plain. The Lower Siwaliks are mainly fine-grained being derived from the Himalaya without suggesting fierce erosion (Gill 1952a p.377). Above these lacustrine beds, the deposits are extremely complicated with rapid facies changes and vigorous molasse-type sedimentation. The Middle Siwaliks (Upper Pliocene) contain the first definite evidence of

large, south-flowing Himalayan rivers including the early Indus (Gill 1952a p. 390; Gee in Gill 1952b p. 415).

Actual deformation by the third orogeny did not reach the sub-Himalaya until mid-Pleistocene times. However, massive, heterochronous fans of conglomerate, spreading from the Indus and other gorges, are held to record sharp uplift and accelerated erosion to the north. The conglomerates attain thousands of feet in thickness (Gill op. cit.). Eventually the Siwaliks themselves were intensely folded and faulted. The Pir Panjal Range, immediately north of the Potwar Plain, has been uplifted 6,000-8,000 ft. since the mid-Pleistocene (de Terra & Paterson 1939).

To sum up; the long term geological evidence is thought to show three main phases of orogeny since the mid-Cretaceous, initiating at least three distinct erosion cycles. The first cycle was the longest, but the second may have reached a quite advanced stage. Such, at least, is the consensus of opinion to be gained from the literature. Here brief comment will be added concerning the evidence, and certain assumptions of the relation between tectonics, sedimentation and erosional development. The points relate particularly to the weakness of the evidence for the advanced stages reached by the two early cycles.

Firstly, there is the validity of the depositional material as direct evidence of erosional conditions. There may have been an uncritical willingness here, to associate coarse facies with uplift; fine facies with subdued landscape. Only in the Pleistocene is due recognition given to the role of climatic changes. Yet, in relation Gansser's assessment of the Pleistocene sandstones of Nanga Parbat, we must note the pre-Pleistocene sediments of the Indus trough which indicate a well-vegetated landscape. Even with high relief a good plant cover tends to check movement of coarse material and reduce floods. Meanwhile, the present Indus is itself incompetent to move most of the large boulders of its bed and terrace gravels, most of the time. They probably owe their existence to Pleistocene inter-montane deposition, and to the catastrophic floods which alone can move them. Meanwhile, the run-off regime of the Indus must have

changed drastically since the Tertiary as the rise of surrounding Asiatic Ranges increasingly obstructed the inflow of various air masses (Note 3.1.).

The Nimradic evidence of subdued erosion preceding the late Pliocene orogeny has a basic weakness: the southward encroachment of the Alpide belt could have destroyed coarse facies deposited at the earlier mountain fringes. (There is no geological evidence of this as yet. See Pascoe et. al. Vol.3. p. 2064). Tectonic development greatly affects the survival of erosion surfaces developed in the mid- or late- Tertiary. Using de Terra's work, King recently showed a regular, warped Tertiary erosion surface across the Karakoram (King 1967 p.528). While, tectonic and related depositional evidence does indicate three periods of intense orogeny with quieter periods between, it does not reveal simple radial uplift. Each phase has been accompanied by intense folding and faulting of great magnitude. In the area of King's diagram it is possible that thousands of feet of rock have moved laterally 50-100 miles, since the mid-Tertiary (c.f. Gattinger 1961), (Note 3.2.). In these terms the geological evidence for erosional developments to be described, may carry less force than is sometimes given to it.

3.3. <u>Denudation History: Long-Term.</u>

De Terra recognised five main planation levels in the region: two pre-Pleistocene, and three in the Pleistocene and Recent Periods:-

a) Level 1 (20,000-24,000 ft.): a late Tertiary relief of post-mature or old character, with monadnocks and low ranges. Certain crest-lines of Ladak, and high desert basins to the east represent the surface, while the Mustagh and other high peaks are the residuals.

b) Level 2 (16,000-17,000 ft.): carved when the late-Tertiary surface was uplifted, and represented by accordant spurs and benches, inflected stream profiles, and small desert basins.

c) Level 3 (14,000 ft?): records downcutting during an early (presumably the first) interglacial period. It was later buried by a phase of deposition.

d) Level 4 (12,000 ft?): a patchy development following renewed uplift and associated with a suite of freshwater lakes in the region.

e) Level 5:the contemporary level of stream incision cut after post-Glacial uplift and rejuvenation. Particularly effective along the main Indus drainage where downcutting of several thousand feet has occurred in places.

Only the first two surfaces will be considered in this section. The evidence is morphological, and refers largely to the eastern periphery of the Indus Basin. In the Central Karakorum only summit accordances have been invoked as westward extensions of the old surfaces. Gross morphometric evidence for the Upper Indus Basin does suggest a "two-tier" landscape: albeit strongly dissected everywhere, with most of its mass concentrated below 16,000-17,000 ft. (see 1.1.). But in terms of the contemporary geomorphology there are two limitations to incorporating ancient surfaces into the scheme of controls:-

a) the very small areas which the surfaces can be said to occupy and manifestly affect.

b) the absence of firm grounds for preferring an interpretation of de Terra's evidence in terms of ancient erosion cycles to other explanatory models. For instance, there is the thesis recently advanced that upslope changes in process type and vigour in regions of high relief could allow separate climageomorphic surfaces to develop contemporaneously (Garner 1965; Thompson 1961-62: c.f. Wahrhaftig 1965 on another approach).

Even more relevant is the development of planation surfaces at different altitudes when contiguous regions have differing base levels of erosion. This is quite common in the great cordilleras of the world (Note 3.3.).

Another important field for long-term reconstruction is that of ancestral river patterns. The generally held belief is that drainage is primarily antecedent. By implication the contemporary

geomorphology should have dissection patterns at variance with, and therefore not explainable in terms of, present structural and climatic patterns.

The theory of two Tertiary rivers flowing parallel to the Greater Himalaya is given considerable prominence by Spate (1954. pp. 28-33); a theory suggested by Oldham (1894) and developed independently by Pascoe (1919) and Pilgrim (1919). Most persons actually working in the area since 1919 have rejected the southern "Indobrahm River" (See. Prahshad 1939; de Terra and Paterson 1939; Krishnan 1940; and Gill 1952, p.390). However, as well as Spate, Gansser recently gave some support to the idea (1964 p.48). The writer would agree that the evidence brought against the Indobrahm is not convincing. Gill's statement may invalidate Pilgrim's ideas on the oil-bearing series of the Potwar, but this is a microscopic portion of the hypothetical river basin. However, it is rather difficult to refute any theory which itself lacks a basis of crucial evidence. Such might be gained for the Indobrahm by studying palaeocurrents in the Indo-Gangetic Plain.

De Terra's dismissal of the Tibetan-Kara Kum river - the ancestral Upper Indus - is more tangible (1934 pp. 38-40). On better grounds than the "map interpretation" of Pascoe, he suggested that the pre-Pleistocene Indus, at least from Skardu, flowed eastward to the Tibetan or Brahmaputra drainage, not westwards (Note 3.4.). This also raises problems for Davies' early Indus, (1940) though Gill's work supports his idea of the recency of the present Indus, and its Himalayan tributaries south of the Karakoram. But, for the Upper Indus, de Terra's local evidence carries more weight than deduction from maps or from gross structural and tectonic conditions. Once again information on sediment sources and paleocurrents is needed.

De Terra denied that the Upper Indus drainage was sufficiently discordant to structure to indicate antecedence. Neve found widespread correspondence of drainage lines to structure (1910, p.571).

Although Spate (1954) and Gansser (1964) accept the fact of antecedence there is no clear evidence to support the thesis except for local areas. Apart from such cases as the Indus between Kargil and Skardu, or the Hunza between Gilgit and Chalt, there is a close correspondence of gross drainage patterns and structure. Meanwhile, discordance between drainage and general structural grain need not imply antecedence or superimposing of ancient stream patterns (Note 3.5.). Also, there are many local patterns most unlike components of an originally integrated drainage system; for instance, the peculiar centripetal drainage of the Siachen, Upper Hushe, Chogo Lungma, Sosbun, Panmah, and Sokha-Solu Valleys. The Upper Biafo is similar. There are many tributaries joining main longitudinal valleys at angles facing sharply upstream (e.g. Tarmik-Indus, Shigar-Indus, Biafo-Braldu, Thalle-Shyok, Hushe-Shyok, Dah-Indus, Chorbat-Indus, Nubra-Shyok, Upper Shyok-Shyok). While sceptical of interpretation based simply on formal patterns, the writer thinks these anomalies within the Upper Indus system might be explained by capture of ancient basins of interior drainage (c.f. Note 3.3.).

3.4. Denudation History: The Pleistocene.

A summary of Pleistocene events according to de Terra and Dainelli is given in Tabular form (Table 3.1). We shall only discuss those features which seem directly relevant to present-day conditions. Of particular importance are the abundant glacial and fluvio-glacial deposits left in the mountains; and the interpretive problems of interacting recent orogeny and climatic fluctuations.

As is usually found, (e.g. Flint 1957 pp. 424-5) de Terra and Paterson associated glacial epochs with deposition and inter-glacials with erosion (1939 p.220). Only Neve seems to invoke glacial protection to any extent (Neve 1913, c.f. also Heim and Gansser 1939 p.232). What de Terra seems to mean is that glaciation, (glacial retreat?) was associated with massive deposition of valley train and mass-wasting materials. These were cut into during inter-glacials. But there is no evidence that the

TABLE 3.1. Features associated with Pleistocene events in the Upper Indus Basin (after de Terra and Dainelli).

PERIOD	KARGIL	INDUS VALLEY at SKARDU	INDUS VALLEY at LEH	PANGONG BASIN	CHANGCHENMO BASIN
Post-glacial			Upper moraines in side valleys above 15,ooo ft.	Fifth moraine of Man. Landslide deposits	No glaciation
IV Gl.	Terminal moraines in side valleys at 3,100 ft. above present valley floor	Terminal moraines 500-1,000 ft. above Basin floor*	Younger terminal moraines and fans.	Fourth moraine of Man. Upper gravels and sands. 60 ft. Man lake bench.	No glaciation Lower terrace gravels and fans. Fourth Terrace.
III-IV Int-GL.	EROSION -				
III	Deposit of white lake silt and boulder sand 380 ft. thick	Lake silt and gravel Damming of main valley by ice and moraine.	450 ft. deposit of lake silt at Lamajura. Second stage, fans and loose gravelly sand. Large lake in Indus Valley.	Third moraine of Man, lake silt and 190 ft. lake bench	No glaciation. In valley, lake silt and Second Terrace
I-II Int-GL.	EROSION -				
II	286 ft of boulder gravel and ground moraine.	Longest glaciation* Thick boulder gravel moraines 1,200-1,500 ft. above present Indus bed.	First fan stage with thick fan debris (partly solifluction material) filling old glacial troughs. Also 1,000 ft. of breccias and gravels	Ground moraine and cemented fluvio-glacial gravels. Pangong Glacier	Boulder gravel, Ice-contact deposits and re-deposited solifluction debris 200 ft. thic
I-II Int-GL.	EROSION........				
I	High remnants of glacial troughs	NO INFORMATION			

*NOTE: Dr. W. Kick points out the difficulties or recognising "...boulder gravel moraines 1,200 ft. above present Indus bed, as corresponding to the IInd Glaciation, if lower down the terminal moraines of the IVth glaciation are seen..." (p.com.21.4.67). It should be recognised that all but a minor fraction of the reconstruction is based on lithological evidence with no adequate means of dating. The small amount of fossil and pollen dating from Ladak does not seem very conclusive either (see Deevey 1937; Hutchinson, 1934).

glacial periods were achieving less net erosion than interglacial conditions. There could be a case for arguing the opposite (see Corbel 1959).

Pleistocene reshaping was strongest following downcutting in the First Interglacial and during the large Second Glaciation. The latter invaded all valleys and, according to Trinkler, approached Ice Cap conditions in the east (Trinkler 1931a). It left behind great thicknesses of moraine, fanglomerate and solifluction deposits. The Third Glaciation produced even more intermontane deposition. According to Dainelli, vast ice-dammed lakes formed, as incomplete glaciation disrupted the Indus drainage (ed. Dainelli 1922-1932 Ser. II. Vol.3. Plate 177). The first lake was dammed just below the junction of the Gilgit and Indus rivers, and stretched to Nagar along the Hunza Valley, and 60 miles up the Indus Gorge. Skardu Basin was blocked by another ice barrier and the lake stretched 130 miles into Ladak. Other lakes occurred in Leh Basin (not ice-dammed), and the Chang-Chenmo Valley. Great thicknesses of sediment were deposited in these lakes. Remnants of alluvial fans which led into the Skardu Lake, occur several thousand feet above the floor of the Basin. The amount of removal and transport of sediment left to later times was considerable, and may help to explain the large quantities of terrace and other lag deposits in the mountains (Note 3.6.).

In addition to the thick deposits in main valleys, large sections of valley slope were covered with old till and kame terrace material. These still remain up to altitudes of 15,000 ft. or more. The material may be in situ or sludged downslope. Often it is carved into sets of earth pyramids. These lag deposits are mingled with material weathering from solid rock at present. Since they developed under differing climatic and geomorphic conditions, resulting talus may have properties at variance with those of current weathering products. There may also be variation between slopes with old till, and those where it is absent.

CHAPTER 4

GEOLOGY OF THE REGION, AND BIAFO AREA

4.1. Introduction.

The tectonic history has been considered and we look here at the present-day disposition of major rock groups. The task hampered, however, by a lack of agreement among leading Himalayan geologists. In 1964 there appeared three new maps giving fairly detailed coverage of the region (see. Gansser, 1964, Plate AI; Desio 1964a; Ministry of Industries and Natural Resources, Government of Pakistan, 1964). Though apparently derived from broadly similar sources, the maps differ on facies groupings, and, more strikingly, on age groupings. Neither is there very close agreement with the work of Schneider (1956, 1957, and 1960) or the Japanese (ed. Matsushita and Huzita 1965; and Matsushita and Huzita 1966, Table 2 and Fig. 1). For instance, the metamorphics of the Lower Biafo and Braldu area are ascribed to the pre-Cambrian and Lower Paleaozoic (Gansser); to the Cretaceous (Desio; also Zanettin, 1964); to the Late-Paleaozoic (Gansser); to the Cretaceous (Desio; also Zanettin, 1964); to the Late-Palaeozoic, Cretaceous and Early Tertiary (Min. Ind. Nat. Res. 1964); and as being "derived from Palaeozoic sediments and Tertiary granites" (Matsushita and Huzita, 1966). Not all of the differences can be explained by differing scales, emphases or classificatory systems.

In view of these problems regional geology is only described in broad, simple groupings. In the Biafo area we use the classifications of Desio and Zanettin reinforced from other sources and our own field observations.

4.2. The Arrangement of the Main Rock Groups in the Upper Indus Basin.

The major rock groups lie roughly in an arc whose focus is the North-West Himalayan Syntaxis (Fig. 4.1.). In the northernmost rim of the region - uppermost Hunza Basin, and Aghil Range - and again in the south along the main Indus trough in Ladak, occur

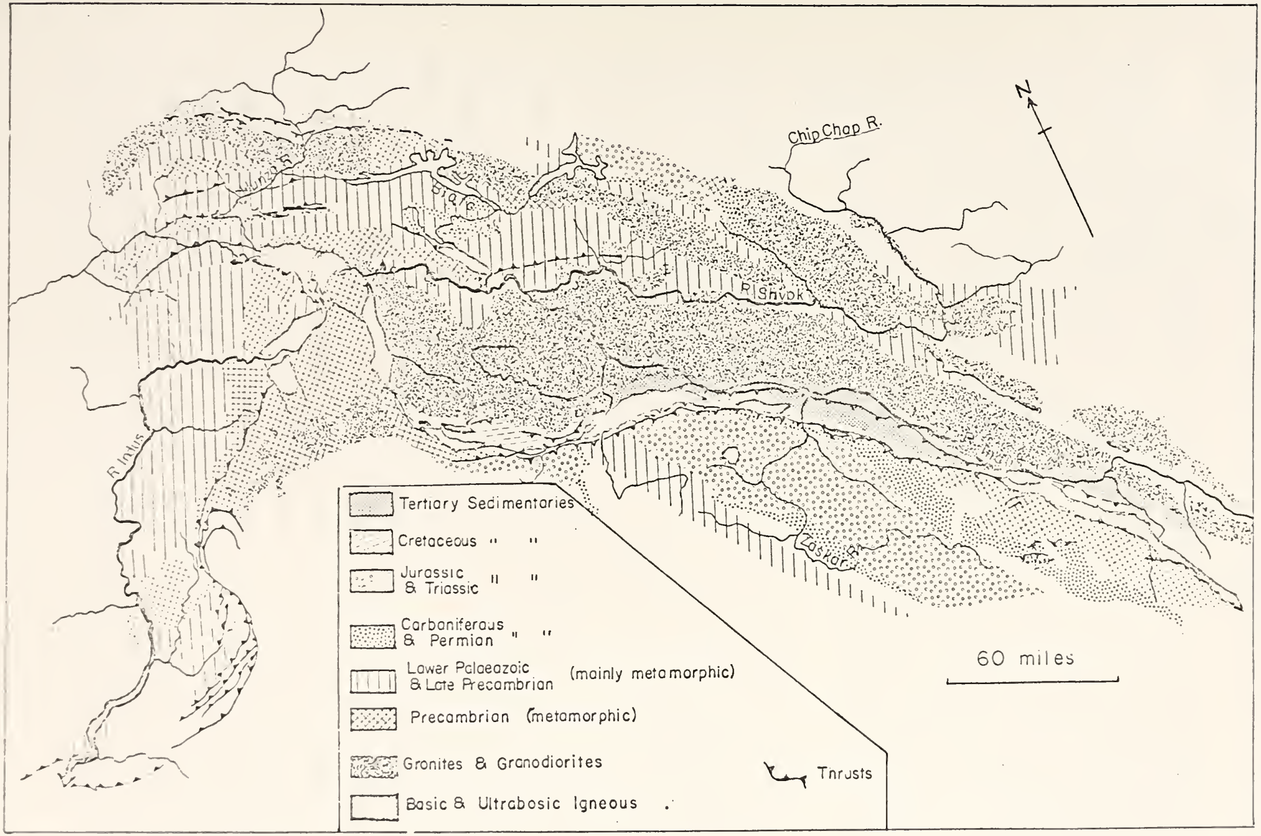

Fig. 4.I. Geological map of the Upper Indus Basin (after Gansser).

sedimentary and metasedimentary strata. These contain fossils. The northern group is mainly Permo-Triassic, the southern one, Cretaceous, Eocene and Oligo-Miocene. Limestone facies are important in all of these.

Immensely long granitic belts form much of the Western and Central Karakoram, the Saltoro, Mustagh, Saser and Ladak Ranges. Nanga Parbat, has a central granitic mass (Misch in Finsterwalder et. al. 1935). Granitic rocks also follow the general structural trend south-westwards into the Hindu Kush (Desio, 1960 and Desio et. al. 1964) and south-eastwards towards the Kailas (Gansser 1964). The granites of the axial batholith and of the Ladak Range are composed largely of biotite, biotite-hornblende; and biotite-muscovite -granites and granodiorites. The Nanga Parbat Massif is predominantly granitic gneiss with small intrusions of tourmaline granite.

The various granitic belts were once ascribed to widely differing periods of time, on the basis of position and, generally rather small, compositional differences. Dainelli distinguished three main Karakoram granites, of pre-Cambrian, pre-Cretaceous and late Cretaceous ages (ed. Dainelli, 1922-34, Ser. II. Vol. 2). More recently, various writers have suggested that all the main granite masses are genetically related, through widespread and progressive granitisation of the mountain belt in association with orogeny. Compositional differences are explained by local geochemical environment rather than age. There appears to be a large measure of agreement on this kind of interpretation (see. Misch, 1949; Desio and Marussi, 1960; and Marussi, 1964). The Italian geologists, making comparisons with the Pamirs, Tien Shan and Hindu Kush Ranges, bring gravitational and petrological evidence to support the thesis. The large negative gravity anomaly of the Tethys Karakoram is, they believe, an expression of a deep granitic root, comparable with that revealed under the Pamirs (Fig. 4.2.). They consider the various granites outcropping in the Karakoram as linked in depth to a single massive batholith, intimately involved in the orogenic process. The

frequent migmatic zones around the granites, with xenoliths, agmatite, granite with intercalated schists, and the gneissose granites, are seen as expressing the assimilation of the country rock by granitisation during and after major orogenic phases (3.1.).

The Eastern Karakoram and K2 area, the Lupghar Group, and a belt south of the Greater Karakoram from the Upper Gilgit River to the Shyok Bend consist of metamorphosed sediments and volcanics with granitic intrustions. A great variety of gneisses, schists, marbles, and slates are included. Dating of the original sediments and volcanics is in a state of flux, an age-range from the lower Palaeozoic to the Eocene being involved.

Along the southern margin of the Tethys Karakoram and in the Shigar Valley are a series of basic and ultra-basic intrusives reaching their maximum development around the N. W. Syntaxis. The rocks involved include norite, hypersthene diorite, and the ophiolites characteristic of geosynclinal environments. Finally, the Zanskar tributaries of the Upper Indus form a large drainage basin in the Paleaozoic, Triassic and Jurassic sediments of the Tethys Himalaya. In these there are considerable thicknesses of limestone.

The area of granitic outcrops in the region, and the generally greater area of crystallines as opposed to sedimentaries is a notable feature (Table 4.1.) helping to differentiate the bulk of the Upper Indus Basin from the Himalaya to the south. At one time this reinforced the belief that the Karakoram and adjacent ranges recorded an older and different orogeny. This is no longer acceptable. The differences reflect complications in the mountain building process and associated erosional development.

4.3. The Biafo Area.

The Biafo Basin lies across the axial granite batholith, and its lower reaches cross the central metamorphic zone of the region. The main glacier cuts obliquely through the main rock groups (Fig. 4.3.). In the north and north-west the axial granites narrow markedly and metamorphics outcrop, some of which Desio identified

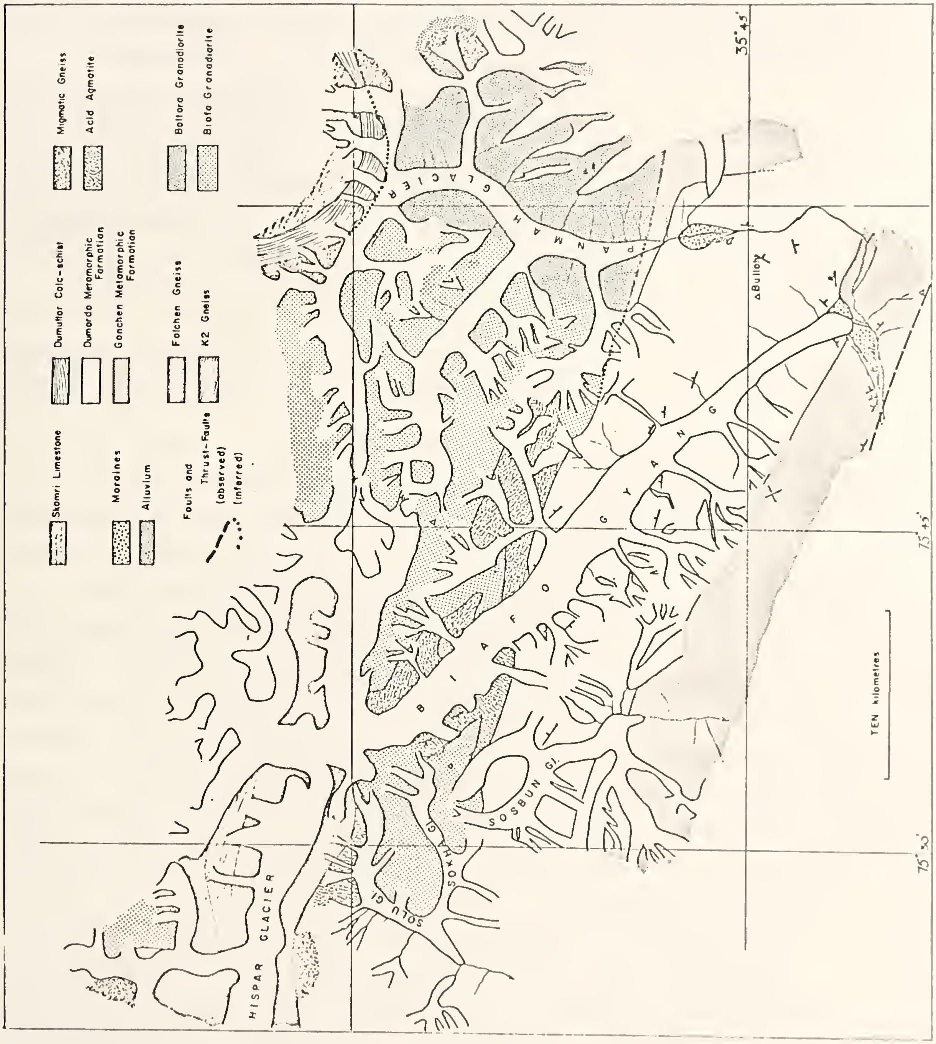

Fig.4.3. Geological map of the Biafo Basin and adjacent areas, based on Desio (I964a), with some structural data from Auden(I935), Matsushita and Huzita(I966) and the present writer.

TABLE 4.1. Areal extent of major rock types outcropping in the Upper Indus Basin.

ROCK TYPE	AREA (Projected)	% TOTAL AREA
(Unmapped)	18,250 sq. mi.	27.5
Metamorphics (dated from pre-Cambrian to Miocene)	17,100 sq. mi.	25.8
Granitic (incl. Axial Batholith and Nanga Parbat)	12,600 sq. mi.	19.0
Recent Alluvium	3,400 sq. mi.	5.1
Cretaceous and Younger Sediments	3,000 sq. mi.	4.5
Ultrabasic Intrusives	2,100 sq. mi.	3.1
Remainder (incl. Triassic and Jurassic Sediments)	9,800 sq. mi.	15.0

as his K2 and Falchen Gneisses (Desio 1964). These are mainly biotite gneisses, but some dolomitic inclusions, and micaschists occur in moraines derived from the area (Desio 1962c p.78).

The eastern flanks of the Sim Gang, the Choktoi, Baintha Brakk and Sosbun Brakk Peaks consist of granitic rocks with a migmatic margin. Desio identified granodiorite as the chief constituent and names the batholithic rocks of the area the Biafo Granodiorite (1964a). Auden, however, found biotite granite in the moraines which suggest a link with the Baltoro biotite-granites of Desio (Auden 1935; Desio 1964a). Auden also found hornblende granite. Along the southern margins of the Biafo Grandiorite, is a broad migmatic zone described by Desio as acid agmatite. ("Agmatite: a heterogeneous migmatite consisting of fragments of crystalline schists in a predominant granitic matrix." - ed. Schiefendecher 1959 p.347). The Biafo granodiorite is extremely massive, while the agmatite zone becomes increasingly finely divided towards the edge of the aureole. The erosional texture, forms and slope angles show a strong relationship to the spacing of joints in the granites (see. 8.3,i).

A broad zone of metamorphosed sedimentaries and volcanics

flanks the lower Biafo. The metamorphics are invaded by sets of dykes and sills, commonly with pegmatites. Marbles, various schists and gneisses including conspicuous garnet-bearing varieties, granulites and amphibolites are found here (see. Bonney and Raisin 1894; Auden 1935; Desio 1962c; Matsushita, et. al. 1966). These are termed the Dumordo Formation by Desio. West from Bakhor Das and the Biafo snout, occurs another set of metamorphics, the Ganchen formation (Desio 1964a). This includes a variety of gneisses, biotite being an important constituent, and thick beds of crystalline limestone and dolomite (Desio 1964a; Matsushita et. al. 1965). Auden mentions marbles increasing in quantity between Askole and the Biafo (Auden 1935). To give some insight into the complexity of the rock types a list of analysed specimens from the area is given (Table 4.2.).

The structures in the metamorphics have received little attention. Desio describes a series of folds with roughly east-west axes crossing the Biafo (Desio 1962c). However, other structures occur with them. Just below the Sim Gang entry the Biafo cuts through the centre of an anticline parallel to its axis. The area around the Biafo-Braldu Junction is highly complicated. To the south the rocks of Bakhor Das dip N.N.E. at between 40° and 50°. Opposite them, on the Laskam shoulder is a horizontal fold overlapping the rocks of Mount Bullah which pass beneath it dipping S.S.E. at about 45°. The dip of the Bullah metamorphics changes in an arc around the mountain becoming easterly in the Dumordo valley at about 60°. On the west side of the Biafo snout the rocks dip 54° towards the E.S.E. A little farther west the beds dip between N.E. and E.N.E. at about 60°. Matsushita and Huzita show a major fault running up the centre of the Biafo valley from Bakhor Das (1966). This is not on their detailed sketch maps and may be an assumption based on erosional features. Steeply dipping metamorphic strata occur in much of the area and are strongly reflected in the large and small scale features of the landscape.

TABLE 4.2 Some rock-types gathered in the Biafo area.

Location	Rock-type	Source
Middle Braldu		
Hoto	Felspar and mica in pegmatite	Hewitt/British Museum analysis (Note 4.1)
Shinlep Bluk (18.1oo ft)	Amphibolite with tremolite, diopside, and biotite	Hewitt/R.James analyst
Surongo	Garnet-epidote (bearing), biotite-hornblende-orthogneiss	ed.Mataushita and Huzita (1965)
"	a) Garnet-biotite-schists b) Calc-granulites c) Marbles d) Pegmatite dykes	Auden (1935)
Askole	Garnetiferoua, epidote-biotite-gneiss	ed.Matsushita and Huzita (1965)
Choblok	a) Hornblende-Scapolite gneiss (incl. sphene, clinopyroxene, plagioclase felspar, alkali felspar, calcite, apatite and garnet)	Hewitt/James
	b) Garnetiferous, biotite-muscovite-schist, (incl. plagioclase, quartz, sphene, ferric iron)	" "
	c) Garnetiferous, muscovite-schist (incl. quartz, felspar, sphene and biotite	" "
	d) Gedrite (anthophyllite)	Hewitt/B.M.
Laskam	a) Sillimanite-kyanite-garnet-staurolite-muscovite-schist (amphibolite facies)	ed.Matsushita etc.
	b) Marble (entirely calcite)	Hewitt/James
Lower Biafo		
West Flank	a) Amphibolite (incl. hornblende, clinopyroxene, sphene, quartz, plagioclaae felspar, minor perthitic alkali felspar and calcite)	Hewitt/James
	b) Gneiss (incl. augite, hornblende, scapolite, calcite, zoisite, plagioclase felspar, minor red-brown biotite)	Hewitt/James
	c) Hornblende-scapolite-gneiss	Hewitt/James
	a) Biotite gneiss, h) Garnet-mica-schist, c) Marble, d) Amphibolites and e) Epidotes	Auden (1935)
	a) Gneiss, b) garnetiferous mica-schist, and c) crystalline limestone.	Desio (1962c)
	also"...alternating micaceous gneiss, micaschist, garnetiferoua micaschist, calcareous schist, crystalline limestone, and granitic dykes and sills..."	" "
Middle Biafo		
Hoh Blukk	a) (in morainea) marble, amphibolite, biotite-sericite-schist, biotite-achiat, quartz-biotite-granulite with garneta, pegmatite	Auden, (1935)
	b) (Mostly) crystalline limestone	Desio (1962c)
Baintha	Acid agmatite	Desio (1964a)
Axial Granitic Zone	a) (moraines) hornblende-granite and b) biotite-granite	Auden (1965)
	c) Granodiorite	Desio (1964a)
Soabun Brakk	Paraschiats	Deaio (1962c)
Lukpe Lawn and Sim Gang	a) Biotite gneiaa, b) Micaschiata, and c) phyllitic paragneiss	Desio (1962c) Desio (1964a)
	Migmatitea, granitic gneisa, biotite gneiss, (in Moraines)	Deaio (1962c)

4.4. A Note on the Seismicity of the Region.

The Asiatic portion of the Alpide Belt is the most active seismic zone in the world outside the Circum-Pacific Belt (Gutenberg and Richter 1954). The distribution of seismometers, and the recency with which shocks below magnitude E (ibid) could be detected at long distances, has led to rather poor coverage of our region. Nevertheless, a considerable number of large earthquakes are on record for the region and its immediate neighbourhood. Inventories of shocks and epicentres may be found in Oldham 1883; de Montessus de Ballore 1911; and Gutenberg and Richter, op. cit. In areas of detailed seismic observation such as California it has been found that the frequency of shocks is an inverse logarithmic function of magnitude. While the increase in number of shock with decrease of magnitude is uniquely slow in the Hindu Kush records, undoubtedly there are large numbers of small, and shallow shocks in the region that have gone unrecorded. These can still have significant geomorphological effects. For Eastern Nepal an average of three seismic shocks a day is reported (Bhaskaran 1962 p.81); and Suslov mentions over a thousand shocks a year in Central Asia (trans. 1956 p. 532). As well as the small and large ones within the Basin, the Upper Indus region can be affected by high magnitude earthquakes well outside itself. Of particular importance is a persistent hypocentre at a depth of 140 miles, and location $36^{o}5'N$, $70^{o}5'E$. Between 1905 and 1953 over seventy shocks originated there, several of them highly destructive. For details on a number of major earthquakes originating here and in the adjacent parts of the S. W. Asian mountain complex, see Baird Smith 1842; Oldham 1884 and 1899; Coulson 1929, 1938a and 1940; Mukherjee and Pillai 1941; Stenz 1945; Mukherjee 1950; Ritsema 1955; and Marussi 1964 pp.189-199.

In the course of these investigations, the effects of seismic activity will be examined in relation to primary mechanical failure of superficial rock, triggering of mass-movements and formation of landslide dams and glacier surges. Earthquakes play an important part in extreme or catastrophic events in landscape development.

Not so clear is the role of frequent small and medium as well as large shocks, in break-up of superficial, brittle rock; in preparing and triggering mass-movements, and re-ordering ground-water movement. In a region combining heavy snow accumulation at high altitude, a predominance of steep slopes in rock and talus, innumerable ice-falls and "hanging" snow and ice carapaces; and high, undercut river terraces, persistent seismic activity could have a hithertoo underestimated role in promoting erosion. At this time it is impossible to find evidence to estimate the overall effect of seismicity. Nevertheless, as with many other points in the present study, we have to acknowledge that a factor which can reasonably be neglected in most areas where geomorphologists have worked, is of more than incidental interest.

CHAPTER 5

THE REGIONAL CLIMATE

5.1. The Broad Pattern of Climatic Controls.

Very little has been written specifically about the region's climate, and much that is available is outmoded. Some weather records began in the Nineteenth Century but the stations are few, and confined to main valleys unrepresentative of much of the mountain area. Since climatic conditions are a vital consideration in this study, we must look at broader atmospheric patterns as an aid to understanding and supplementing the poor local information (Note 5.1.).

To understand the climatic environment of the Upper Indus Basin its location must be seen in three dimensions. The orographic effect here involves more than simple lifting or obstructing of air masses. The exceptional height over large areas, the abrupt edges of the mountain block, and certain thermal effects, isolate the region in many respects from the "weather layer" of the surrounding lands. Reaching well into the mid-troposphere the region is influenced directly by upper air conditions.

Throughout the year the prevalent air stream is westerly, often with the Westerly Jet at its core (Lockwood 1965; Trewartha 1958). Even in summer a westerly air movement prevails as far south as the Himalayan foothills. Air masses moving in at high levels from as far away as the Mediterranean and Azores High dominate the weather. But the region is also marginal to other powerful atmospheric systems which occasionally modify and even destroy the westerly pattern. In particular, the Indian Monsoon, thermal effects over the Tibetan Plateau, and changes in the distribution of pressure and circulation over mid-Latitude Asia, can disrupt the Westerlies.

In winter the Westerly Jet, found in the 300-200mb zone, steers depressions from the Mediterranean towards the Hindu Kush. Where the Jet divides around the mountain block there is renewed cyclogenesis and additional moisture may be drawn in from the Indian Ocean. Such "Westerly Disturbances" are well-known in northern India-Pakistan

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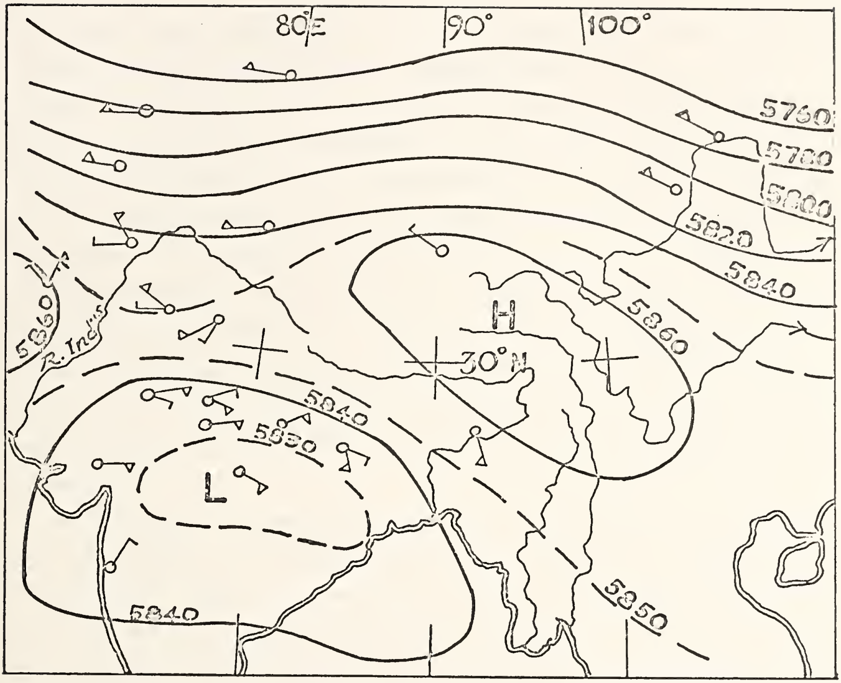

Fig. 5.1. Height of the 500mb surface over South Central Asia in July and August (after Flohn). Heights in metres, and △——o resultants of winds at 5-6km; ι——o resultants of movement of middle cloud layer (altostratus and altocumulus).

(Mooley 1957), and are thought to bring the bulk of the precipitation falling on the Upper Indus Basin (see Walker in Hedin 1917 vol. 2, p. 191; Burrard and Hayden 1933, p. 147). Winter conditions depend especially on the number and intensity of the depressions and are subject to great variability.

Almost simultaneously in the first half of June, the Jet disappears from south of the Himalaya, and the monsoon begins to move over the Indian sub-continent. A thermal anticyclone develops over the Tibetan Plateau and subsiding air on its southern side helps keep the monsoon out of the mountains. (Modern interpretations give small importance to the Himalaya as a purely mechanical barrier).

Events in the Upper Indus Basin at this time are less clear. While the valley stations mostly record negligible precipitation, expeditions invariably report periods of heavy cloud and precipitation at high altitude. Low altitude, fohn effects and the valley wind systems probably insulate the valleys from the westerly air stream with its high cloud layer. Undoubtedly, the regional airstream is westerly at this time (Fig. 5.1.) and the high altitude storms are related to those which bring the Eastern Pamir its main precipitation season (see Suslov trans. 1956 p.34). Summer cloud and precipitation help to explain the large concentrations of snow on the larger ranges, especially the Greater Karakoram. Westerly disturbances may continue to occur in the mid-troposphere at this time further increasing cloud and snowfall.

Occasionally, the movement of horizontal waves in the westerly drift over Siberia may thrust troughs with roughly north-south axes far southwards. These can temporarily destroy the Thermal High over Tibet, and, while creating a break in the monsoon over India, draw shallow monsoonal depressions into the mountains. The ensuing precipitation may be very heavy (Flohn 1958 p.303). For the Upper Indus, a return period of fifty years has been suggested for these monsoonal intrusions (Finsterwalder 1960 p.787), but there is little data to support it. A major intrusion occurred in 1959 (ibid).

The possible fluctuations in summer circulation and generally "marginal" nature of precipitation make the regional climate open to large periodic and aperiodic variations. Especially critical are changes in precipitation, summer cloud and humidity which regulate the mass balance of snow and ice, chief sources of moisture for geomorphic processes.

5.2. Climostatics.

Measured values of climatic parameters must depend upon readings take at Gilgit (4,9oo ft.), Skardu (7,5oo ft.), Dras (10,o8o ft.), and Leh (11,5oo ft.); all stations in or close to the main Indus trough. (Fig. 5.2.) Figures for these stations reveal large annual temperature ranges, usually over 50^{o}F, and sub-humid to arid levels

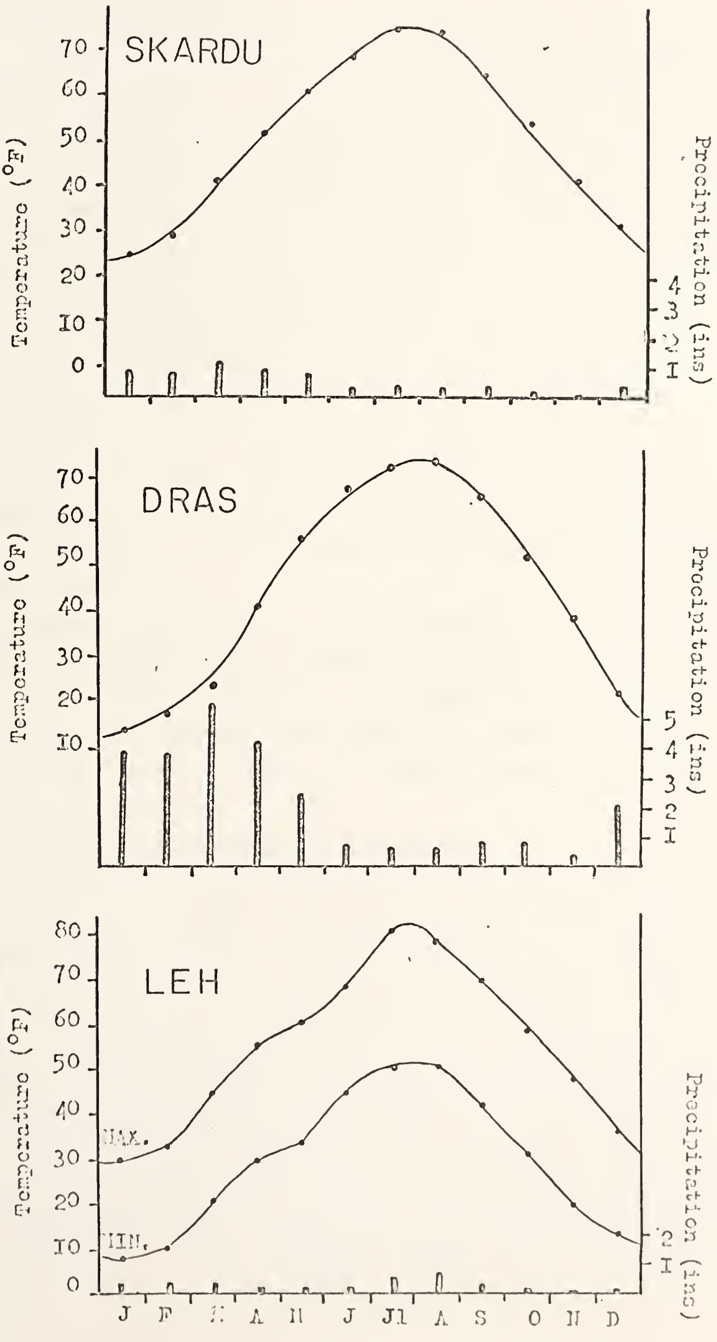

Fig.5.2. Climatic graphs of temperature and precipitation (mean monthly values) for permanent weather stations in the Upper Indus Basin.

of precipitation. The records of precipitation show large fluctuations from year to year, with an average 30% departure from normal,- where "departure" is defined as "...the ratio of the mean of all the deviations from the mean averaged without regard to sign..." (Petterssen 1958 p. 282). There are fewer years when precipitation exceeds the mean, but on those occasions a chance of very extreme falls (see Central Board of Irrigation 1948 pp. 93-111). While this may not be representative of the high mountain areas, it shows the important sub-nival zone of geomorhic activity to be subject to large variations in local moisture supply.

There are no records of evapotranspiration available but this is expected to be large in view of the high latitude, low humidities, and high summer temperatures. Using the Thornthwaite system Subrahmanyam calculated the annual Potential Evapotranspiration as 38.1 inches at Gilgit where the annual precipitation is 4.75 inches (Subrahmanyam 1956).

Unfortunately observations at the permanent stations are to a considerable degree misleading for much of the region. For instance, average annual runoff is equivalent to 17 inches of water over the whole region, and that figure masks evaporation losses which may approach 70% (c.f. Banerjee 1957 on the Kosi Catchment area, Central Himalaya).

5.3. <u>The Effects of Altitude and Topography.</u>

Altitude alone has significant effects on local climate in addition to locational factors. Windspeeds in the mid-troposphere are generally higher than those close to sea level, an important factor in relation to snow movement and packing, evaporation and the effect of topography-controlled wind systems in exposed mountain masses. The density and composition of the atmosphere changes with altitude having a marked effect on insolation received at the surface. The chief absorber of solar radiation is water vapour with dust another significant factor. More than half the atmospheric moisture and dust occurs below 8,5oo ft. One half of the atmosphere by weight lies below 19,ooo ft. Air mass movements modify this picture locally,

but the diurnal and day to day fluctuations in solar radiation at the surface in high mountains are invariably very large. From a geomorphological point of view temperature conditions are thus poorly represented by shade readings.

At every season of the year, there is a persistent belt of average minimum humidity between 10^{o} and 40^{o} N and at 2½ to 6 miles a.s.l. (London 1957 pp. 10-11). These average conditions would place most of the Upper Indus Basin in a zone of less than 50% R.H. with a considerable part below 40%. Most records indicate that this is the case. On the other hand, there is no clear evidence of strong vertical decrease in humidity (Table 5.1). This is consistent with the high altitude precipitation season of summer, and the effect of upslope movement of the valley winds in day-time (Flohn p. com.).

TABLE 5.1. Variations of Relative Humidity with altitude from records of the Visser Expeditions (from Bleeker 1936).

Zone (ft.)	June	July	August	September
16,500-18,000	69%	6%	60%	47%
14,000-16,000	46	38	51	54
10,500-13,000	36	44	51	53

The spatial distribution of precipitation in amount, form and to some extent timing is dominated by orographic conditions. Altitude induces upslope changes, topography induces variations due to exposure, obstruction and steering of moisture-bearing winds, and local heating and circulation effects. Of special interest is the zone of maximum precipitation, since it controls the run-off available to different drainage units and the relative proportions of direct and melt-water run-off. Evidence is poor in detail, but maximum precipitation must occur above 13,000 ft. in the Central Karakoram - much higher than in the Alps, the southern slope of the Himalaya or the Western Pamirs. In 1961-62 snowfall on the Upper and Middle Biafo was always much heavier than in the Braldu Valley, when the latter received any. This

concentration of precipitation at high altitude means that something under 50% of the Basin area of the region is supplying most of the run-off. If we consider the enormous moisture deficit in most of the sub-nival zone, and the considerable evaporation potential at high altitudes, the upper regions must be receiving of the order of 40-60 inches precipitation a year. Nearly all of this is in the form of snow. An average position of maximum precipitation close to or above the firn lines of the large glaciers (14,5oo-15,5oo ft.), is a major factor in their maintainence in an otherwise dry region (see Flint 1967 p. 48).

There are well-defined differences between mountain ranges in the region. The central and especially east-central ranges have smaller total precipitation and less at given altitudes. This relates both to smaller mass of mountain and to shadowing by the Karakoram, Hindu Kush and Himalayan Ranges. Little is known about shadowing and steering of moisture bearing winds by the regional topography. Clearly the low altitude of thick, permanent snow along the Upper Hispar and Biafo Glaciers, in contrast to the Braldu Valley, reflects a concentration of precipitation in a favourable longitudinal trough within the Greater Karakoram.

5.4. Snowlines.

Geomorphologically, the climatic and orographic snowlines (Flint's defintions 1957 p.48) are important as dividing lines between fundamentally different process situations, and in the occurrence and size of glaciers. The seasonal snowlines (called "orographic" by Peattie 1936 p. 47) indicate the extent and duration of temporary nival conditions.

Recently, von Wissmann (1959) made an exhaustive study of Central Asian snowlines, which, though largely dependent on pre-1940 information makes some important improvements on Dainelli (1924 and 1922-34 v. 4 p. 120), and Visser (1938 v. 2 p. 15). Von Wissmann has identified the broad regional snowline patterns (Fig. 5.3.). In detail the snowlines are more complicated being

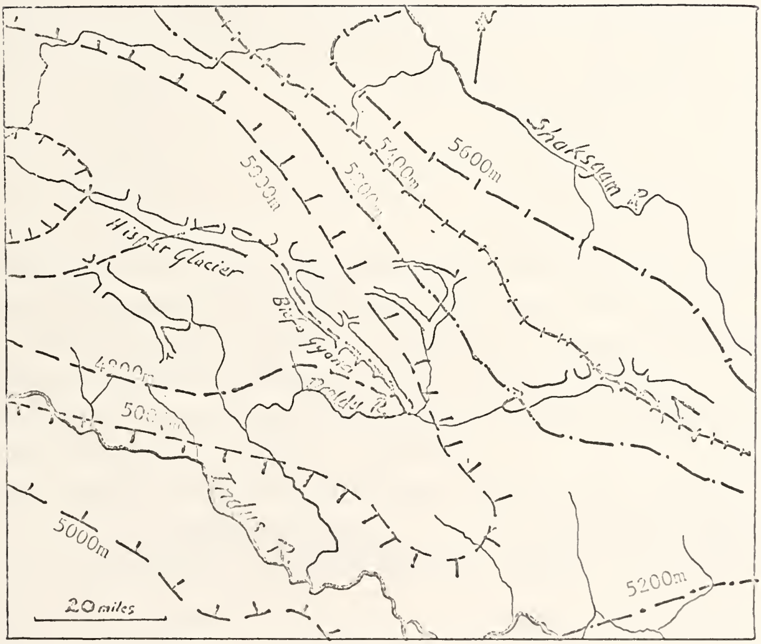

Fig 5.3. Snowlines of the central Upper Indus Region (after von Wissmann)

very sensitive to aspect, and steering of moisture-bearing winds. Except on the north wall of the middle Sim Gang all north and south slopes of the Upper Biafo (above 15,5oo ft.) are above the snowline (Note 5.2.). This is an effect of topographic concentration of cloud and snowfall. Towards the Braldu insolation becomes increasingly important in differentiating slopes of different aspect. Snowlines on all aspects rise towards the Braldu but along that valley and the lower Biafo permanent snow was found as much as 3,ooo ft. lower on northerly slopes.

Information on seasonal snowlines in the region is poor. The Schlagintweits gave the following figures (1861-66 v. 4 p. 568):-

Months	Mean height of snowline
Dec.-Feb.	8,ooo ft.
Mar.-May	15,ooo ft.
Jun.-Aug.	18,5oo ft.
Sept.-Nov.	18,4oo ft.

Their work dealt mainly with Ladak conditions. Observations of the migration of snowcover in the Braldu and Lower Biafo were made in 1961-62. While these are limited by conditions of a single year and poor mapping in much of the area, they offer some much-needed information. Snow cover never lasted more than a week below 12,ooo ft. The valley floor was at 10,ooo ft. (Table 5.2.).

TABLE 5.2. SEASONAL MIGRATION OF SNOWLINES. Upper Braldu 1961-62

Month	Northerly Aspect		Southerly Aspect		Mean
	Firm Cover.	Intermittent	Firm.	Intermit.	Firm.
(1961)					
September	15,8oo	-	18,ooo	-	16,9oo
October	15,8oo	15,ooo	18,ooo	15,ooo	16,9oo
November	14,ooo	13,ooo	17,ooo	14,ooo	15,5oo
December	14,ooo	12,ooo	15,5oo	12,ooo	14,75o
(1962)					
January	12,ooo	10,ooo	13,ooo	10,ooo	12,5oo
February	12,ooo	10,ooo	13,ooo	10,ooo	12,5oo
March	12,ooo	10,ooo	14,ooo	10,ooo	13,ooo
April	13,ooo	10,ooo	14,5oo	10,ooo	13,75o

5.5. <u>Moisture Availability and Changes of Phase</u>

Climate affects geomorphic processes largely through controlling moisture and heat input and their interrelations. In the Upper Indus Basin it is essential, but extremely difficult, to grasp the areal and altitudinal variations in relations of these two factors. In order to synthesise these broad controlling conditions of the regional climate available information on temperature and precipitation has been organised in two complimenting diagrams (Figs. 5.4 and 5.5.). Together, the altitudinal zoning of moisture input, and seasonal movement of temperature represents the large-scale controlling or "system" conditions in clima-geomorphic events. By representing the precipitation zones on an area-height graph, though very stylised, the spatial arrangement of moisture availability emerges much more clearly than in expedition reports and weather records which are biased towards the arid valleys where men spend most of their time. The temperature graph is most significant in relation to changes of phase of water. Freeze-thaw is present over a broad zone of landscape at all seasons. Temperature movement in relation to the belt of highest precipitation is important, especially the short, two-to-three month period of "melt-days" above 12,ooo ft. This relation produces the short but intense ablation season on the glaciers (see Hewitt 1967), and sharply peaked run-off of the main rivers. More than 65 per cent of the Upper Indus' discharge occurs between mid-June and mid-September.

In detail the picture is, obviously, more complicated. Somewhere above the summer isotherm of 32^{o}F begins a zone where melting is negligible and does not contribute to run-off. Snow is lost through sublimation, wind action, avalanching and glacier flow. The 32^{o} isotherm rises from about 18,7oo ft. in the Western Himalaya (Hann's figure, 1908 p. 250), to between 19,ooo and 20,ooo ft. on the Tibetan Plateau (Flohn p. com. revising his figure in 1958 p. 297). Freeze-thaw occurs even above 26,ooo ft. on exposed rock, but the amounts of water involved are small. High winds, intense insolation and low vapour pressure produce large sublimation losses at these altitudes (see Henry 1916).

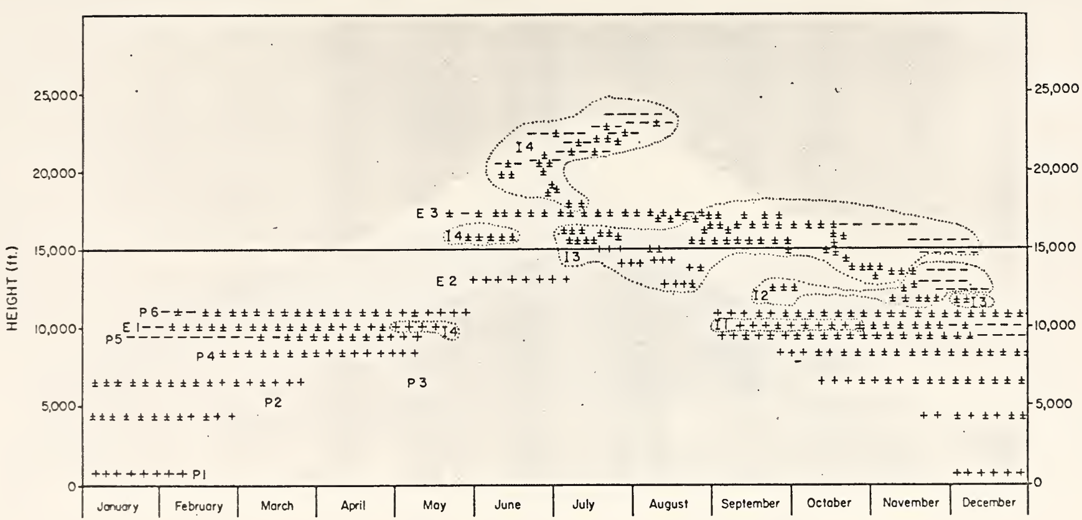

Fig. 5.4. General migration of temperature conditions with season and altitude for the Upper Indus Region from available published data. Where, + refers to three days' positive temperature readings, - to negative readings, and ± to diurnal frost shifts. The white band is the zone of frequent freeze-thaw cycles. For sources and other details see Hewitt(1968)and Appendix 9.

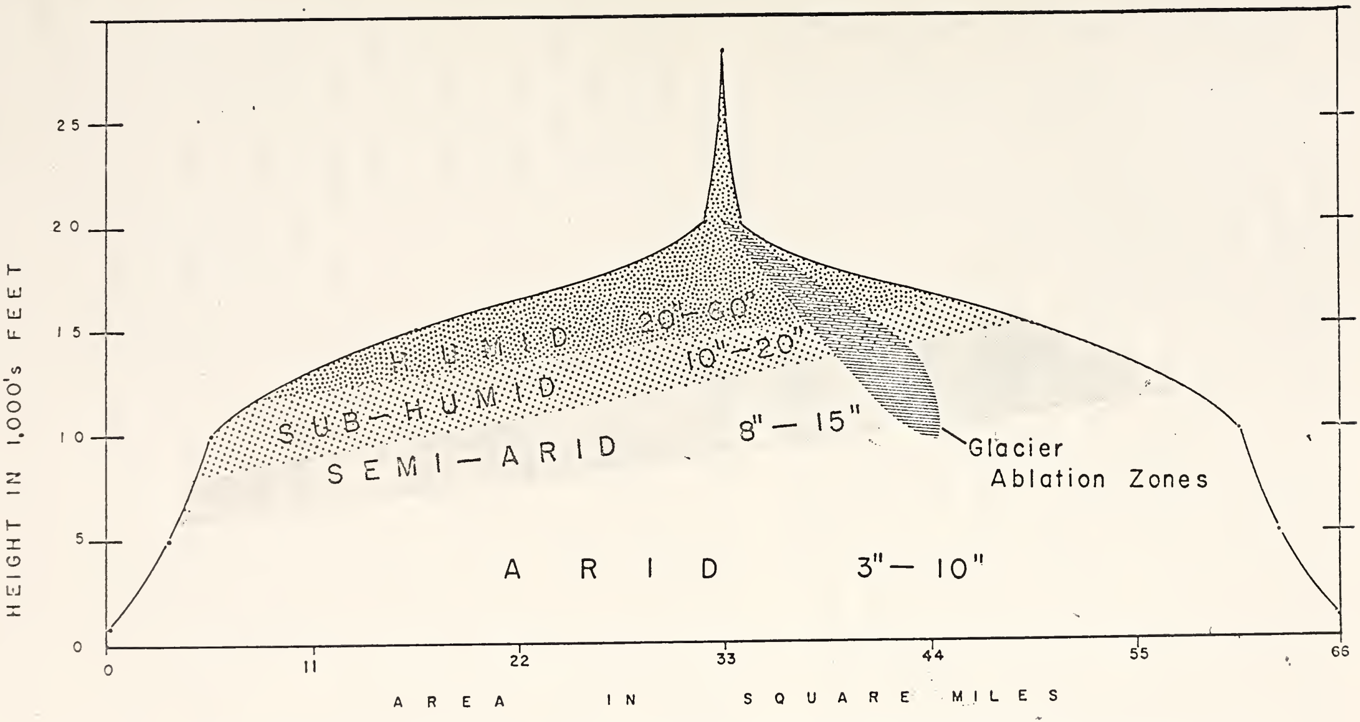

Fig.5.5. Diagrammatic representation of broad precipitation belts superimposed on the area-height curve of the Upper Indus Basin.The general rise of the belts from west to east is suggested.As is made clear in the text the zones are very general and boundaries tentative owing to poor data at this time.

Below 20,ooo ft. the effects of aspect become increasingly marked. Rapid removal of snow from southerly slopes occurred throughout the winter of 1961-62. A morning's sunshine in January and February would remove snowfalls of 3-6 inches up to altitudes of 14,ooo ft. with air temperature remaining below freezing and the ground being hardly dampened (see also 7. 3.v.). However, with equal periods of exposure lower angle slopes lost their snow more slowly, with more seepage into the ground, an important factor on the "alp" shoulders (see Lunn 1927 p. 455). The extreme contrast is, however, with northerly slopes at angles above 45^{o} which the sun fails to reach throughout the winter. Along the Braldu, and ravines around the Biafo there are large areas of such slopes, and the melting of snow and ice there followed air temperature closely. In the main valleys the drying valley winds removed snow from lower northerly slopes repeatedly through the winter.

5.6. Conclusion.

Characterising the climate of the region and its importance to landforms, Martin Conway said: "...it possesses two main qualities; extraordinary dryness and extreme and rapid variation of temperature. The rainfall is trifling over the whole area, except where the mountains reach great altitudes, and there snow is precipitated in considerable quantities..." (1894 vol. 1 p.127).

In terms of erosion one would make much more of the significance of precipitation at altitude and the contrast of the moist winter, even in many valleys, with the dry summer. But his assessment is basically sound. The large, and rapid variation in temperature is very important especially since it serves to regulate the release of melt-water with maximum geomorphic impact. Sudden melting promotes short-lived, high energy processes on slopes. The short, but intense hot season gives to the rivers a sharply peaked summer discharge, with greater transporting capacity than equivalent discharges spread over longer periods. Thus the regime of the Upper Indus makes best erosional use of a moderate runoff per unit of area.

In addition to the great variety of geomorphic conditions created by strong spatial contrasts of climate, erosional effects are strengthened by direct downslope linking of the different environments. Most important, the erosional media, snow, ice and melt-water are introduced in large quantities on watersheds and upper slopes, and descend directly to valley areas of arid climate and sparse vegetation with devastating impact.

In a variety of ways climate and topography are organised to produce highly efficient erosional processes. The details of this are complex, but the broad arrangement is for strong contrasts in climatically controlled factors to be exaggerated in their effects by great relief energy.

CHAPTER 6

THE BIAFO-BRALDU METEOROLOGICAL OBSERVATIONS AND RELATED RECORDS.

This section deals with the observations for Biafo-Braldu meteorological station maintained from November 1st to April 9th. Where available, day-to-day observations from other parts of the mountains will be used for comparison. Despite the limitations of data collected for one season only, some data are better than none at all, especially for the cold season.

6.1. Position of the Meteorological Station.

The instrument station was located at Lat. 35°. 40 N, Long. 75°. 50 E, on an old terminal moraine of the Biafo in the Braldu Valley. The edge of the ice lay about 150 yds away, to the northeast. The altitude approximated from Shipton's 1939 map, was 10,2oo ft. The Boiling Point Hypsometer registered 194.4°F, and the mean pressure from 1st November to 11th December was 708.15mb.

The station horizon was very high in its north and south aspects, but the broad trough of the Braldu Valley stretched for several miles, roughly east-west, in view of the site. The Biafo Valley curved away northwards (Fig. 6.1.).

6.2. Pressure.

Barometric readings are avilable from November 1st to December 11th. They show some steep pressure gradients associated with the passage of the Westerly Disturbances which characterise the winter half of the year (Fig. 6.2.).

6.3. Temperature.

The temperature record is complete for the period (Fig. 6.3.). The table shows the main characteristics of the temperature regime. (Table 6.1.).

There were four successive months with means below freezing point, but the figures do not suggest severe cold. They are slightly colder than the average upper air temperature for this latitude,

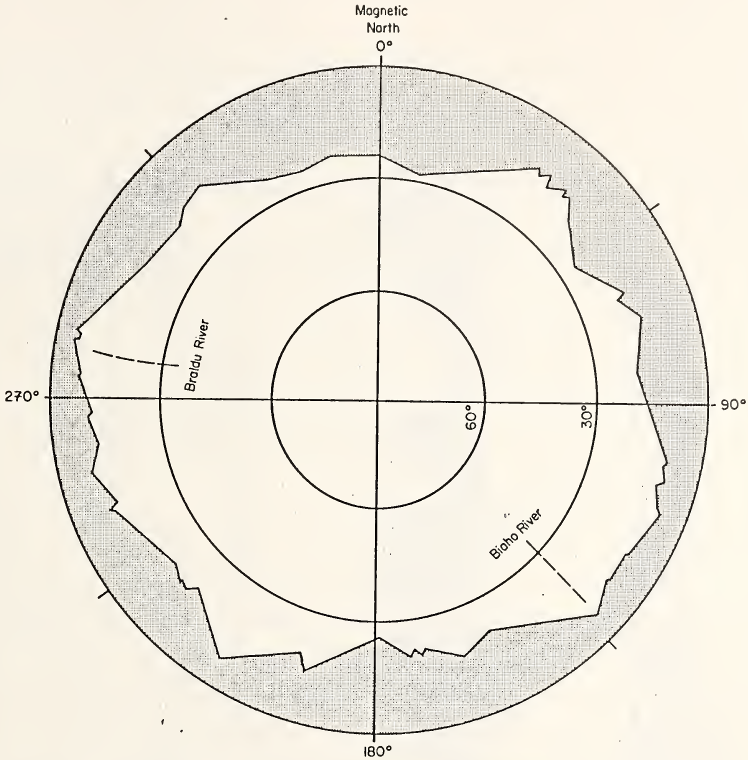

Fig 6.I. Horizon of the Biafo-Braldu Weather Station. (Surveyed by K.Hewitt with Wild T2 Theodolite. Booker, A.Rahman.Khan.)

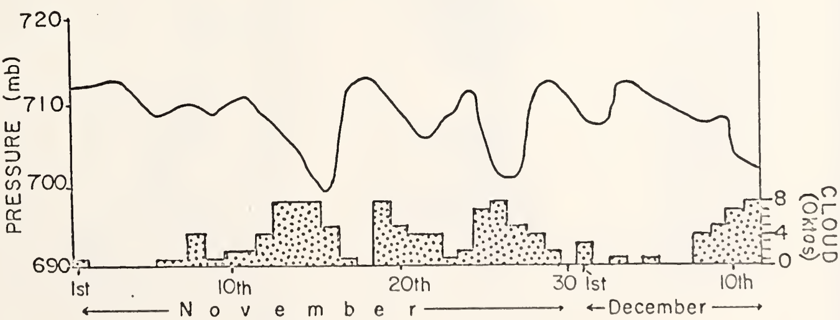

Fig 6.2. Variations in air pressure at the Biafo-Braldu Station for November and part of December 1961. A histogram of mean daily cloud cover is added to show the close association of weather conditions to the passage of westerly depressions.

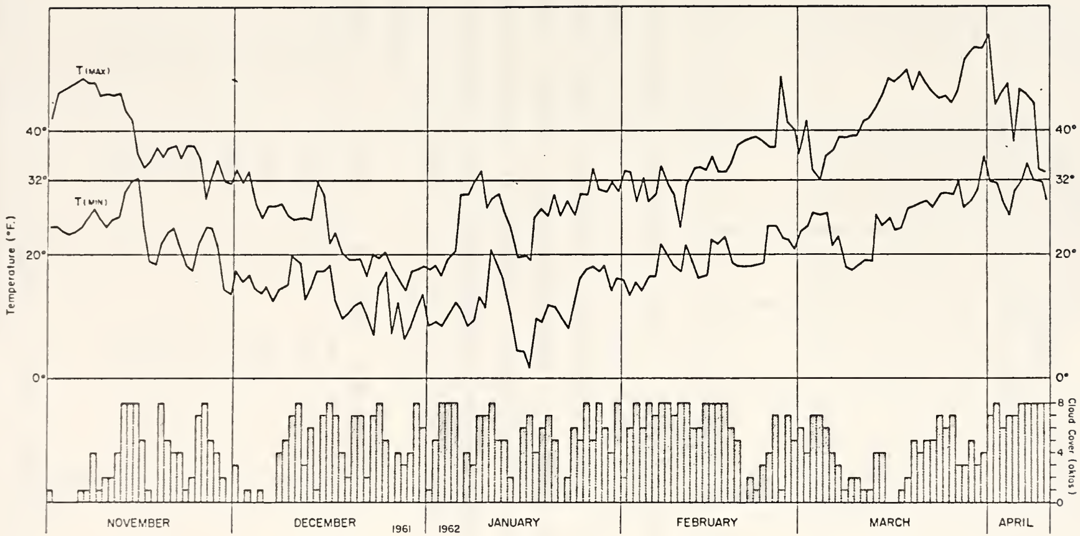

Fig. 6.3. Graph of maximum and minimum daily temperatures recorded at the Biafo-Braldu Station in I96I and I962. The histogram of mean daily cloud cover is added to show the close association of, in particular, diurnal temperature variations, to cloudiness.

TABLE 6.1. Summary of characteristics of the Biafo-Braldu temperature record, November 1961 to April 1962. (^{O}F)

MONTH	Monthly Mean	AVERAGE DAILY			EXTREME DAILY			DAYS WITH FROST-SHIFTS
		T_x	T_n	Range	T_x	T_n	Range	
Nov.	31.6	40.0	23.2	16.7	48.4	13.8	24.0	27
Dec.	18.3	23.2	13.4	9.8	33.7	5.0	17.3	2
Jan.	18.9	26.2	11.6	14.7	34.0	1.0	22.6	2
Feb.	26.9	34.5	19.3	15.2	48.0	13.3	24.5	21
Mar.	35.6	45.5	26.0	19.1	55.0	17.5	26.0	29
Apr. (1-9)								6

height, and season (Shaw 1928 vol. ii, pp. 100-103). Winter temperatures in these regions are generally close to, or marginally lower than those for the free atmosphere (Flohn 1958 pp.295-297). By contrast, summer temperatures tend to be much higher than the free atmosphere average. The latter is about 35^{O}F (Shaw op. cit.).

In September our stream-gauging party recorded the following temperatures fifty years from the subsequent site of the Biafo-Braldu station (Note 6.1.):-

Date	Time	Air Temp.*	Weather
Sept. 23	13.00	85^{O}	Sunny and Windy
24	12.00	80^{O}	Sunny and Windy
26	13.00	75^{O}	Cloudy and Windy
27	12.00	71^{O}	Sunny, no Wind
28	13.00	68^{O}	Sunny, no Wind
30	13.00	59^{O}	Cloudy, windy, snow falling at high altitude.

*Instrument: Whirling psychrometer.

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The 23rd and 24th were typical of the valleys in autumn. On the 28th the first of strong Westerly Disturbance began. Temperature observations taken in the area at other times are tabulated (Table 6.2.).

TABLE 6.2. Published observations of temperature by other expeditions in the vicinity of the Biafo-Braldu Station. (Note. With the wide variations in local conditions these only serve to indicate the order of daytime temperatures encountered).

Date	Time	Place (alt. in ft.)	Temperature (°F)	Source
31/7/92	1100	Laskam (12,ooo)	62°	Conway (1894)
1/8/92	Afternoon	Dumordo (10,8oo)	85°	" "
13/5/09	1600	Chongo (9,7oo)	54.4°	de Filippi (1912)
14/5/09	1000	Askole (10,ooo)	55.1°	" " "
15/5/09	0800	Askole (10,ooo)	48.0°	" " "
15/5/09	1000	Askole (10,ooo)	55.1°	" " "
28/7/09	1100	Skoro La (13,15o)	60.2°	" " "
7/33	daytime (in tents)	Biafo Snout (10,2oo)	94° (in tents)	" " " Auden (1935)
19/7/56	1700	Askole (10,ooo)	77°	E. S. Williams (p.com.)
20/7/56	1700	" "	77°	" " "

From the available figures in comparison to the permanent stations, a July mean of 65°, and an annual range of about 46°, is suggested for our station. These figures are not very extreme for Central Asia. The summer temperatures are high for close proximity to a glacier.

Geomorphologically, information on the position and amplitude of daily variations is important. These are generally smaller in winter, but more significant in frequently crossing freezing point. The actual figures are not especially large. They are less than those for Chamonix (1034m) for example (Peattie 1936 p.27, quoting

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Vallot 1893). Here the factor of mass of mountain, and perhaps the valley wind-systems, off-set continentality and greater altitude. However, extremeness of the geomorphic situation also depends on the relation of daily variations to the annual temperature curve. The further the tropics are entered the greater the opportunity for diurnal fluctuations across freezing point, when the annual mean approaches 32^{o}. Through not comparable to the Equatorial Andes (Troll 1944), the Biafo-Braldu records indicate some 100 frost cycles per annum, at least. Professor Flohn writes he would estimate 110-12o air temperature frost cycles from the data, and many more at ground level (P.com.) (see 7.7.ii.).

The shape of the diurnal temperature curve affects the impact of a given range of temperature. The curves for clear days at the Biafo show a marked left-hand skew, and peakedness within daylight hours. The higher southeast horizon of the weather station produced the sharper rise at sunrise. The fall at sunset was quite sharp. Such is characteristic of south-facing slopes and valley floors in mountains, with more rapid effects on snow and ice, than on northerly slopes. This was reflected in the rapid warming and removal of snow on Choblok slope.

6.4. Precipitation.

All precipitation for the period of record was in the form of snow. Many expeditions have reported rain-storms in early summer in the area (Conway 1894; Workman 1901; Auden 1934; de Filippi 1909; Shipton 1936; Streather 1954 p.com; Desio 1955a).

The following is a summary of the Biafo-Braldu station records:-

Month	No. of days with Precipitation	Amount (water equiv.)
November	7	0.06 inches
December	9	0.1 inches
January	7	0.18 inches
February	7	0.18 inches
March	2	0.00 inches
April 1-9th	3	.33 inches
	35	0.85 inches

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A poor precipitation season is indicated. Of 35 days on which snow fell, 21 had unmeasureably small amounts. Apart from November which is generally dry, the monthly figures are less than averages for Leh, the driest of the mountain stations, and for Gilgit which has the smallest winter precipitation. Often, when the Meteorological Forecast predicted snow, it did not fall, although the general synoptic situation was right. The local population considered this a dry year (see 6.9.). There was much heavier precipitation only a few miles up the Biafo. Between 28th September and 1st October the writer measured falls amounting to 6 inches depth of snow around Baintha Camp (14,ooo ft.). No falls occurred at the snout during this period. By November 16th an average depth of 8 inches of snow lay on the Biafo glacier at 14,5oo ft. despite appreciable losses through wind action, melting and evaporation. The eastern valley walls were, however, clear of snow up to 17,ooo ft. The depth of snow on the glacier increased appreciably towards Lukpe Lawo.

6.5. Cloud Cover.

The average monthly cloud cover as calculated from all reading was:-

November	December	January	February	March	(April 1-9)
3.3 oktas	4.3	5.3	5.7	4	7.6

The mean coverage for the five complete months was 4.45 oktas, or 55.6% which is close to the regional average for winter months at the permanent stations (Table 6.3.). However, if cloud cover was average the low precipitation suggests that either the Biafo situation is normally more cloudy than the other stations, or the cloud was average in amount but less dense. The latter is important, since temperature variations and the nature and rate of snow wastage vary appreciably between thin and thick cloud conditions.

TABLE 6.3. Cloud cover at the Biafo-Braldu Station (%) compared with averages from the permanent stations.

	Nov.	Dec.	Jan.	Feb.	Mar.	Mean	(oktas)
Biafo-Braldu	41.2	53.7	66.2	71.2	50.0	55.6	4.4
Skardu (mean)	35	61	72	66	62	59.2	4.7
Dras (mean)	27	52	63	57	53	50.5	4.0
Leh (mean)	32	58	67	66	61	56.8	4.5

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[illegible]	[illegible]	[illegible]

Cloud type was recorded for the period Jan. 7th to April 9th. For an average of five observations per day for 58 cloudy days in that period the breakdown according to dominant cloud type was:-

Cloud Type	Incidence as Dominant Form
"High" Clouds	
Ci	21
Cc	8
Cs	19
"Medium" Clouds	
As	44
Ac	2
"Low" Clouds	
Sc	0
St	122
Fs	9
Ns	24
Cu	0
Fc	3
Cb	0
Hilltop Cumulus	9

According to altitudinal type, the dominant cloud-types of the day (i.e. type observed 50% or more of the observation times in a day), were:-

High Cloud	Medium Cloud	Low Cloud
12	12	35

These data seem generally representative of winter conditions. Nevertheless, it is likely that with stronger frontal activity and higher precipitation low cloud would play a greater part.

The altitudinal ranges for the respective cloud-types according to our empirically established margins were:-

"High Cloud"	29,000-40,000 ft.
"Medium Cloud"	20,000-29,000 ft.
"Low Cloud"	10,000-19,500 ft.

(c.f. de Filippi 1912, p. 208)

In general the low and medium cloud types seemed thinner than their normal equivalents. Visibility perceptibly less than infinity occurred only on 12 days between January 1st and April 9th.

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[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]

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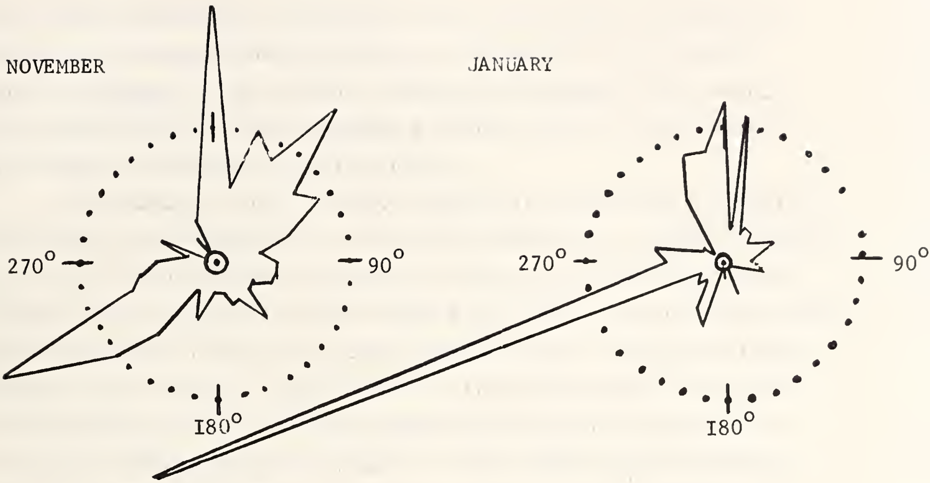
Progressing up the glacier, cloud was normally thicker, and stratus came lower, during storms. Cloud amount and type emerged as an important regulator of geomorphic activity. Heavy stratus particularly would eliminate the large daily temperature extremes and was associated with those breaks which occur in the intensive frost cycle periods. The heliograph continued to burn with complete cirro-stratus coverage, but an appreciable reduction in the actinograph values occurred. Altostratus in February and March reduced but did not generally stop melting of snow. However, there was more run-off and infiltration and less evaporation. At such times atmospheric counter-radiation (long-wave) offsets the lessened short-wave radiation since it is more effective in melting snow. Since heavy cloud can reduce maximum temperatures by 16°, as in late February or 22° as in early April (Fig. 6.3.) its possible role in short-,and long-term climatic fluctuation is obvious, and consequently its geomorphic significance.

6.6 Winds.

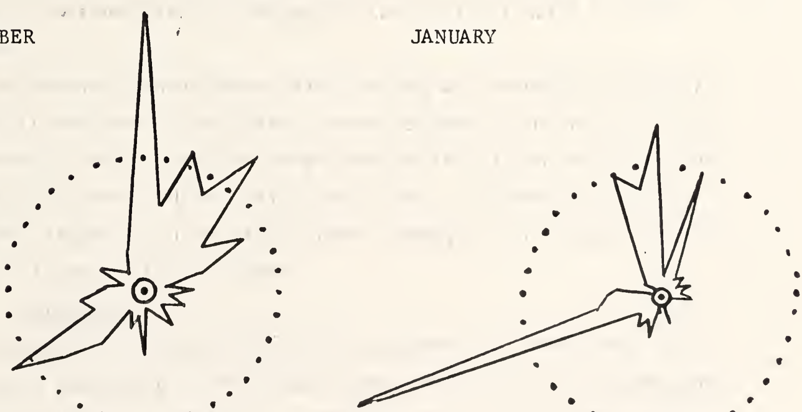
Calm air was extremely rare. There was only one reading without wind in the whole of January and February. On the other hand, speeds were not high, never exceeding a "moderate wind". The average for November, January and February was 7 ft. per second.

The wind regime was dominated by an alternating patter of Valley Wind (upslope) and Katabatic Glacier Wind reinforced by the normal Mountain Wind (downslope) (Definitions as in Godefroy 1948, p. 329). On most days, early and late readings recorded the Glacier/ Mountain Wind, and during the day the Valley Wind. Wind roses mirror closely the topographic situation especially the angle between the Biafo and Braldu Valleys. (Fig. 6.4.). The diurnal pattern was sometimes broken during Westerly Disturbances.

Such topography-controlled wind regimes are typical of mountain valley stations, but normally, as in the Alps the Valley Wind is the more powerful (Fruh 1930 Bd.2. p. 299). At the Biafo the Glacier/ Mountain Wind was dominant. The sand-dune patterns in the Basin of Skardu are controlled by downslope winds off the northern slope of



a) Frequency of winds. I/IOth inch equivalent to one reading.



b) Relations of speed of winds . I/IOth inch is IOft per second.

Fig. 6.4. Wind speed and frequency roses for Biafo-Braldu Station in November 1961 and January 1962. Bearings are magnetic.

the Deosai Mountains. Possibly, the long, narrow, low-gradient valleys of the Upper Indus dissipate the energy of the upvalley winds of daytime. Also, direct convective exchange between warm, dry valley-bottom air and immediate higher slopes of deep gorges can weaken the general up-valley flow.

The humidity of the two main winds at the Biafo was generally low, often less than 30% R.H. The valley wind had a slightly higher R. H., but the difference was small, and the well-known production of haze and cloud banks by this wind quite rare. The situation seems to be comparable with that of the "Sequin" wind of the Midi Valley, Provence (see Godefroy 1948 p.332). In the Karakoram, the effect on the winds of moving through dessicated valleys is intensified by the fact that imported air must at some stage form descending winds to reach these valleys. While the relations of humidity between the two winds at Biafo-Braldu over-rides the diurnal variation in humidity which favours the glacier wind, it is the greater spread of R.H. readings into high values, rather than an absence of low humidities which gives the valley wind a higher average.

In some of the ablation valleys along the middle reaches of the Biafo there was occasionally some movement of finer particles by the winds, while, in the deep Dumurdo Valley the mountain wind removed fines and moulded small sand-dunes. However, the main geomorphic effect of the valley wind systems, is to intensify the aridity of lower valley slopes.

6.7. Humidity.

The Biafo records indicate the dryness but also the large day-to-day and month-to-month fluctuations of vapour pressure and associated relative humidity. Monthly averages for the station were, November 42.32% R.H., December 63.7%, January 43.53% and February 42.6% (Fig. 6.5.). The average diurnal variations in Relative Humidity show lowest values occurring between 11.00 hrs and 17.00 hrs. Throughout most of the period of record, changes of 50% to 60% between 3-hourly readings were quite common. In

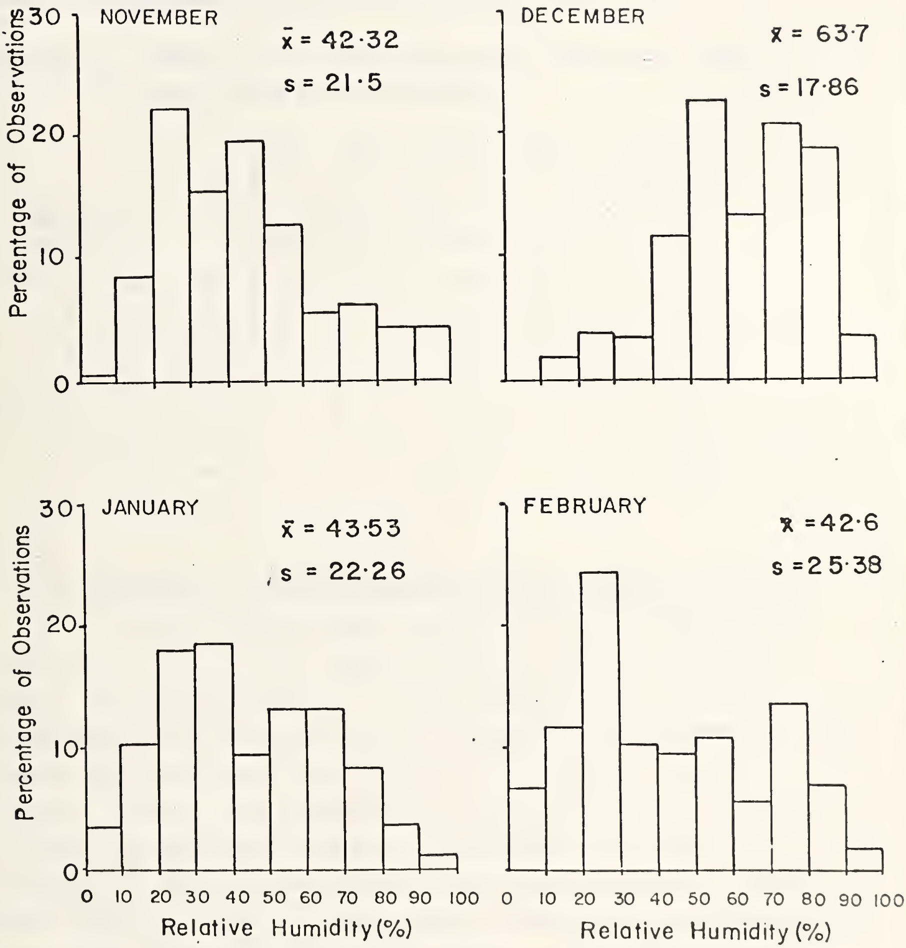


Fig.6.5. Histograms showing the frequency distributions of all Relative Humidity readings at Biafo-Braldu Station from November to February. Observations at 3-hourly intervals but not at 23.00hrs or 02.00hrs. The mean monthly value($\bar{x}$) and standard deviation (s) are given.

terms of certain weathering phenomena of the sub-nival zone (7.6.), attention is also drawn to the many readings of what would be exceptionally low readings for most areas (Table 6.3.).

TABLE 6.3. Number of R. H. observations for values less than or equal to 30% at Biafo-Braldu.

	Nov.	Dec.	Jan.	Feb.	March 27 - April 9th.
Total No Readings	164	154	144	130	69
R. H. 30% or less	56	7	46	52	28
R. H. 25% or less	40	6	33	40	25
R. H. 20% or less	20	4	19	24	19
R. H. 15% or less	11	0	12	16	15
R. H. 10% or less	4	o	5	10	14
R. H. 5% or less	3	o	0	3	11
R. H. 1% or less	3	o	o	2	7

6.8. Comparison of Biafo-Braldu Record with Permanent Stations.

Permanent meteorological stations were operational during the winter 1961-62 at the towns of Leh, Dras, Skardu, Gilgit and Misgar (Upper Hunza Valley). It was intended that by detailed comparison of daily reports, their relation to the Biafo-Braldu station and some idea of the 'normality' of the year could be defined. However, the relevant data in the Daily Weather Reports of India and Pakistan are erratic in occurrence and patchy in coverage. A detailed examination did not seem warranted. However, some figures are given for departures of temperature and precipitation from normal (Tables 6.5 and 6.6.). Analyses of daily reports of temperature departures are tabulated first (Table 6.5.). The results suggest a somewhat cooler November and December, while the first three months of 1962 were generally warmer than average. January and March show a tendency to greater extremes of temperature which one associates with fewer or thinner clouds, and reduced snow

covers of shorter duration. While there is generally no large departure of temperatures from normal, they do fit in with the picture given by the precipitation figures.

TABLE 6.5. Analysis of the departure of temperatures from normal at Gilgit and Leh for the period November to March 1961-62. (A.D. signifies average departure for all readings. E.D. is extreme departures recorded).

	November		December		January		February		March	
	Tx	Tn	Tx	Tn	Tx	Tn	Tx	Tn	Tx	Tn
LEH.										
A.D.	-3.3	-0.5	-3.1	-4.2	1.4	-0.4	2.6	0.3	2.7	-1.6
E.D.-	-6.0	-5.0	-5.0	-7.0	-6.0	-5.0	-1.0	-6.0	-3.0	-7.0
E.D.+	none	3.0	none	none	14.0	7.0	5.0	4.0	4.0	4.0
GILGIT										
A.D.	-	-	-	-	2.7	-1.6	4.5	2.0	0.2	1.0
E.D.-	-	-	-	-	-2.0	-6.0	-1.0	-3.0	-6.0	-4.0
E.D.+	-	-	-	-	32.0	5.0	10.0	9.0	12.0	5.0

TABLE 6.6. Departure of precipitation from the normal seasonal amount up to the date shown, for the Upper Indus and some stations in North-West Pakistan, and Kashmir. (Stations with Westerly precipitation source).

Date	Leh	Dras	Srinagar	Peshawar	Rawalpindi	Sialkot
Nov. 28th	-2	-	32	33	41	24
Dec. 5th	-	-27	-	-	-	-
31st	-	-	12	5	-12	39
Jan. 26th	-8	-82	-61	(deficit)	(deficit)	(deficit)
Feb. 6th	-8	-112	-	-	-	-
28th	-3	-	-87	-23	-73	-
Mar. 29th	-6	-130	-64	-3	-7	-1

The information from Leh and Dras show the period to have been one of considerable dryness compared with the average. That for the stations to the south of the region indicate a precipitation deficit over most of the area affected by the Westerly Disturbances. This driness may be expected to inhibit moisture-dependent geomorphic processes.

CHAPTER 7

WEATHERING FEATURES AND PROCESSES

Up to altitudes of 15,ooo ft. on north-facing slopes, and 17,5oo ft. on south-facing, there was abundant evidence of in situ break-up and rotting of rock. Features included crumbling, scabrous and pitted surfaces, streams of fragments pouring down from outcrops, severely rotted boulders, and chemical staining. Such features were found close to the Biafo Glacier throughout the ablation zone. Angular break-down along the primary rock divisions was also common everywhere, but became predominant above 15,ooo ft. In this chapter, the visible weathering forms, and composition of weathered materials will be described, and an assessment made of those weathering processes and associated environmental characteristics which emerge as important. Most of the detailed evidence necessarily comes from the sub-nival zone.

7.1. The Superficial Forms of Weathering

Evidence of rock weathering may be found in the colour, surface texture and small-scale relief of rock outcrops, and in the disintegration products immediately derived from them. The variety of surface weathering features assists both in typifying the landscape, and discovering the weathering processes at work. In this respect the Karakoram was favourable in having a range of well-defined superficial weathering features up to the snow-line.

7.1.i. Colour

The main discoloration and staining of rock throughout the area visited was of a reddish type, ranging from pale orange to dark mauve. This was particularly strong below 15,ooo ft., but could be identified to outcrops up to 20,ooo ft. Below about 11,ooo ft. there were extensive patches of dark-brown to almost black veneer of the "desert varnish" type. Occasional large patches of bright yellow and pale green staining were seen. Locally, rocks were covered with white crystal efflorescences or grey crusts of precipitated material.

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7.1.ii. Micro-Textures

This refers to superficial weathering patterns that have a relief generally less than an inch. A great variety of these textures was found throughout the sub -nival zone of the Karakoram. There is no established terminology and the forms observed are given provisional terms and definitions here:-

a) Loose, granular surface: a rough, crumbling surface breaking down to individual crystals of the rock, which could be removed by gentle scratching (Plate 7.1). It was localised on small outcrops and boulders, which, in all cases were below 14,ooo ft. on southerly slopes or the valley floor. Although this texture occurred on a variety of rock-types, all the well-developed examples were on marble outcrops and boulders. Streams of granular waste ran down from these (see 9.7.ii). The break-down in the marbles was nearly perfect 'granular disintegration ,"...mechanical weathering...into component crystal units...without chemical decay..."(American Geol.Inst.,1960). Only the faintest corrosion of the released crystals could be found.

b) Flaking: lifting from the surface of thin flakes of rock,usually less than 1/30th inch thick (Plate 7.2),seen mainly on fine-grained, schistose rocks below 14.ooo ft. generally parallel to the foliation. There were examples of flaking at an angle to the lamination of the rock.

c) Blistering and Scaling: small blisters consisting of thin films of rock, usually less than 1/30th inch thick. When these crack and fall away, thin irregular scales remain weakly attached to the rock surface. These were observed in localities below 14.ooo ft. where gneissic and some intrusive rocks had been polished smooth by earlier fluvial or glacial action (Plate 7.3). When the scales fell away, a rough grainy surfaces was left beneath.(see ed.Matsushita and Huzita, 1965 Fig.4 opp.p.89 , for examples on the Upper Gilgit River.)

d) Folia-etching: finely etched lines in the surface following cleavage planes in schistose rocks, generally found as high as 17.ooo ft. The lines of weakness were generally identifiable as mica-rich planes in the rocks (Plate 7.4).

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e) Fine differential weathering: well-defined differential etching out of narrow bands of rock, observed up to 17.000 ft. but mainly below 14.000 ft. in schists with swarms of small intrusives or in banded gneisses (Plate 7.5, and Note 7.1).

f) Precipitated crusts and efflorescences: common throughout the sub-nival zone below 15.000 ft and generally concentrated along particular bands of rock, or fissures, or in pits and cavities under overhangs at the base of outcrops (Plates 7.6 and 7.7). There were fine films of precipitates on rocks in most situations.

g) Rock Meal: this term, first used by Griffith Taylor for weathered material in the McMurdo Sound area, refers to a rotted, porous outer layer of rock invaded by precipitated salts (see Wellman and Wilson 1965 p.1097). In the Karakoram, most large outcrops and many large boulders up to 14.000 ft. had areas of rock meal. Commonly it occurred in niches and cavities, under overhangs and at the base of cliffs. The material would fall away at gentle pressure from the hand. Many of the examples consisted of two or more pastry-like layers of rock meal parallel to the sub-aerial surface and independent of structure (Plate 7.9). The original pattern of the metamorphics was preserved but cohesion derived from the precipitates.

7.1.iii Micro Relief

This refers to distinct but minor relief forms related to weathering and varying in scale from a few inches to several yards.

a) Minor exfoliation: spalling of thin sheets of rock, - one inch to two feet thick - parallel to the sub-aerial surface, and independent of structural lines (see Wilhelmy 1958 p.80). Common throughout the sub-nival zone below 17.000 ft., particularly on relatively fresh cliffs near to the glacier (Plates 7.10 and 7.11).

b) Spheroidal spalling: the spalling of curved shells of rock from small outcrops and boulders, also called "onion weathering"(see Chapman and Greenfield 1949 p.408), observed on a few boulders on southerly slopes, composed of marble(Plate 7.12).

c) Niches, cavities and tafoni: features classed under"cavernous weathering", where holes and sharp overhangs develop in outcrops (see Bryan 1928; Segerstrom and Henriquez 1964). The smaller

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niches, - one to twelve inches diameter - were often deeper than the height of their entrance, many opening out inside (Plate 7.13 and 7.14). The larger cavities and tafoni included some large holes but most were concave overhangs at a break of slope (Plate 7.15). Inner surfaces were encrusted with precipitates and rock meal, and were different from limestone lapies or "pits" described, say, by Bakker (Bakker 1960). That characteristic also distinguishes the features from relict pot-holes. There were few regularly developed niches in the form of "honeycomb" weathering. The features were not seen above 15,000 ft. but occurred on both northerly and southerly rock walls and boulder faces below that altitude. In the Indus valley between Skardu and Leh, the Workmans described, "... boulders...strewn about all levels, honeycombed in the most remarkable way, some being mere shells eroded inside and out..." (1905 p.254). They ascribed them to river action "...thousands of feet above the present rivers...", but they were probably weathering cavities as with similar features described in the Eastern Karakoram and Kun Lun (see Trinkler 1930c p.514).

Some tafoni-like gaps at the base of cliffs were over 50 ft. high with rock meal 18 inches thick lining them. One example in the Dumurdo Valley at 12,500 ft. stretched along the base of a high cliff for 150 yds, rock-meal lining the basal concavity to a height of 100 ft. (c.f. Wilhelmy 1958 p.157). A trough ran along the base of the cliff similar to that at the base of certain inselbergs.

d) Warping: where particular strata show curling over or distortion not present in the original structures. This was seen where the sub-aerial surface had been cut transverse to bedded planes in banded gneisses (Plate 7.16).

e) "Woolsacks": convex surfaces of small outcrops or boulders having loose, granular texture. These were frequently encountered on southerly slopes below about 14,000 ft. primarily in the marbles.

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f) Angular break-down: break-down and removal of rock following primary divisions such as bedding planes and joint systems. While present at all altitudes it was the dominant weathering relief between 14,ooo and 18.ooo ft.(Plate 7.17). At these levels occurred some areas of shattered cliff, but the well-known angular, autochthonous debris of mountain tops was uncommon (see Dahl 1955). A few small block fields were found on flattened spurs and crest-lines between 15.ooo and 17.ooo ft. notably above Baintha Camp.

In addition to these strict weathering features, there was major exfoliation or sheet structure (see Jahns 1943) exhibited by the Biafo Granodiorite. Spacing of the exfoliation cracks here varied from several tens of feet to as much as two thousand feet in the Baintha Brakk area and Biafo West Wall (see 8.4.i).

7.2 The General State of Rock Walls

Since the Biafo Basin alone has tens of square miles of rock wall, the general state of these assumes considerable significance revealing the role of primary rock divisions in the initial breakdown of exposed rock walls(c.f. 7.9). Little has been written on this by geomorphologists, but descriptive frameworks are available in the literature on rock mechanics. An initial classificatory framework was developed from Coates (1964), Burton (1965) and Muller (1960) whose ideas fitted fairly well with the field observations. An unresolved question in the available frameworks is that of scale. Every rock body is discontinuous if the scale chosen is large enough. Since the question cannot be answered with generality here, scales are adopted to fit the Karakoram situation. In the field blocks in excess of 15ft^3 were uncommon in mass movements, and certainly less than 5 per cent of talus material, avalanche debris and the like exceeded 6ft^3. These values suggest provisional scales to describe gross homogeneity, and tie in with Coates' continuity dimension of 6 ft.(Table 7.1).

TABLE 7.1. Terminology and provisional scales for description of the density and disposition of primary divisions in rock outcrops. (Modified after Coates, Burton and Muller).

Class	Characteristics	Scale
GROSS HOMOGENEITY		
1. Homogeneous	Massive, single rock type, bed or pluton	> 15 ft^3
2. Heterogeneous	Several layered/intercalated rock-types	< 15 ft^3
CONTINUITY OF ROCK FORMATION		
1. Intact	No planes of weakness with spacing	≤ 6 ft
2. Tabular	One group of weakness planes with spacing	≤ 6 ft
3. Columnar	Two groups of weakness planes " "	≤ 6 ft
4. Blocky	Three groups of weakness planes spaced	3 ins-6 ft
5. Seamy	Many irregularly disposed fissures spaced	3 ins-6 ft
6. Crushed or Granular	Passes through three inch mesh seive	< 3 ins

7.2.i. <u>Rock Walls in the Biafo Area</u>

In the metamorphics of the Lower Biafo and Braldu Valley four main planes of weakness were normally identified. For example, rock walls west of the Lower Biafo had the following well-defined planes of weakness:-

System	Orientation of Dip	Dip Angle	Spacing
Bedding Planes	70° (Magnetic)	54° 30'	6 ins - 2 ft 6 ins
Joint System I	10°	60° 10'	3 ft - 8 ft
Joint System 2	20°	85° 50'	8 ft -10 ft
Joint System 3	0°	0.0 - 5.0°	15 ft -20 ft

There were other irregular fractures while intrusive sills and dykes followed planes of weakness defined by the primary devisions (Plate 7.17). Although there were many local variants, these systems and their spacing were representative of the picture in most of the area. This is reflected in the predominantly <u>tabular</u> character of

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rock wall geometry in the metamorphics. The intrusives, however tended to break up more clearly into blocky or columnar masses. Minor exfoliation tended to produce tabular break down in units 1 inch to 2 feet thick. The fullest expression of the three or more joint systems was usually confined to corners or buttresses where the diverging rock-walls met at sharp angles.

In places, presumably where mass-movement was less active relative to weathering, finely laminated metamorphics broke into angular pieces small enough to be in the granular category. The same was true for some of the small intrusions. In general, the intrusive units were compact and the metamorphic ones platy. Here, as in the larger units, the primary divisions accord well with the forms of coarse fragments found in talus material (see 9.6.).

In the peripheral grandiorites and some of the acid agmatite areas of the Middle Biafo two well-defined vertical joint systems were found giving rise to columnar units. Joint spacing was generally more than 3 ft. The outermost parts of the agmatite zone had three or more steeply dipping joint systems oriented to produce coarse, blocky units of rhomboidal form but low angle joints were widely spaced, as reflected in the pronounced development of "needles" and "spires"(see 8.3.i.).

The central granodiorite zone was dominated by homogeneous and intact rock. The principal primary divisions were spaced at many hundreds and even thousands of feet apart being mainly sheet structures and near vertical joints. Superficial exfoliation was found in places producing a tabular appearance.

Most of the present chapter will concentrate on the detailed processes of weathering. When general slope geometry is considered in the next chapter it will be the major landscape units which will be emphasised. It is therefore important to stress that, at scales between one, and one hundred feet or more, the geometry of most solid rock landscape features reflects very closely the primary divisions in the rocks. Since solid rock composes most of the exposed landscape this has major significance, though perhaps a common-place of

the 'alpine' landscape. It reflects the fact that, at this scale, the great relief energy, detailed weathering process, and mass-movements emphasise rather than over-ride structural controls. This is a point not brought out in the geomorphological literature, perhaps because it deals primarily with more subdued mountains, or ones where the legacy of glaciation appears dominant.

7.3 Physical and Chemical Characteristics of Weathered Specimens

To assess the weathering situation especially in process terms the detailed composition of weathered materials needs examination as well as the morphology of weathered surfaces. Information on specimens gathered in the area will be given here.

7.3.i. The B.R. Locality and Samples

In keeping with the main theme of the study evidence was needed of weathering clearly related to contemporary conditions. This requirement was satisfied by a large rock salient near the Biafo snout ("The Nose"). In maps from 1861 and 1899 the salient is shown as being under the glacier. In 1962 evidence of weathering was quite marked over most of the salient, though it had not destroyed all glacial and fluvio-glacial polish and striations. The latter were not found anywhere in the adjacent areas beyond the level of recent glacier fluctuations. While the weathering found on "The Nose" may represent several hundred years' work if the glacial engulfing was less complete than the maps show, it still seems reasonable to attribute it to contemporary rather than past conditions. Certainly, processes observed on the immediately adjacent areas of ice-contact were inimical to the preservation of material in so advanced a state of weathering as that on the salient. All specimens gathered were either scraped gently with a wooden spatula or pulled away with the fingers.

7.3.ii. The Samples from Localities A.G.,WATS,P.N.,C.,F.R.,and LASK

The choice of letters was for mnemonic purposes and has no particular significance otherwise. These localities were in the sub-nival zone in various situations, and include materials from

certain special features such as tafoni. For purposes of comparison with the B.R. samples some specimens were chosen as having the appearance of the most advanced in situ weathering. The samples A.G., and WATS come from chutes at 16,ooo - 17,5oo ft. on Shinlep Bluk (18,1oo ft.); those marked P.N. from a large tafoni in Dumurdo Valley and the remainder from slopes between 11,ooo and 14,ooo ft.

7.3.iii. Analysis of Finely-divided Materials

Materials thoroughly weathered to fine sand and powder were sent to the Physical-Geographical Laboratory of the University of Amsterdam where Prof. J.P. Bakker kindly had them analysed. A number of the analyses requested proved impractical (e.g. X-ray diffraction of clay minerals, and aluminum content counts) mainly because the material was, in detail, far less weathered than its crumbled appearance suggested. The analyses performed were mechanical analysis, heavy mineral counts, and determination of water soluble salts present.

Mechanical analyses are presented here in tabular form (Table 7.2). Despite the finely-divided nature of the in situ weathering, the clay fraction is extremely small. This contrasts with many of the talus samples (Chapter 9). Those few talus samples with similar size distributions and the small clay fraction were clearly related to present-day waste streaming from outcrops, as opposed to that mixed with old slope deposits.

Heavy mineral counts were requested as a basis for indicating degree of weathering through the presence or absence of minerals of differing susceptibilities to chemical weathering (Table 7.3). The heavy mineral fraction of the sand was obtained after pre-treatment with hydrochloric and nitric acid using a field count of one hundred grains. The results indicate that large quantitities of mafic minerals highly susceptible to chemical decay still remain in the fine-grained residues.

Water soluble salts content was requested because of the obvious presence of precipitated salts in the samples (Table 7.4).

TABLE 7.2. Mechanical Analyses of in situ weathered rock from the Biafo-Braldu area. (analysed by Physical-Geog. Lab. Amsterdam).

Grain-size % less than 2 mm.
(after pre-treatment with H_2O and HCL.

Sample Number	1.7-1.2 mm	1.2-0.85 mm	850-600 μ	600-420 μ	420-300 μ	300-210 μ	210-150 μ	150-105 μ	105-75 μ	75-50 μ	50-32 μ	32-16 μ	16-8 μ	8-4 μ	4-2 μ	< 2 μ		Humus %	$CaCO_3$ %
BR - 2	0,5	1,5	3,0	4,5	8,0	13,5	15,0	14,5	11,0	6,0	8,5	5,0	3,5	0,7	1,0	4,0		0,1	6,3
- 3	4,5	4,0	4,0	5,0	6,5	8,5	10,0	13,0	10,0	8,0	10,0	6,5	4,5	1,0	1,0	3,0		0,7	24,4
- 4	5,5	4,0	5,0	5,5	8,0	9,0	9,0	10,5	8,0	7,5	10,0	6,0	3,0	4,5	1,5	3,5		0,1	17,1
- 10	7,5	5,5	12,0	11,5	11,5	10,0	7,5	7,0	3,5	3,0	3,0	1,5	3,0	0,0	5,5	7,5		0,7	74,2
- 11	16,5	11,0	12,0	11,5	11,0	8,5	6,5	6,0	4,0	3,0	2,5	2,0	1,0	0,7	0,0	4,0		0,9	2,0
- 14	23,5	21,0	17,5	14,0	8,5	5,5	3,0	2,0	1,0	1,0	0,3	0,7	0,6	0,0	0,1	1,0		1,3	
- 16	13,5	7,5	9,5	13,0	14,0	12,5	8,5	6,0	3,0	2,0	0,0	3,5	3,5	1,0	0,4	2,5		0,5	
- 18	21,0	12,5	12,5	11,5	10,5	9,0	6,5	5,5	3,0	2,0	0,0	2,0	2,0	0,0	0,4	2,0		0,7	
- 21	4,0	4,5	8,5	13,0	16,5	14,5	11,0	10,5	5,5	4,0	4,0	1,5	1,0	0,0	0,2	1,0		0,3	
- 23	22,0	18,0	16,0	13,5	9,0	6,5	3,5	3,5	2,0	1,5	0,0	2,0	1,0	0,1	0,0	1,5		0,8	
A.G. - 2	6,5	5,5	8,5	10,5	12,0	12,0	11,0	10,5	6,0	5,0	4,5	3,0	2,0	0,9	0,3	2,0		0,5	
- 3	31,5	7,0	16,0	15,0	13,0	8,0	4,0	2,0	0,7	0,3	0,0	0,5	0,0	0,5	0,0	1,5		0,3	
P.N - 2	15,5	8,5	7,0	7,5	9,5	14,0	14,0	10,5	5,5	2,5	0,7	0,8	0,6	0,0	0,2	2,5		0,0	1,3

[illegible]

TABLE 7.3. Heavy mineral content of the in situ weathered rock on the Biafo-Braldu area.

MINERALOGICAL ANALYSIS

	Opaque	Alterite	Zircon	Tourmaline	Corundum	Spinel	Rutile	Anatase	Brookite	Titanite	Monazite	Barite	Staurolite	Topaz	Garnet	Kyanite	Sillimanite	Andalusite	Pistacite	Clinozoisite	Zoisite	Hornblende	Tremolite	Augite	Diopside	Muscovite	Biotite
BR - 2		1	2							9					3	1			1	2	2	37	32	3	8		
3	2		3							3					4	2						73	9	3	3		
4										5					2							89		4			
10										2												1	96	1			
11										8					1							89		2			
13				1						25				25	3							4	12	5	25		
14										1					1						2	20	4	20	52		
16																										90	10
18														1	4				1		1	2					91
21										2												95		2	1		
23										37				2						6	13	36			6		
AG - 2	3									2			1		4						2	89		1	1		
3															1							9	90				
PN - 2										2					3							20		40	35		

Field count, 100 grains

Pretreated with hydrochloric acid and nitric acid.

but is quite intact elsewhere. A section cut through the specimen shows a 1/16 inch outer rim of iron stained, slightly crumbly dark material. However, the garnet cluster is fractured and iron-stained throughout. The ferric oxide suffuses from the garnets along the

[illegible]

TABLE 7.4. Water soluble salts from in situ weathered rock in the Biafo-Braldu area.

Electric conductivity and composition of the filtered extract of 20 g. soil (< 2mm) shaken during 3 hours with 200 ml. of distilled water

K. Hewitt	E.C.x 10^3 (milli mhos	Na^+ mg / 11	K^+ mg / 11	Ca^{++} mg / 11	$SO4^=$ mg / 11
BR - 2	0,189	1,0	2,3	32,7	44,4
3	0,106	0,5	2,0	n.d.	0,0
4	0,143	0,0	1,3	32,7	36,2
10	0,291	1,0	2,7	75,4	100,4
11	1,885	3,0	2,0	686,2	1434,9
13	2,228	19,0	1,0	755,6	1698,3
14	0,211	0,0	0,0	32,6	78,2
16	0,197	1,0	1,7	49,0	84,7
18	0,193	0,5	1,2	32,6	78,2
21	2,195	4,7	7,7	686,2	1576,5
23	0,201	1,3	1,7	49,0	88,9
PN- 2	1,028	1,0	5,0	265,4	613,8
AG- 2	0,054	1,0	2,2	0,0	21,4
3	0,025	0,5	3,5	n.d.	0,0

The reactions for chloride and phosphate were negative.

but is quite intact elsewhere. A section cut through the specimen shows a 1/16 inch outer rim of iron stained, slightly crumbly dark material. However, the garnet cluster is fractured and iron-stained throughout. The ferric oxide suffuses from the garnets along the

The generally very high content of salts is evident and these are largely derived from the reprecipitated material in the specimens. The dominant component of the precipitates is gypsum,$CASO_4$.

7.3.iv. Analyses of Intact Rock

It might be expected that the severe rotting observed at the surface would give way to decreasing decay inwards, and that an examination of such might give insight into the development of the weathering. With this in mind a series of thin sections were prepared, cut from the intact rock immediately adjacent to completely crumbled surface material and where possible including any visible weathering 'aureole'. These were then given to a mineralogist who was asked to identify the minerals and look for any phases, alteration products, recrystallisation, or fracturing which might be attributed to sub-aerial weathering. Description of the visible weathering features in the hand specimens are this writer's. The thin section analyses given in quotation marks are taken direct from the notes of the mineralogist (Dr.Richard James, p.com.).

A. B.R.5. - "The major phases ...are hornblende, clinopyroxene, sphene, quartz, plagioclase felspar, ...minor amounts of perthitic alkali felspar and calcite... In the second section ... large garnets are present."

The original specimen consists mainly of fine-grained, dark gneissic material with a small quartz vein and cluster of large almandine garnets. The sub-aerial surface is iron stained, the staining being strongest around the garnets. The outer garnet crystals are fractured and break away easily. Irregular flakes and fine rods break away from the dark material when rubbed gently with the fingers. Where the quartz vein is iron stained it crumbles but is quite intact elsewhere. A section cut through the specimen shows a 1/16 inch outer rim of iron stained, slightly crumbly dark material. However, the garnet cluster is fractured and iron-stained throughout. The ferric oxide suffuses from the garnets along the

quartz vein, into the core of the specimen.

"(In the first thin-section) All the minerals are fresh and exhibit no evidence of chemical alteration. Quartz-felspar intergrowths are occasionally cracked in an irregular fashion; this may represent abrasion when the section was cut...(in the second section)...very slight alteration to chlorite is present in a few (garnet) crystals. Also, intergrowths of hornblende and pyroxene are common; the pyroxene appears to be altering to a combination of hornblende and chlorite. The alteration is very limited...".

B. B.R.7. - "The minerals present are pyroxene (augite), hornblende (green pleochroism), scapolite,calcite, zoisite, plagioclase felspar, iron oxide,minor red-brown biotite. The biotite and iron oxide are commonly closely associated. Plagioclase is often rimmed with halos of scapolite."

The hand specimen has the appearance of banded gneiss, but is platy and elongated at right angles to the bedding. This appeared to be a minor exfoliation structure at the sample site. The sub-aerial suface is stained red-brown,and spalls easily along a crack 1/8-1/16th inch in from the surface. This crack is lined with fine, yellow-orange dust. The flakes breaking away can be rubbed to a fine sand-sized residue with the fingers. Several other closed cracks pass into the specimen parallel to the sub-aerial surface, and have strong iron staining on their walls. There are distinct small patches of ferric iron staining throughout the body of the rock. A section cut through the specimen reveals numerous small cavities rimmed with iron oxide, occasionally with some easily powdered crystal wreckage remaining.

"(In thin-section) Pyroxene appears to be altering to hornblende and/or chlorite in a few instances...Hornblende slightly altered to chlorite along fractures...In general the rock exhibits a fresh appearance in thin-section."

C. B.R.22. - "A hornblende-scapolite-gneiss... (consisting of) bands of silicate minerals and bands of marble with minor silicates..."

A thin platy hand specimen consisting of three bands of gneissic rock which came apart along the bedding planes when collected. This was from any area showing <u>warping</u> of strata. The surface is faintly stained, but strong, red-brown staining occurs in a network of small pits covering it. The surface of the white (marble) band has a granular texture and the coarse crystals fall away at slight pressure from the fingers. In section there are a few tiny pockets of ferric iron staining, of which, the most conspicuous sets are aligned along the bedding. Iron staining occurs all along the bedding interfaces where the specimen split up. (For thin-sectioning, the original specimen was sealed together with resin.)

"(In thin section)...None of the minerals exhibit any evidence of alteration to secondary minerals."

D. B.R.17. - "Minerals present are quartz, plagioclase and alkali felspar, biotite, hornblende, muscovite, iron oxide."

A platy hand specimen of dark gneissic rock. The surface is iron stained, and small pieces could be flaked off with the finger nail.Some ferric iron staining suffused the whole of the rock, with concentrated rims of iron oxide in pores.

"(In thin-section)...Biotite and hornblende exhibit slight alteration to chlorite along their crystal boundaries...."

E. C.3.- "The major mineralic phases are hornblende, clinopyroxene, sphene, and scapolite; in lesser quantity plagioclase felspar, alkali felspar, calcite, apatite and almandine garnet... and very small amounts of deep-brown biotite... in thin-section the rock is foliated..."

A platy specimen whose principal fracture occurs at right angles to the bedding and parallel to the sub-aerial surface. A closed crack in the specimen has the same orientation. There are

three distinct bands of rock, but the crystals are intergrown at the edge of each band and no splitting along the bedding is apparent. The subaerial surface is stained dark brown and reddish brown. It is smooth with a suggestion of "desert varnish". A section through the rock reveals a distinct outer weathered layer of discolored rock which crumbled slightly during cutting. Material from this layer can be crumbled to fine sand in the hand. The inner fissure walls have some calcareous precipitate and dark red-brown stains on them. There is a suggestion of ferric iron staining through the rock but particularly in the whitish bands. About ¼ inch in from the surface is a band of small pores lined with ferric oxide and some have the wreckage of garnet crystals in them.

> "(In thin-section).... i) Hornblende altered slightly along fractures to a greenish-brown phase which is probably chlorite. ii) Pyroxene...in a few instances was noticed... to be altering to hornblende. This is probably due to a metamorphic process rather than a low temperature chemical weathering process. iii) Biotite shows evidence of break-down to form iron oxide which probably represents a high temperature reaction...... No cataclastic structures suggesting physical break-up...were observed..."

F. F.2. - "... a garnetiferous biotite-muscovite-schist. The minerals present are biotite, muscovite, plagioclase, quartz, garnet, sphene, and iron oxide. The major mafic mineral is biotite; it varies from colourless to red-brown in thin section and is commonly associated with iron oxide. "

The hand specimen is a thin slab of dark schist separated along the bedding planes from surrounding bands. Its surface shines with mica "scales", and is stained reddish-brown. A section cut through the rock shows it to be iron stained throughout but with oxidation most strongly concentrated in the outer 1/16 inch and along fine fissures. The latter consist of an irregular suite of cracks sub-parallel to the schistosity,

and ramifying through the whole specimen. The outer layers appear more porous and show some slight warping unrelated to folding. Some pores and tiny pits at the surface have calcareous material precipitated in them. Crumbling flakes fall from the surface at slight pressure from the fingers. Rubbing in the fingers reduces these to a fine-and medium-sand material.

"(In thin-section)... the minerals show no evidence of chemical weathering..."

G. R.1. - "... a muscovite schist...the minerals present are muscovite, quartz, felspar, garnet, sphene and iron oxide. Biotite is also present as a very minor phase and is closely associated with iron oxide..."

The hand specimen shows a complexly foliated rock with 1/8 - 1/4 inch garnet crystals. The subaerial surface bristles with flaking, deeply iron stained mica crystals. This is an outer weathered layer 1/8 - 1/4 inch which crumbles readily in the hand. Beside the irregular release fracture are small cavities coated with ferric oxide and containing garnet crystal wreckage. In addition, a distinctly brownish weathered zone occurs 1/2 - 1 inch into the intact rock, advancing in tongues along certain foliation lines. There are some small pores lined with ferric oxide in this zone.

"(In thin-section)...none of the phases exhibit any evidence of chemical alteration...(In another thin section)...along irregular fractures in some large garnet crystals a reddish-brown phase is common (but) it does not appear to be a product of chemical weathering..."

H. WATS I and 2 - "The tremolitic amphibole is the major mineral phase with tremolite, diopside and minor amounts of biotite and iron oxide."

Composed of fibrous, radiating crystal masses. The surface of the hand specimen has some iron staining and white calcareous

precipitate in pits. The subaerial surface is friable and can be rubbed to fine sand with the finger to a depth of 1/4 inch. A fracture passing through the specimen had walls stained dark brown and revealed small, stained cavities with crystal wreckage in them. No visual evidence of weathering could be detected in the section cut through the specimen. (N.B. This sample is from 17.5oo ft.).

> "The diopsidic pyroxene shows very minor alteration along its crystal boundaries, possibly to chlorite."

I. LASK.1. - "... a marble; it consists entirely of calcite..."

The hand specimen is a flake of rock released by spheroidal weathering of a small boulder on a southerly slope at 13,ooo ft. (Plate 7.12). There was a very slight amount of iron staining.

> "No hydrous phases are present. No evidence...of mechanical breakage...due to weathering. The grains of calcite are intergrown forming a typical metamorphic fabric...re-crystallisation of such a sample due to chemical weathering should form a porous structure..."

7.3.v. Solutes in Surface Waters

Since most of the precipitation of the sub-nival zone occurs in winter as snow, - and is also lost fairly quickly, even before air temperatures rise far above freezing - it is important to know whether snowmelt at low temperatures has much chemical effect (c.f.Williams 1949). On two occasions in winter 1962, when snow was melting at air temperatures below freezing samples of the melt were collected. The site was a south-facing rock wall sloping at 45^{o}(Plate 7.18) and the water was sampled as near to the snow-patch source as possible. Temperatures were taken of the snowmelt at various points and are interesting in themselves (Table 7.5).

Table 7.5 Temperatures of snowmelt running over rocks, and the points at which it was sampled, winter,1962.

Position	Jan.11th (11.30 a.m.)	(Sample)	Feb.12th (11.30 a.m.)	(Sample)
Snowpatch	32.0°F		32.1°F	
Meltwater pool beside snowpatch	32.3°	(B.R.I.)	33.4°	(B.R.28)
Meltwater,13 inches below snowpatch	33.0°		36.5°	
Meltwater, 4 feet below snowpatch	33.2°	(B.R.Ia)	49.1°	
Air Temperature	21.0°		29.3°	

Notes . Readings in water with shaded thermometer. Mean of five values in each case. January observations after 1½ hours direct sunlight,February after 2 hours direct sunlight with intermittent cloud.

It is of considerable significance that local snowmelt can be 20° warmer than the air temperature even in February. However, snowmelt samples were deliberately taken at the lower temperatures, and close to the snow patches owing to the high evaporation which would artificially increase the relative solutes content.(i.e. The increase between B.R.1 and B.R.1a probably reflects this more than increasing dissolution).

In addition, samples were taken from two "sweetwater" streams, one at the western end of Choblok (W.7.), and the other from a stream in the same geological sequence on the opposite, north-facing wall of Mt.Ganch(W.8.). A sample of the Biafo melt-water (O.W.4) was also brought home for analysis (Table 7.6).

[illegible]

[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

[illegible]

[illegible]

Table 7.6 Tests for dissolved solids in water from the Biafo-Braldu area. (Analysis kindly performed at the Physical-Geographical Laboratory, University of Amsterdam).

Sample	Dissolved Solids (p.p.m.)				Conductivity mhos.cm^3
	Chloride as Cl	Sodium as Na	Calcium as Ca	Potassium as K.	
B.R.I. (snowmelt)	-	2	73	3	407
B.R.Ia "	-	3	128	5	659
B.R.28 "	-	24	56	11	464
O.W.4 (glacier-melt)	0.6	5	18	6	159
W.7. (stream)	0.4	15	52	12	397
W.8 "	-	3	52	3	288

7.3.vi. Clay Minerals in Superficial Deposits

It was significant but disappointing that insufficient clay material was present in *in situ* weathered products to permit identification of the minerals. Sufficient amounts of clay were, however, extracted from some superficial materials to allow X-Ray diffraction analysis. Since most clay-size material in a regolith derived from igneous and metamorphic terrain should reflect weathering action, the analyses are given here and some comments on their possible relation to weathering conditions. Analyses were performed on the Department of Geology, King's College diffractometer with kind permission of Dr. Hall. Analyses of pro-glacial lake sediment clay are added for comparison (Table 7.7).

Table 7.7. Percentage clay fraction and clay mineral content in order of importance for superficial materials in the Biafo area (Note 7.1)..

Source		Clay Fraction (<0.002mm)	Clay Minerals
Taluvial Apron (see 9.6.ii)			
	E.4.	6.0 percent	Illite
	T.4.	5.5 "	Illite + tr montmorillonite
Fine Waste Apron (see 9.7.iii)			
	T.M.2.	4.0 "	Illite +? (strong peak at 6A^{o}) + tr kaolinite
Granular Disintegration			
Stream (9.7.ii.)			
	LASK.2.	2.0 "	Illite + kaolinite + tr Dolomite
Slope wash from mudflow area (9.8.iii.)	S.I.	2.0 "	Dolomite + Illite
Mudflow deposits (9.8.iii)			
	T.3.	10.0 "	Illite +? (strong peak at 6A^{o})
	F.3.	11.0	Illite + tr kaolinite + tr Dolomite
Earthpyramids (9.9.)			
	T.1.	22.0	Illite
	T.M.1	14.0	Illite = tr dolomite
	T.M.4.	12.0	Illite + dolomite + tr Quartz + tr kaolinite
Pro-glacial Sediments			
(12.8)	O.W.1	48.0	Illite + tr kaolinite
	O.W.2	14.0	Illite + tr kaolinite
		12.0	Illite + tr kaolinite

In all cases illite appears as the dominant clay mineral.(Dolomite is not a clay mineral in the strict sense.) Minor amounts of kaolinite occur in many cases, and a little montmorillonite in one case. It will be argued later that much of this clay material derives from earlier superficial deposits, possible dating back into the Pleinstocene (9.9.). The data, however, does not indicate any clear variation between the earth pyramid deposits which are old, and the material being mixed with contemporary weathered material, or between these and the contemporary pro-glacial deposits. This could mean that contemporary weathering does not produce clay minerals differing significantly from those of the past, or that it has not modified those developed under earlier conditions, or both. Undoubtedly a little clay is being produced at the moment, while weathering to clays is likely to proceed more rapidly in regolith materials since these are already disaggregated. Modification of illite to, say, montmorillonite or the reverse; or production of kaolinite, could conceivably occur with changes of climate here. Such changes cannot be inferred from the available information. This being the case, it is difficult to be sure of the relations of these clays to the contemporary weathering environment. Some points of interpretation will be raised here rather than in the subsequent sections which concentrate on contemporary circumstances.

Firstly, the role of rock-type should not be overlooked. It is a relatively short step geochemically from muscovite to illite. The rocks of the area are rich in muscovite, and fragmental mica is a major constituent of material analysed and in stream waters. Illite may therefore represent a relatively low grade of weathering to clay material which would occur under a more-or-less wide range of climate.

Secondly, it is possible that, in different ways, both the glacial and the sub-nival environments of the region are favourable to the production of similar clay minerals. Illite is the most common constituent of glacial deposits in many areas, often with some kaolinite and minor montmorillonite (Grim 1953 p.355). The sub-aerial environments

most favourable to the production stability of illite are believed to be those with fairly arid conditions, alkaline soils where Ca, Mg, K and Fe ions are present, and where, in particular, there is free potash (K) available and little tendency for it to be leached away. Poor vegetation is favourable since it reduces the demands for K as a plant food. Similar conditions, of course, favour montmorillonite except the need for available potash. Keller also suggests that alternate wetting and drying will be more favourable to illite in assisting the fixing of K ions (Keller 1957 p.66). Thus, with the climatic conditions and the evidence of fairly abundant K ions in snow-melt and stream water (Table 7.6), it seems the sub-aerial environment is favourable to illite formation in the Karakoram. If illite is fairly stable in the contemporary environment and also forming at the present time, we are unlikely to be able to differentiate ancient (pro-glacial) sediments from those forming under present conditions on the basis of clay mineral composition. Finally, it is not necessarily the case that the general relation of climate of glacial and pro-glacial environments has changed drastically since the Pleistocene as opposed to their relative extent. With the high altitude, great relief and valley wind systems it is not unlikely that glacier flanks even with much higher ice levels had microclimates approaching the aridity of the present-day. The accumulation of clay in pro-glacial areas then, as now, may have been a function of preferential deposition rather than much higher rate of clay production than at present (c.f. 9.9.; 12.5; 15.3 and Appendix 8).

It should be apparent, therefore, that while these arguments point up some important questions needing investigation, a lack of information on clay minerals clearly forming at present makes it difficult to use the clay mineral analyses as indicators of the contemporary weathering conditions.

7.4. The Problem of Process.

While there are some well-established physical and geochemical principles, and a few laboratory experiments which apply directly to weathering, for the most part processes must be inferred from the kinds of circumstantial evidence given above. Discussions by geomorphologists are largely based on general description of end products and environmental characteristics, with a tendency to formulate explanation by opposing physical and chemical weathering types. Unfortunately many of the significant manifestations of weathering are at a microscopic or ultra-microscopic level. This is, perhaps, the major reason why modern detailed research points increasingly to the greater importance of chemical weathering, and limits the certainty with which clearly physical or chemical processes can be identified. Logically, the distinction between chemical reactions and mechanical failure is fairly clear; but in terms of the processes affecting rocks exposed to the atmosphere it is much less obvious. The two activities are as likely to reinforce, as to exclude one another, and nowhere is it likely that one of them is entirely absent. This emerges strongly in the Karakoram situation.

7.5. Chemical Weathering Processes.

In terms of the normal diagnostic characteristics of chemical weathering to be found in the field, the following points may be made concerning the Biafo area:-

a) Marked discoloration occurred on rock surfaces, fissure walls and in the outer layer of most rocks inspected in the sub-nival zone. Most of the staining was by ferric oxides. Some of the dark brown and black "varnish" found, almost certainly indicates oxidation of manganese.

b) Crystal efflorences and crusts on surfaces and in the outer layers of friable rock, while immediately due to evaporation of moisture, must record prior solution weathering. Normally, the initial liberation of these solutes involves hydrolysis and/or carbonation of elements in the primary rocks or their local derivatives.

c) Many situations where strata were warped, and the examples of spalling, blistering, flaking and some minor exfoliation point to permanent volume increase through chemical reaction. Hydration and oxidation are the most likely processes to explain these features.

d) While less certain, the thorough rotting of crystallines to a fine-grained state with a suggestion of clay present would normally be attributed to chemical action.

In sum, microscopic field evidence points to effective chemical weathering in the sub-nival zone, - certainly more clearly than in the mountains of N.W. Europe. The descriptions of the appearance of hand specimens given above; and the abundant solutes in snow-melt and small streams, further reinforce the idea of vigorous chemical weathering. The large outcrops of marbles and other metamorphics rich in mafic minerals susceptible to chemical action, should assist.

Unlike the field of evidence, laboratory analysis, while revealing some chemical decay definitely makes it seem less significant. In relation to chemical action the laboratory evidence shows:-

a) All of the thoroughly rotted in situ specimens consisted almost entirely of fine and medium sand size particles. Clay sized material was often absent and rarely present in quantities greater than three per cent.

b) In the same fraible materials, heavy mineral residues contain abundant quantities of those minerals usually least resistant to chemical attack (i.e. the mafic minerals such as augite, diopside, biotite, hornblende and sphene.)

c) The sand-size fragments have a fresh appearance, the fracture surfaces when cleaned showing only minor, or no detectable corrosion. Even granular products of nearly pure calcite show negligible surface corrosion.

d) Minerals in intact rock, even adjacent to throroughly rotted material showed only minor, or ambiguous evidence of chemical decay when examined in the thin section. No clear cataclastic features were found.

At first glance it would seem the macro evidence points to chemical, the micro to physical weathering. However, this apparent conflict of evidence is partly resolved by not thinking in terms of rigid opposition of physical and chemical break- down. Also the erosional context must be considered, not simply a weathering climax. First, it will be argued, however, that the apparently more "scientific" laboratory evidence may not be more reliable in all respects than the field observations.

With respect to the thin-section analyses two points need consideration. Firstly, standard thin-sectioning is not a very sensitive technique. It is used primarily to study sound, intact rock. In the process of cutting, decomposed material tends to be abraded away, and fracturing of the minerals may be initiated or exaggerated. Several of the thin sections have small gaps in them, jagged edges and fractures possibly due to cutting, but may have developed from initial cataclastic features. Secondly, it is well-established that even high grade metamorphics have micro- and ultra-micropores which are the first lines of advance of chemical decay between individual crystals (see Grigor'ev 1965 p.145). But such decay at the crystal boundaries is initially on so minute a scale that it need not be identified with a normal petrological microscope, and is certainly difficult to distinguish from usual optical interference patterns at crystal boundaries. Obviously, these points are even more relevant to low power microscopic examination of grains for superficial corrosive features.

The fact that there are abundant mafic minerals in thoroughly rotted rock cannot be gainsaid. It will be argued, however, that the apparently minor chemical decay which could be missed by thin-section analysis should be sufficient to allow other weathering

and mass-movement processes to commence or accelerate, whose rate of action in this environment is far more rapid than the most vigorous chemical decay. However, the unequivocal evidence that chemical decay is taking place will first be stated.

Despite the thin-section dat there is undeniable evidence even in the intact rocks from which sections were cut, that chemical decay has occurred. The evidence is the presence of iron staining. Ferric oxide is virtually insoluble under subaerial conditions. It is therefore only mobile in water if in suspension, a process that cannot be invoked for the pore-spaces within intact rock. It could be argued that the iron was introduced into the rocks as soluble ferrous iron. However, since that requires the movement of moisture through the pore spaces, and later aeration at those points with no other chemical effect, the argument is hard to justify. The introduction and oxidation of the iron will itself have a disruptive effect. There is also clear evidence of replacement of rock material by iron oxide.in the crystal cavities rimmed with iron and containing only a little crystal wreckage. The concentration of ferric iron around iron rich minerals such as almandine garnets reflects in situ oxidation. The macroscopic evidence leaves no doubt that the ferric iron is a weathering product, and the limitations of thin-sectioning would explain failure to identify it microscopically.

The significance of vigorous oxidation must be seen in context. In semi-desert areas a superficial skin of chemical weathering,- mainly oxidised iron, "desert varnish" and salts - may form in a very short time, perhaps in a matter of months. Oxidation of iron tends to be more complete in alkaline environments associated with high evaporation (see Krauskopf 1967 p.249). But, in any environment, for chemical weathering to penetrate deeply; for it to transform the materials in individual crystals within the rock; and above all, for it to begin to produce clay

minerals in appreciable amounts, is a very slow process measured in thousands rather than hundreds of years. Most of this advanced decay is unlikely to occur before the rock is already well broken up by minor weathering along joints and crystal boundaries. It follows, therefore, that advanced chemical decay in situ requires very slow removal of subaerial materials.

In relation to the Karakoram it is pertinent to ask whether the degree of in situ decay is a realistic measure of the ultimate effectiveness of chemical weathering, in this environment: whether, assessing weathering in terms of an essentially time-dependent clay-rich climax, is appropriate? Nearly all of the specimens were, of necessity, collected from outcrops where slope angles exceeded 30°. Many of the cliff exposures were steeper than 60° (see 8.2). As the declivities suggest, these are very active mass-movement situations, and those few low-angle areas not subject to stream or glacial action show too active a build-up of sediments for soils to form by progressive weathering. All this implies that in situ superficial rock does not long remain so, and, in particular, that a relatively low order of weathering is sufficient to release the material for entrainment processes. In relation to the very extensive rock-wall areas showing break-up and release along primary rock divisions, and to the widespread though more localised finely-divided weathering, these arguments are relevant. There are, however, some differences with respect to weathering in these two cases. Clearly, quite minor decay along joints and micaceous bedding planes in high-angle cliffs can release blocks for mass-movements. The gravitational stresses to which the rocks are subject greatly reduce the weathering required. One would not look here for advanced chemical decay. Erosional situation serves to obviate the need for well-developed in situ decay. Thorough rotting to granular state is another matter.

The fact of insufficient time for advanced decay should clearly apply to the recently exposed rock areas of the B.R.

locality. However, the B.R. specimens do not differ significantly in mafic mineral content, or thin section properties from those samples taken in areas not glaciated for thousands of years. This should be the case with rapid removal as much as when advanced chemical decay is prohibited by the hydro-thermal environment. The problem is to decide how thorough breakdown can occur so rapidly and without appreciable decay. The answer is the presence of a most effective weathering process in nearly all of the cases of thorough rotting; a process which, while in "physical" in its impact depends initially on chemical action. The process is generally called "salt-weathering", and will be dealt with in the next section. It is introduced here as a process capable of accentuating minor chemical weathering, and rapidly fragmenting rocks at the crystal level. In erosional terms, salt weathering , by its high rate of action in superficial rock produces fine grained material which can be quickly removed by entrainment processes before chemical action can proceed very far. However, some chemical weathering is required to supply salts and possibly to open micro-pores where preferential recrystalisation can commence. It is, of course, likely that salt weathering acts partly as a direct suppression mechanism within chemical weathering. The rich matrix of salts in porous superficial rock must retard chemical action in the rock minerals. The salts are generally hygroscopic , will easily tend to saturate available water with solutes and concentrate any ion exchange on themselves at the expense of the rock crystals. However, this would seem to be a secondary factor compared the importance of rapid release of fine material.

In relation to solution weathering, the high concentrations of dissolved solids in snow melt are of interest (7.3.v) . They are consistently higher in total than the glacier and stream waters, and the records of dissolved solids on the Upper Indus and its

tributaries (WAPDA, West Pakistan p.com.). The values are also several times higher than those quoted by Williams (1949). But we cannot invoke the effect of accumulation of carbon dioxide in snow patches over many days or weeks as he does. The Karakoram samples were from snow which remained on the rocks only 24 hours. The rarified atmosphere may also inhibit the build-up of $C.O._2$ in the snow. However, while the Karakoram results demonstrate the large amount of solution which is possible at low temperatures, they do not necessarily invalidate William's thesis that the greatest results would occur under the deepest snow having the longest period on the ground. He was dealing with a high precipitation, acid soil environment. The Karakoram examples come from a semi-arid, alkaline environment. While the snow-melt was on intact rock without regolith, precipitated solutes were present in pores and over the rock. The solution was not wholly and probably not mainly, of native rock but included easily dissolved precipitates over the surface. The fact that nearly all snow-melt not removed by the writer evaporated, implies this. It also helps to explain the extremely large difference between sub-nival snow melt solution, and dissolved solid concentration in run-off. At the same time there is considerable potential for solution by low temperature snow-melt.

To conclude, it seems there are two equally valid explanations of the combination of rapid superficial chemical weathering with relatively low level of decay: one climatic, that chemical decay is retarded by water starvation; the other on the basis that the rates of removal of superficial material are too rapid to allow advanced decay. On the available evidence, since the latter is a major factor, it is not possible to decide whether the environment is ultimately one in which chemical weathering would be poorly developed. Certainly, the level of chemical decay which is achieved, in relation to other weathering and erosional processes, is sufficient for it to play an important role in releasing rock material in this environment.

7.6. Salt Weathering.

Reiche (1950, p.12) noted weathering by salts recrystallising in rock pores as a minor process of arid and semi-arid environments (also, Leopold et.al. 1964 p.113). However, there is mounting evidence that the process has been underestimated. In addition to many dry tropical and sub-tropical areas, its occurrence has been described in the Antarctic (Taylor 1922; Kelly and Zumberge, 1961; Nichols, 1965), and South Island New Zealand (Wellman and Wilson 1965), in the Swiss Alps (Brückner 1966), and in many coastal locations (Bartrum 1936, Cotton 1942 p.10). The writer has seen numerous minor instances on exposed knolls of the Lewisian Gneiss of Sutherland. In parts of the Antarctic, salt weathering is described as the dominant agent of rock decay (Wellman and Wilson op.cit). In an early paper, Merril described the effectiveness and rapidity of the process in rotting building stone (Merril 1900).

The chief diagnostic characteristics of salt weathering are the present of "rock-meal" (see 7.I.ii) cavernous weathering, and often minimal or no clay fraction despite an advanced stage of break-down of rock. The conditions necessary for the occurrence of salt weathering are "... a supply of salts, sites protected from wind and rain in which salts can accumulate and cyclic changes in humidity and/or air temperature that include the crystallistion of at least one of the salts present..." (Wellman and Wilson op.cit. p.1097). The stresses set up by crystallisation must exceed the mechanical strength of the rock. An important factor is also the size distribution of pores in the rock, especially as it promotes preferential crystallisation where larger crystals grow at the expense of the smaller ones. Thus salt weathering tends to be selective in terms of micro-climate, hydrology, and to a lesser extent, rock type.

All of the diagnostic features are, as we have seen, abundantly present in the sub-nival zone of the Karakoram. Climate, topography and rock structures are favourable. In most of the sub-nival zone potential evaporation greatly exceeds precipitation, and there is a net upward migration of moisture towards the ground surface.

The ubiquitous patches of precipitates on rocks and cut-banks indicate that it is an area of salt accumulation. Leaching of weathered material produced very large quantities of Ca^{++}, $SO4^{=}$, Na^{+}, and K^{+}. Seasonal and spatial variations in climate assist the cyclic renewal of the process. In winter, local soil and ground moisture is renewed, and the conditions contrast strongly with the high temperatures, intense solar radiation and low humidities of summer. This allows the local alternation of solution and recrystallisation that promotes salt weathering. At the same time, the steep slopes link lower arid to upper humid areas with consequent throwing out of seepage moisture and dissolved solids in the drier areas at a faster rate than is suggested by the local precipitation. This is important for steep rock walls where local moisture supply is negligible. The varied rock types thrown into sharp folds lead to selective migration of ground water, and its reappearance at particular horizons where evaporation and salt accumulation are concentrated. This intensifies salt accumulation in those porous rocks most susceptible to its weathering effect.

The effects of semi-aridity and steep slopes are further enhanced by the many bare outcrops and large, barren boulders. The flanks of these, and especially cavities in them, tend to have markedly arid micro-climates (see Troll 1958 tr. p. 24). Moisture falling on low angle portions of outcrops and boulders seeps down through the rock and reappears at lower levels carrying solutes (see Merril op.cit. and Bryan 1928). The arid micro-climates of the cliffs and cavities aid evaporation and recrystallisation of salts. The cavernous weathering itself further enhances the process. Undoubtedly, the drying valley wind systems are an important factor in promoting the process on northerly as well as southerly slopes (see 6.6; and Schweinfurth 1956).

The localities where salt weathering was most evident were the bases of cliffs, particular strata truncated by an erosional cliff, and the flanks of small outcrops or boulders. Some bands of cavernous

weathered strata or superficial rock-meal ran vertically up the face of cliffs. In such cases localised reappearance of moisture was a key factor, in turn controlled by topography and structure. However, while rock-meal and cavities were prevalent in particular rock horizons, they showed no detailed relation to structure within these. Once in existence the cavities appeared to have grown with little regard to structural detail. In the cases inspected, well-defined holes or cavities occurred in moderately coarse-grained rocks; thoroughly rotted (rock-meal) surfaces without cavities occurred in fine-grained metamorphics with marked foliation. The large tafoni at the base of cliffs showed no regard for local structure or crystal grain size, except for quartz-rich intrusive bands which resisted salt weathering. No rock-meal or cavernous weathering was observed in coarse grained intrusives or the metamorphosed limestones. The granular disintegration of the marbles may be due in part to salt weathering (c.f. Kelly and Zumberge 1961), but no sure evidence of this was identified. The highest altitudes at which the process was found were 16.ooo ft. on southerly and 14.ooo ft. on northerly slopes. Thoroughly rotted, rock-meal surfaces were only found below 14.ooo ft. It should be stressed however that such obvious morphological evidence need not represent the only areas where salt weathering occurs. Environmental conditions should promote the process in some degree at all levels at least to the snow line. Rock walls even in humid areas can have dry microclimates, and solution by snowmelt takes place at sub-zero air temperatures if there is intense insolation. It is quite likely that minor salt weathering is a prime factor in the rarity of striated and polished surfaces throughout the zone of Pleistocene and recent deglaciation, this being particularly true of the drier southerly slopes. Since advanced salt weathering is structurally controlled to an important degree, its minor development over large cliff areas, though important in sum, would be less striking compared with break-up and release

along primary rock divisions.

The interrelations of chemical and salt weathering were stressed in the previous section. There it was suggested that salt weathering may act much faster to reduce rock to a fine-grained state than chemical decay. For the B.R. rock-meal samples with their relatively fresh mineral grains and high mafic mineral content most of the advanced break-up seemed due to salt accumulation. The process would, on the evidence of intact samples, have been preceded by, as well as accompanied by oxidation of iron and manganese, and some solution weathering in the adjacent rock body. This linked set of processes, is evidently capable in certain strata of producing thorough break-down of rock to powdery and fine-grained material and to depths of 1-3 inches, in a time span certainly not exceeding 500 years (c.f. Hewitt 1964), and possibly less than 100 years (see 7.3.i). In relation to mass movement this rapid breakdown may be more significant than its relatively localised nature suggests, being concentrated at the base of cliffs, or attacking relatively immobile boulders resting on low-angle slopes. In Dumurdo Valley there were several moderately large rock falls whose release could be traced to undermining by salt weathering and tafoni formation.

7.7. Frost Weathering.

7.7.1. General Remarks.

Most of the literature gives precedence to frost weathering over all other forms in high altitude, and middle to high latitude mountains (e.g. Pearsall 1950 p.26; Longwell and Flint 1962 p.118; Dury 1959 p.6; Strahler 1965 p.254). However, frost action in hard rock is little understood and rarely observed. Break-up of rock could take two main forms: freezing and consequent large volume expansion of water held in fissures - "frost wedging"; or steady migration of films of moisture to centres of freezing in porous rocks, the growing ice crystals fracturing the rock - "frost bursting." Undoubtedly, stresses large enough to fracture most crustal rock material can occur with either process (see Grawe 1936; Wiman 1964; and also, McDowall, 1960 on microscopic frost weathering of clays).

Unfortunately, both require sets of conditions of which only temperatures is clearly favourable in many mountain areas. Thus, frost wedging of all but the softest rocks requires that once frozen at the surface the water shall not escape; freezing shall penetrate the fissure despite the high insulation property of ice, and at a rate exceeding the tendency of the ice to relieve high stresses by flowage. There is also some doubt as to whether wedging could begin until other processes have partially opened fissures. A serious problem with frost bursting of bare rock, except in wet areas, is the combination of superficial aridity and the extremely shallow penetration of atmospheric temperatures normally involved. Successful laboratory experiments employ stones partially immersed in water, and the break-up is mainly of superficial grains (see Tricart 1956; Wiman, op.cit.). These objections are raised not to suggest frost weathering cannot take place in high mountains, or that it is unimportant. Rather, it is necessary to question the normal assumption that frost weathering is the over-riding process when other processes are clearly present, and, in fact, should help to make frost action more effective than it can be when acting alone.

7.7.ii. The Temperature Environment Relevant to Freeze-Thaw.

Elsewhere, the writer has dealt in some detail with the available evidence on freeze-thaw cycles and related features of the Upper Indus Region (Appendix 9). Diurnal freeze-thaw cycles were very conspicuous at the Biafo-Braldu Meteorological Station. Seventy-five were measured at screen level, and the shape of the seasonal temperature curve indicated about one hundred as the annual number (Flohn, p.com.). There were approximately two months with screen temperatures below freezing (Fig. 6.3). Indications were that fluctuations were more frequent and larger at ground level than the standard shade temperatures indicated.

By using published temperature records it was possible to construct a diagram of the temperature movement for the region according to altitude and season (Fig. 5.4). The results suggest that almost all altitudes in the Biafo Basin should experience some

freeze-thaw activity, though aspect will restrict this in space. Interestingly, there is a continuous zone of frequent freeze-thaw from early April to the end of October at about 15.000 ft. Dr. E. S. Williams' observations in the Lukpe Lawo area of the Biafo in August 1956, show large temperature ranges and frequent frost shifts at between 17.000 and 21.000 ft. even above the snow-line (p.com.). Thus, with certain restrictions due to aspect and exposure nearly all altitudes have frequent and large frost shifts in several months of the year. In the zone 8,000 - 18,000 ft. frost cycles may dominate the temperature environment for four to seven months.

7.7.iii. Frost Weathering in the Biafo-Braldu Area.

In the Central Karakorum, the main observations which might be used to build up the case for frost weathering were:-

a) Ice-filled fissures and holes, found mainly on northerly slopes where moisture was issuing from the rock.
b) Open-textured growth of ice crystals in some narrow rock fissures on both north and south facing cliffs.
c) Films and crystals of ice adhering to blocks in a fresh rock fall.
d) High intensities of rock-falls during periods of pronounced freeze-thaw (9.2.ii).
e) Snow-melt water seeping into fissures on sunlit slopes where the shade temperatures remained well below freezing point.
f) Small ice-crystals dispersed through the "rock-meal" of a large tafoni.
g) Poorly developed needle-ice in fine-grained talus material.
h) Concentration of shattered cliffs between 14.000 and 18.000 ft.

At the same time, the outstanding impressions of the winter of 1961-62 was of a general lack of frost-growth in the sub-nival zone. Here, the superficial aridity of late autumn and poor snowfall of the winter were important factors. In relation to points c) and d), it was not possible to decide whether their significance

related more to melting and lubrication than to frost triggering (see. 9.2.ii and iii).

On the traditional interpretation of angular shatting, the concentration of cliffs with severely broken surfaces between 14.000 and 18.000 ft. would seem to be good evidence of frost action. The belt of maximum precipitation probably lies somewhere in this zone (see. 5.3.ii), while it is subject to large numbers of frost cycles. There was some chemical weathering in the form of oxidation stains and (hydration?) warping throughout the zone, but the autocthonous, shattered debris was in no way distinguished from that normally attributed to frost shattering. In several of the sites where the writer tried to monitor frost action in the winter, some ice was found. It consisted of small crystals in narrow fissures and films of ice. The crystals were mainly oriented across the fissure from wall to wall, which could be very significant in terms of wedging. However, they were not seen in sufficient quantities to be likely to move a block not already free, and no certain evidence of movement or significant pressure build-up during nocturnal freezing were found. However, the methods of monitoring were not very shophisticated and would not take into account the possibilities that critical stresses for frost bursting are "rare" geomorphic events, or that they require many months of slow build-up (Note 7.2).

The traditional idea of frost-wedging resulting from the large volume increase of water filling a fissure may be too narrow or even wrong, in view of the many physical problems involved. Fewer difficulties surround the idea of directed ice-crystal growth from damp fissure walls, due to the enormous pressures of crystal growth, the steady migration of moisture from the rock to the centres of freezing, and the continual penetration of cold by "Balch Ventilation" into the frost zone and below the level of superficial aridity. But to monitor such a process one would need extremely sophisticated equipment. Even for this process, the actual observations in the Karakoram indicate severe restrictions

due to unreliable water supply. It is quite likely that if frost shattering is important it achieves much of its work in relatively short periods of time when moisture and temperature conditions coincide favourably; and perhaps only in certain years.

One of the important reasons for undertaking winter field-work was to be present during the period of ice days and intense freeze-thaw below the snowline. The frost shattering case suffers from lack of direct evidence. However, even in winter unambiguous evidence for the process was not obtained in the Karakoram, and if the dryness explains this, there are still the "frost-shattered" cliffs and angular talus to be considered. The unsatisfactory field evidence leads one to reconsider the logic of the frost-shattering case. Dahl noted the common, circular reasoning that "mountain-top detritus" means frost-shattering, means "mountain-top detritus" (Dahl 1955 p.1514). Also, this writer has seen few examples of autochthonous shattered debris in mountains which did not show some, albeit minor, chemical decay. But the greatest weakness of the frost-shattering case is the, often automatic, assumption that it is the only explanation of the relatively fresh, angular debris of the mountains. Break-down of this type can be equally well explained by mechanical failure of uncovered rock along primary divisions, a process which is accelerated by the addition of water or ice (see 7.8). Not only could much of the actual "weathering" attributed to frost action be more plausibly explained by primary mechanical failure; but also this should make the possibility of frost action much greater as an ancillary process causing micro-bursting along primary divisions, and macro-wedging of blocks only held together by friction. The provisional conclusion of this investigation is that frost action in the area is just part of a complex of processes including primary mechanical failure, secondary mechanical failure of rock exposed in steep cliffs with lubricated primary divisions, minor chemical weathering, insolation effects, and snow and avalanche loading. All of these, given the

high relief environment and rapid removal of material at an early stage of weathering, are consonant with angular break-down. Until such time as techniques exists to differentiate the relative role of each there seems no case here, or perhaps in any mountain area, for assigning precedence to frost shattering, certainly not on the basis of angular break-down products alone.

7.9. The Role of Primary Mechanical Failure in Weathering.

Traditionally, geomorphologists have considered subaerial denundation to commence with weathering, and weathering is seen to begin by exploitation of primary divisions in the rock. However, this starting point is rather arbitrary since the rocks undergo mechanical changes as they are uncovered, even without weathering. For a high relief area where much of the cliff geometry reflects structure detail, it is unlikely that primary mechanical deformation and failure, and changing stress conditions, play a merely passive role. Geomorphologists have long recognised the place of exfoliation in "weathering". The much larger role of rock dynamics in relation to weathering and mass movement is rarely recognised. While no detailed observations of rock mechanics in the Karakoram are available, this is a context in which we need to have before us the prima facie case for giving the matter weight in our interpretive framework.

Most crustal rocks, if entirely as homogeneous as small pieces of freshly quarried building stone, are capable of standing in vertical cliffs many thousands of feet high (Terzhagi 1962 p.252). However, few rocks near the earth's surface are homogeneous over radii of more than a few feet, and even fewer have near-vertical cliffs of any great extent. Discontinuities in the rocks, even in the absence of weathering, include joints and bedding planes ramifying through the rock and cohering simply by sliding and interlocking frictional resistance. Concentrations of pore spaces, inter-grain fractures, and large compositional differences add to heterogeneity. Given a lack of homogeneity the mechanical stresses which occur in crustal rocks become capable of promoting movement and failure as a

component of "weathering" even without other sub-aerial processes. The fact that most break-up does take place in the presence of water, air and sub-aerial temperature change does not diminish the importance of stress conditions. Given the latter, water and ice for example may promote break-up simply by a passive role of reducing frictional resistance along primary divisions, resulting small or large movements being directed by the stress field in the rock, or failure occurring through concentration of stress at remaining intact parts of the rock. Some of the important stress-strain features of crustal rocks which cause primary mechanical failure can be listed.

a) Rock that has been compressed within the crust and subjected to tectonic stresses, contains varying amounts of conserved elastic strain energy. When erosion exposes new rock there is both immediate elastic rebound, and time-dependent "relaxation" involving inter-grain shifts until mechanical equilibrium is restored and/or failure occurs. These decompressioneffects have a much larger role in primary mechanical break-up than the creation of exfoliation structures which are relatively limited features. All joint systems and much minute fracturing are affected by and in many cases created by these readjustments. Fracture due to release of strain may be catastrophic in highly folded rock (see Bain, 1931).

b) Undercutting and exposure of rock walls removes the lateral support from the wedge of rock remaining, which, in effect, directs stress towards the cliff face. In particular, where the rock wall is convex in plan, horizontal tensional stresses develop (see H.R.B. 1966 pp. 11-15). Most rocks have a much smaller tensional than compressive strength, especially in the case of laminated metamorphics (see 9.2.iii).

c) Lateral tectonic stresses within a few tens of feet of the surface can be very large; several thousand pounds per square inch higher than the normal component (Obert and Duval

1967 p.475). This is likely to be a major factor in young, active orogenic regions.

d) Fold mountain areas such as the Karakoram are very active earthquake areas (see 4.4). Transmission of seismic waves through surface rocks can promote disaggregation along primary planes of weakness and cause large failures (c.f. 9.2.iii).

The fact that most of these mechanical factors become important geomorphologically when denundation exposes the rock, means that they are hardly separate in their action from weathering and other erosional processes. But this means that the role of "structure" is more than a mere passive, varying resistance to erosion. States of stress in exposed rock are positive agents in the break-up and preparation of rock for entrainment. The formal relations we can find between rock characteristics and such things as weathering texture, slope angles and accidentation, size and shape of releasedparticles, are useful guides to the role of rock in landform development. In the Biafo Basin, this emerges in the differences between the erosional topography of the grandodiorities and metamorphics, and between differing structural situations in the metamorphics (see 7.2., 8.2.iii, 8.3. and 9.2). However, when we consider processes of weathering and mass-movement, unavoidably the dynamic as well as formal role of rock is involved. With fairly rapid uncovering of new rock, and the relatively slow rate at which most weathering processes act, undoubtedly the dynamic effects of stress in the rocks can play as large a part in "weathering" as the mechanical and chemical effects of atmospherically generated processes, and will be intimately related with the latter. It is important to note that primary mechanical failure tends to produce angular, disaggregated rock materials either *in situ*, or by triggering their release from cliffs. If other forms of weathering are very slow, or removal of divided rock material rapid; and in the absence of soil and vegetation cover, angular surface debris will be a conspicuous feature of the landscape simply as a result of primary mechanical break-up. Of course, this will rarely occur without other

sub-aerial weathering, and should serve to enhance the effects of wetting and drying, freeze-thaw, insolation and gravitational creep. However, with primary break-up alone we are manifestly creating a situation closely analogous to the autochthonous mountain-top detritus to which the blanket term "frost-shattered debris" is normally applied. We have demonstrated elsewhere the difficulties of showing frost-action alone to be a sufficient condition of such detritus; now it seems possible that it is not a necessary condition either. Whether or not it is an actual condition must therefore be demonstrated rather rigorously. In the Karakoram we have a situation in which there is a clear potential for chemical and physical break-up, and the effects of primary mechanical failure are liable to be closely integrated with these processes. Nevertheless, of all the processes relevant to mountain geomorphology in every area, the field in which there is a most urgent need for research is that of the dynamic and structural role of the rock itself.

7.9. Summary and Conclusions.

In the Karakoram, the end-products of present-day in situ weathering are, by volume, mostly coarse units of moderately intact rock. Locally, there are patches and bands of thoroughly rotted material, especially in sheltered localities and in certain rock strata. However, even here it is found that the finely-divided materials consist of chemical phases little-removed from the original rock minerals. At the same time, in the sub-nival zone there is evidence of fairly vigorous chemical action, in the build-up of precipitated salts, advanced iron staining and decay of some crystals even in rocks recently exposed to sub-aerial weathering. While noting the dryness of much of the area as a retarding factor for chemical action, it was found that such moisture as is available in snow-melt has a high solution potential. No large differences in in situ weathered products were found between recently and anciently deglaciated areas.

Salt-weathering is the best-established of the "physical" weathering processes and it seems clear that this process can

thoroughly rot surface rock in a few hundred years, and possibly only a few tens of years. The other major elements of in situ break-down are believed to be freeze-thaw of moisture, and the primary mechanical responses of the rock itself. Unfortunately, neither of these processes leaves the kind of evidence in the rock that can be substantiated easily. It is suggested that separately and jointly, these processes are a key field in which research needs to be done.

As a general thesis, the intimate relation between each of the weathering processes in detail as well as in broad morphological effects is emphasised. In this particular environment, the inter-relations are made particularly sensitive by the large gravitational component, and large changes in heat and moisture environment. Spontaneous mechanical response of rock is present everywhere, and particularly significant where slopes are steep and bare. Melting of snow permitting solution weathering continually alternates with re-freezing which should promote frost action. Chemical decay along joint-faces, should assist frost-wedging; frost-bursting should assist chemical action which tends to be enhanced where the accessible surface area of the material is greater. But it is the fact of large changes in heat and moisture conditions, and high relief which gives these interactions their particular importance. Furthermore, since a little weathering is sufficient to release material for entrainment no particular process appears far advanced or predominant.

Any interpretation of the weathering features must be seen in terms of the thresholds and rates of removal by entrainment processes. In particular, the low level of chemical decay must be measured against removal, and not simply against some general idea of rate and degree of weathering towards a "climax". We have no certain measures of rates of removal in the area studied. The high sediment yield for the Upper Indus Basin need not apply uniformly through the basin (see 15.3). However, the similarities between recently and long-exposed weathered rock could be explained better by rapid removal, than by sudden slowing of weathering after initial

rapid action. Rapid removal is supported by the investigations of mass-movements (Chapters 8.9. and 10). In relation to this, it is important to ask whether, in the absence of actual measurements, the weathering on clean steep rock walls can be inferred to be slower than that of low angle areas where rock is deeply rotted? Wahrhaftig (1965 p.1176-79) recently stated this was the case in a mountain area, and it is implied in much of the writing on degree and rates of weathering in different environments. But, if this is true elsewhere, the Karakoram weathering situation tends to suggest the opposite. The degree of _in situ_ weathering is _not_ a reliable indicator of weathering effectiveness. The more efficient the entrainment of waste, the cleaner the surface and the less advanced the weathering prior to release. It seems likely that steep rock walls will release material at an earlier stage of weathering than gentle slopes, especially if the latter have a vegetation cover. A major weakness in many of our discussions of weathering is to use local end-products to infer the overall effectiveness of the weathering environment and to look upon them as directly related to climate. Climate exercises a control over all phases of erosion; through vegetation, entrainment processes and rates, as well as weathering. Change in climate affects weathering directly, but may have even larger indirect effects by modifying entrainment and other constraints. Furthermore, available relief is a major factor in the impact of a given climate and in determining the level of weathering required to release rock debris. In these terms, a tendency to interpret the angularity and low level of chemical weathering in many Karakoram weathered materials, as simply a reflection of a predominantly "physical" weathering environment might be entirely in error. Relief, lack of vegetation and rapid removal are probably more important in inhibiting advanced chemical decay than is climate.

CHAPTER 8

SLOPES AND MASS-MOVEMENT I: GENERAL SLOPE GEOMETRY AND FEATURES

8.1. Introduction.

In this chapter an analysis of slope geometry in the Biafo area is presented and the relations of slope angles to certain factors. The slope features of the areas shown in the morphological maps are described giving a preliminary areal picture of processes and features to be dealt with individually in the subsequent two chapters.

The term "slope" is taken to embrace the parts of the sub-aerial landscape descending to permanent drainage lines and on which linear drainage occurs rarely or not at all. This is not an entirely satisfactory definition as will be seen when we deal with chutes. However, terminology has proved difficult in this whole field. Difficulties stem from peculiarities of the region, and confusion in the vocabulary required for the unambiguous classification of field features. The confusion results from a proliferation of local terms for similar features and preference for genetic terms even when the underlying controls are little understood. Meanwhile, when terms seem well-defined, the Karakoram examples are often somewhat different from their obvious counterparts. A case in point is the "stone-stripe" features (9.7.). Again, the terminology for slope geometry, perhaps the best organised in the whole field, raises some problems. The useful Categories of Slope devised in Britain for instance, are unhelpful where more than seventy per cent of the slope area should be classed as "cliff" (see Curtis et.al. 1962).

As a basis for description, terms found in a sample of the relevant literature were rationalised according to certain formal and compositional factors. Where the features described in the text fit existing definitions an appropriate source is cited. Otherwise terms are defined as they arise (see Appendix 2).

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While every effort is made to distinguish actual observations from interpretive statements, it has been necessary to include both within individual sections to avoid repetition. A general synthesis in terms of major controls is suggested in the conclusion.

8.2. General Slope Geometry.

Apart from small areas of river and kame terrace, very steep slopes occur throughout the area. Much of the slope area lies at angles steeper than those normally quoted in the literature (see Savigear 1956; Leopold et.al. 1964 p.365). Hence, to give a perspective on conditions as compared with other regions, it is important to obtain some measure of slope geometry. This can only be done along cruder lines than those recently pioneered in geomorphology. Field conditions prohibited a representative programme of slope measurement, and the writer's data are restricted to local features. Cartographic material has to be used, but, while good by Himalayan standards, is not reliable for detailed slope information. Of course, this is a situation for which the explanatory models are equally crude.

8.3. Techniques of Cartographic Analysis.

The nature of the terrain reduces both the accuracy of mapping, and the adequacy of sampling procedures for map data. In terms of the information on the maps:-

a) Accuracy tends to decrease with increasing slope angle, at least above 40^{o}. This is inherent in the drafting of maps on the scales available for this area - two inches to the mile on the originals of the Shipton Survey.

b) Positional accuracy can decrease with altitude, above 15,ooo ft. mainly owing to difficulties of surveying.

In terms of the sampling of slope angles from the maps:-

c) Very steep angles cannot be shown by contours.

Profiles must be measured between spot heights and/or lower-angle segments. Often these are not present and the sample point must be passed over. Inflections in those steep slopes which are measured will be missed, and the steepest angles continually lost.

d) Since maps represent projected areas, each unit of the true landscape does not have an equal chance of being sampled. The chances decrease with increasing steepness, given a range of slope angles. This problem only becomes acute with large areas of slope over 45°, when samples tend to be biased towards lower slopes compared to the real landscape.

e) It follows that, if the lower angle slopes are concentrated on a particular rock type or at particular altitudes, these will figure disproportionately in the sample.

Were the available maps more detailed in the steepest areas some form of stratified sampling might be warranted. In the event one can only bear the points in mind when assessing the results. The actual measurements were made on the draughtsman's originals of the 1939 Survey.

8.3. i. Slope Angles in Rock.

Firstly a set of slope orthogonals was obtained for slopes free of snow and ice. The measurements were taken from contour separations where no break of slope was shown. Selection was guided by a sampling mesh, but the ramifying glacier areas and impossibility of measuring many steep cliffs precluded rigid adherence to mesh sampling. The adjacent glacier basins were used as well as the Biafo to give sufficient measurements. Solid rock and talus slopes are included (Appendix 3). To obtain a general picture, these measurements are first tabulated according

Altitude Range (ft.)	Aspect	Slop3 Angle Class in Degrees 15-17.9	18-20.9	21-23.9	24-26.9	27-29.9	30-32.9	33-35.9	36-38.9	39-41.9	42-44.9	45-47.9	48-50.9	51-53.9	54-56.9	57-59.9	60-62.9	63-65.9	66-68.9	69-71.9	72-74.9	75-77.9	78-80.9
24.990	N																						
24.000	S																						
23.990	N																		1			1	
23.000	S													1		1							
22.990	N																1		2			1	
22.000	S											1	1	1		1							
21.990	N																1	1	2			1	
21.000	S											1	1	1	1	1				1			
20.990	N														1		1	1	3			2	
20.000	S											1	1	1	2	2			1	1			
19.990	N												1		1			1	4			2	
19.000	S									2		3	1	4	2	2	2	1	3	1			
18.990	N											2	2		2	1		1	5			1	
18.000	S								2	2	1	4		6	4		3	2	3	1			
17.990	N							1	1			2	4	2	5	1	1	2	5		1	1	
17.000	S							3	3	5	2	9	1	7	6		3	2	4	1			
16.990	N				1		1	1	3	1		4	4	4	7		2	2	1	1	1		
16.000	S			2	2		1	4	4	8	1	9	1	5	6		3		2				
15.990	N		1		2	1	4		5	2	1	5	5	2	6		2	2	1	1	1		1
15.000	S			2	4		2	1	6	5	1	6		2	2								
14.990	N		1		1	2	5		4	1		4	1	1	3		1	1					1
14.000	S		2		3		1		6	2		2		1	2								
13.990	N	1				2	2		4			1		1	2		1	1					
13.000	S		2		1				3						2			1					
12.990	N				1	1			2					1	2			1					
12.000	S				1	2							1					1					
11.990	N								2									1					
11.000	S					2							1										
10.990	N								2														
10.000	S					2						1	1										
	N	1	2	-	4	6	12	2	23	4	1	18	17	11	29	2	10	14	24	2	3	9	2
	S	-	4	6	9	6	4	8	24	24	5	37	9	29	27	12	11	7	13	5	-	-	-
	SUM	1	6	6	13	12	16	10	47	28	6	55	26	40	56	14	21	21	37	7	3	9	2

Table - 8.1. Frequency Count of the Angles of slope orthogonals for Rock Slopes in the Biafo-Hispar Glacial Area.

to aspect, and altitude (Table 8.1.). Several broad features are brought out by the Table:-

a) Although lower angle slopes should have a greater chance of selection, angles in excess of 36° predominate. Thus, the great relief energy of the area is graphically demonstrated.

b) The incidence of lower angle slopes increases progressively with decreasing altitude down to 13,ooo ft. This is not accompanied by a disappearance of the highest values at least down to 14,ooo ft. there being an increasing <u>spread</u> of angles with decreasing altitude. However, the relative decrease of high angles, implies that mean slope angle decreases with decreasing altitude. This is most marked below the snow-line and especially, below 17,ooo ft. where talus slopes become important.

c) Southerly slopes spread further into lower angles than equivalent northerly ones. Furthermore, this is most strongly defined at higher altitudes. A general asymmetry of the mountain masses is implied, and since it is primarily a north versus south slope phenomenon, seems to reflect mainly the influence of insolation.

d) There is a suggestion that the lowest angles have their highest incidence between 12,ooo ft. and 15,ooo ft. and that slopes again become steeper lower down. Some measurements made for the fluvial Hispar and Hunza valleys down to 7,ooo ft. support this conclusion, and record the most recent, powerful downcutting along the Indus drainage. The predominance of samples between 14,ooo ft. and 18,ooo ft. is explained to a large extent by the points made in the preliminary discussion (8.3. d and e).

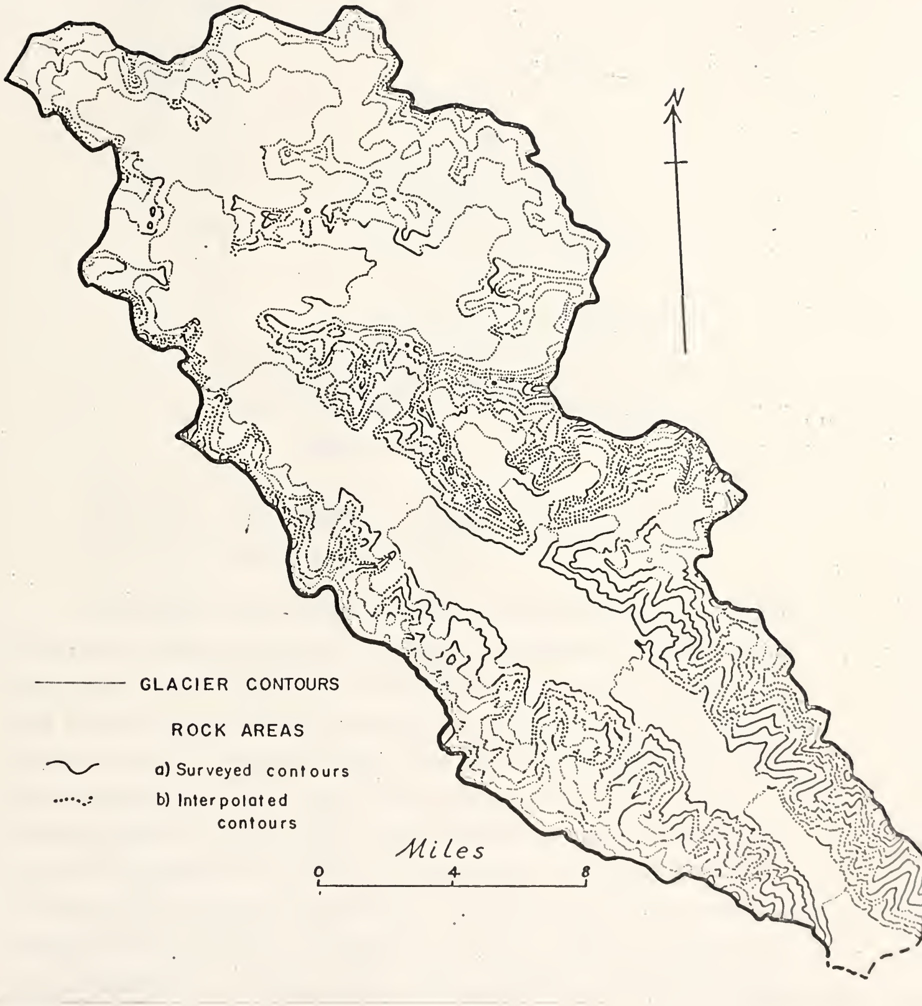

Fig. 8.I. Contour map of snow-free slopes of the Biafo Basin, based on the draughtsman's originals of the 1939 Shipton Survey.

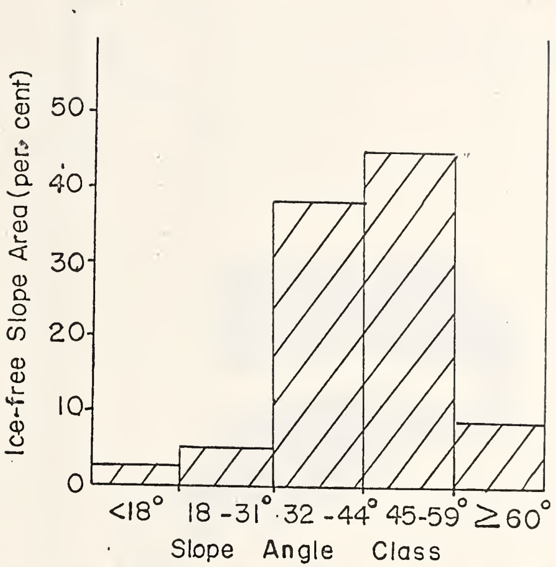

Fig. 8.3. Approximate true areas of rock slopes in broad slope angle classes for the Biafo Basin.

To define the actual importance of high angle slopes and counter the sampling bias of the slope orthogonals, approximate true areas were calculated. First a map was prepared from the 1939 Survey using a larger contour interval and interpolating contours for the steepest areas (Fig. 8.1.). A slope-angle map was prepared from this using broad classes (Fig. 8.2.). By planimetering the slope-class zones and calculating their true areas on the basis of their class mid-value a general idea of the area/slope composition of the landscape was obtained (Fig. 8.3.). Although the procedure is crude the results leave no doubt as to the predominance of steep cliff, with over 60% of the sub-aerial surface lying at angles steeper than 45°.

On the slope-angle map (Fig. 8.2.) some isolated "benches" with angles between 18° and 32° stand out. Mostly they lie in the range 14,ooo - 17,ooo ft. the zone of the 'alp' shoulders

Fig. 8.2 Map of Biafo Basin showing snow-free slopes according to angle classes.

occurring widely along the Braldu and elsewhere (ed. Dainelli 1922-34 Ser. II, Vol. 3, p.36). High sub-nival shoulders are well-known in glaciated landscapes but their explanation is controversial (e.g. Thompson 1962). The writer lacks the evidence to argue whether they result from early Karakoram erosion cycles, or from present or past clima-geomorphic conditions.

8.3. ii. <u>Characteristic Slope Angles.</u>

Despite limitations of accuracy, the measured orthogonals defined clearly certain predominant angles. The results were encouraging when compared with more rigorous investigations (see Strahler 1950; Savigear 1956). 36% of all rectilinear profiles lay within 0.5^{o} of 27^{o}, 45^{o}, or 57^{o}; 42.5% lay within 1^{o} of these four values. Each of these classes of angle was well-defined for both southerly and northerly slopes. In addition there was a cluster of measurements at $40\text{-}41^{o}$ for southerly slopes. These results show some agreement with those obtained elsewhere (Table 8.2.). Attention is drawn to the class of slopes close to 57^{o}. For snow-covered slopes there is also a characteristic angle between 56^{o} and 57.5^{o} (8.2.v). It seems there may be at least one more characteristic slope angle above the usual limit of measurements. The writer tentatively suggests that this may be related to some critical stability for snow of the type found in the Karakoram - that it is perhaps a "characteristic avalanche slope angle" for solid rock.

<u>TABLE 8.2.</u> Characteristic Slope Angles for various regions compared with those in the Biafo area (Values above 20^{o} only considered).

<u>Location</u>		<u>Angles in degrees</u>										
S. W. England	(A)		26-29	32			37		40		45	
Natal	(B)	23	27		33	36				42	45	
U.S. 1	(C)		26		33	35		38		42	45	
U.S. 2	(D)	23		32-33			37-38					
European Alps	(E)		28	32		36			41			
C. Karakoram	(F)		27				37		40-41		45	57

Sources: A. Savigear 1956; B. Fair 1947; C. Strahler 1950; D. Leopold et. al. 1963; E. Piwowar 1903; F. (This Study).

8.3. iii. Lithological Relations of Slope Angles.

From the available geological information, slopes in granitic rocks can be differentiated from those in metamorphics (see Chapter 3). The granites mainly outcrop above 15,ooo ft. This also largely removes the effects of waste-slopes. For profiles measured above that altitude, the granite slopes are, on average, some 13° steeper than the metamorphic ones (Table 8.3). At the same time both main rock-types reflect the influence of aspect on slope angle.

TABLE 8.3. Mean slope angles according to main lithological types and aspect.

Granites			Metamorphics		
Northerly	Southerly	All	Northerly	Southerly	All
58.6°	54.8°	56.7°	46.1°	43.5°	44.2°

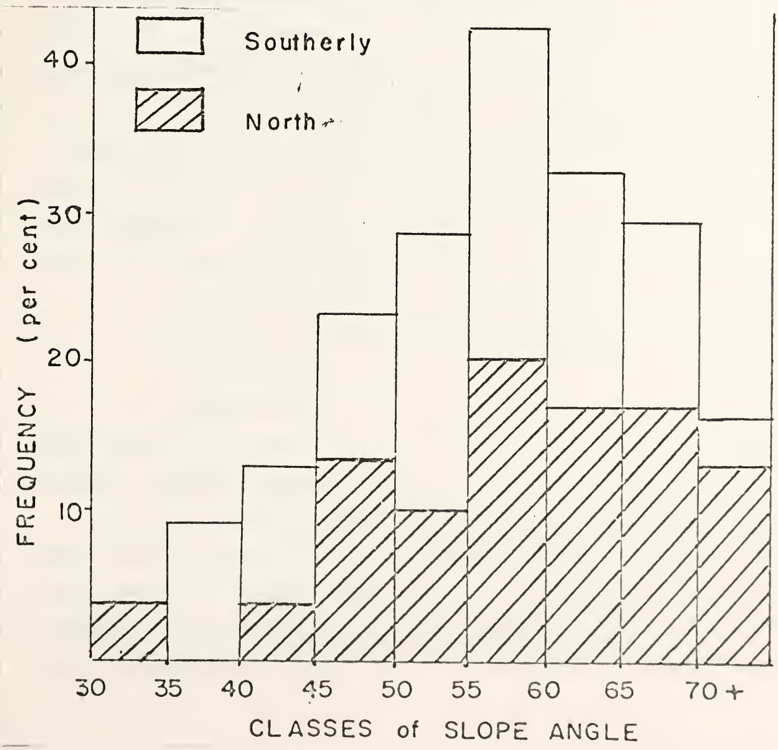

Fig. 8.4. Histogram of slope angle distribution for rock slopes descending to glacier edge, according to aspect; Biafo-Hispar Glacial Basins.

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[illegible]	[illegible]	[illegible]

8.3. iv. Base of Slope Condition.

For each orthogonal measured, the base-of-segment was noted; whether glacier-trimmed, ablation valley or slope inflection. The information showed that most of the steepest slopes descend directly to a glacier surface. The mean slope angles for glacier-trimed slopes were, 54.2^{o} for southerly, and 57^{o} for northerly slopes (Fig. 8.4.). Since nearly all these slopes terminated above 16,ooo ft., explanation of increasing mean slope angle with altitude must take account of the relation to glacial action. The erosional and/or transportational competence of the glaciers may be as important as the upslope change of clima-geomorphic conditions on the slopes. There is insufficient information at this time to differentiate these two factors.

8.3. v. Declivities of Perennial Snow and Ice Slopes.

The significance of slope angles in snow at high altitudes has barely been considered in the Anglo-Saxon literature. (see Hobbs 1938, and Seligman 1936, for some elementary discussion). In an area like the Karakoram it is, however, difficult to ignore the topic. It is not always easy to identify perennially snow-covered slopes. By comparing the snow areas shown on the 1939 map, with conditions in autumn 1961, and high level panoramas taken by other expeditions (Workman 1901b, and 1910b; Shipton et. al. 1938; and E. Williams p. com.) slopes were determined which:-

a) Had more-or-less complete snow cover in each case.
b) Were effectively separated from the flow-controlled snow and ice surfaces of the glaciers (e.g. by bergschrunds).

These slopes were measured on the 1939 map in the same way as the rock slopes (Appendix 4).

The sample of perennial snow and ice slopes from the Upper Biafo (17,ooo-22,ooo ft.) showed them to cluster strongly about the 55-60^{o} class (Fig. 8.5.). 30% of the measurements lay between 56^{o} and 57.5^{o}. No strong variation with altitude was found the angles at each altitudinal class clustering about the

same mean value. Above 20,ooo ft. there are fewer high and low values. Examination of maps of Nanga Parbat (Finsterwalder 1937) and Mount Everest (Erdkunde 1965), indicate these angles of snow slope are similar to those elsewhere in the Himalaya. Snow slope angles on the isolated summit areas of Mount Rainier, Alaska have a similar range. Perennial snow slopes in the Swiss Alps are, however, normally less than 50° according to Fankhauser (see Seligman 1936 p.294).

Explanation of the steep snow slopes seems to relate to the combined effects of high winds, intense insolation, sub-zero air temperatures, and "firnification" of the snow. The hard, dry snow falling at high altitudes has a relatively low angle of repose. However, grain-size sorting, and packing by high winds, along with alternate or simultaneous freezing and thawing enables the snow to stand as slopes in excess of 55°. These slopes can be stable enough for climbing. Wind-packing on lee slopes should not be overlooked. In the Hohe Tauern Welzenbach revealed a mean gradient of 52.5° below cornices (quoted in Seligman 1936 p.256). In relation to mass-movement, failure and avalanching will increase in incidence with increasing slope angle above the critical angle of stability for the particular type of snow forming in the area. It will also be a function of length of slope and volume of snowfall. The former is important in that the effects of a given failure will tend to be greater by gathering more snow into the individual avalanche. Volume of snowfall will be important both in replacing slope snow in general, and particularly rebuilding the all-important snow-cornices (see 9.3.). Unlike the rock-waste situation, it is probable that loading alone is a factor in triggering avalanches (c.f. Hacker 1940), due to the ability of recrystallised snow to 'flow' under an applied stress. On deeply covered crest-lines this leads to avalanching rather than initiation of a glacier.

8.4. Areal Survey of Slope Features.

As an introduction to the slope features of the area, brief

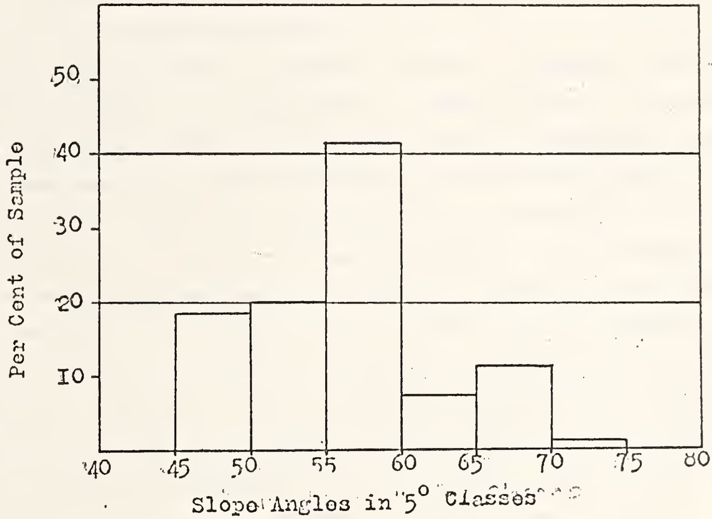


Fig. 8.5. Per centage distribution of perennial snow slopes angles for the Biafo Basin.

descriptions of the areas in which morphological mapping was undertaken are given here (Plates A. 2. and A. 3.).

8.4. i. Slope features in the Baintha-Latok Area.

The area is adjacent to the highest part of the Biafo Watershed, and includes the largest tributary joining the Biafo below the firn line. Slope character and mountain forms strongly relate to the main geological divisions and fall into three main topographical units:-

a) Massive granite topography of the Latok Range, Baintha Brakk and the Biafo West Wall around Sosbun Brakk. This coincides with the axial part of the Biafo Granodiorite.

b) Riven granite and agmatite terrain lying between the granodiorite and the metamorphics.

c) A relatively subdued metamorphic terrain in the angle between Baintha Lukpar and the Baifo, and across the latter around Hoh Blukk.

The massive granite topography consists of compact, sheer-walled towers and buttresses, and deep glacial troughs. There are few minor salients, chutes or chimneys on the valley walls, negligible talus, and the landscape has a remarkable economy of form with large sections of uniform cliff. Four broad components can be recognised. First, the basal parts along the glacier margins consist mainly of massive buttresses with broad embayments or ice-falls between. Most of the slopes terminate at the glacier above the firn line and embayments are filled by wide scoop-shaped ice-aprons, reaching several hundred feet upslope. Some aprons head in snow-filled couloirs but these mostly die out in the cliffs above. Second, there are the uniform rock walls that flank individual ridges and peaks. Many of these walls have distinctly planar surfaces meeting at sharp angles. Individual units may compromise over ½ $mile^2$ of virtually unchannelled rock wall at angles exceeding 60^o. Linear dimensions of these faces are ¼-½ mile across and 5000-8000 ft vertically. Apart from surface pitting, the only signs of disintegration are some exfoliation cracks. Thirdly, the larger mountain masses have steps or benches with glacier carapaces or snow aprons on them. These breaks in the rock walls are 3000-5000 ft. apart and coincide with major sheet-structures. Finally, steep rock walls rise as flanks of isolated towers and pyramidal peaks. Slopes in excess of 70^o are normal. Watershed relief is enormous here (see 9.2.).

The riven granite and agmatite terrain has numerous chutes, needles and spires. In the granite is some development of "organ-pipe" texture though less spectacular than along the Baltoro (de Filippi 1912 Panorama B and p.182-203). Chimneys and chutes pick out vertical and transverse joints, the latter become most apparent in the agmatite spur between Uzun Blakk and the Biafo (7.2.i). In the peripheral granodiorites are some remarkable towers with rock surfaces smoothly-convex in cross-slope direction. Along

the middle Uzun Blakk they produce a topography recalling the quartz-monzonite towers and buttresses of Yosemite Valley though relief is much greater. The features have well-defined exfoliation structures following the convex surfaces.

The metamorphic topography is more subdued and also has gentler relief than the remaining metamorphic parts of the basin (Fig. 8.2.). The spur between Baintha Lukpar and the Biafo has the only significant area of "mountain top detritus" in the basin; mainly block field. Up to 15,ooo ft. there is a dense vegetation cover. Cohesive taluvium covers most slopes up to 16,ooo ft. The base of slopes rests in "ablation valleys" (see 12.5.), with varied mass-movement deposits including rock-fall debris, debris-flow fans and tongues, scree and avalanche boulder tongues. Northerly slopes have some earth slides and slumps. On Hoh Blukk are macro-solifluction features associated with moist, well-vegetated slopes at less than 30°.

North of Hoh Blukk, between it and the igneous areas, the metamorphics suddenly change character. The strata, dipping at about 50° towards the main glacier are carved into steep masses along bedding planes, to give an alternation of sharp-angled buttresses and narrow couloirs. South-eastwards, on both sides of the glacier, the metamorphic terrain becomes more fiercely dissected.

8.4.ii. Slope Features of the Biafo-Braldu Area.

The area is centred on the junction of the Biafo and Braldu, with slopes descending to both, and in some cases having over 10,ooo ft. of relief. The climatic snowline lies below the crests of some northerly slopes but was not found on southerly slopes.

Waste slopes form a major part of the area and show a great variety of features. Vegetation is more dense on northerly slopes than southerly, and corresponds to differences in movement patterns on talus. Some northerly slopes retain remnants of ice-polishing up to 15,ooo ft. but striations and polish have been obliterated from southerly rock surfaces. However, erratics on the Laskam "alp"

(see Lydekker 1883 p. 35) earth-pyramid material and two well-defined spill-ways at 14,5oo ft. on Choblok and Laskam record the earlier glaciation.

In the waste-covered slopes four broad components can be seen:-

a) Basal accumulations, including large rock-fall boulders strewn among bump-holes; large mudflow fans; concave basal scree; small dejection cones and innumerable small tongues of mud- and debris-flow material.

b) Broad "taluvial" slopes of steep cohesive waste, differentiated by varied superficial patterns of streaming waste. Much of the taluvium comes into the category of "bedded-slope deposits." Earth pyramids occur on and around these slopes.

c) Scree slopes, sometimes overlying taluvium but achieving the greatest development between 15,ooo and 17,5oo ft. above most of the taluvial aprons.

d) The "alp" or Blok shoulders; essentially rock-cut benches at angles between 10^{o} and 25^{o} with a variable regolith of mainly cohesive material, and moderately open vegetation (c.f. Fig. 8.2. and 8.2.i.).

In true area, rockwalls still exceed waste slopes. Cliffs, peaks and crestlines show detailed accommodation to structures in the metamorphics. As usual in the region, the slopes are so steep it is virtually impossible to represent these features on a map.

CHAPTER 9

SLOPES AND MASS-MOVEMENTS II: PARTICULAR SLOPE FEATURES

9.1. Introduction.

Here we describe features having a measure of distinctness in the landscape. Such a treatment is favoured by the barren terrain and vigorous processes which produce visually well-defined features. The division of process from forms seemed desirable since, technically, each involved different though converging observational evidence.

9.2. Peaks and Crestlines.

Much has been written concerning high level summit accordance in the world's major mountain systems. But study of the morphology of peaks and crestlines has barely advanced beyond Ruskin's semi-aesthetic analysis of the Matterhorn. This is a disadvantage in the present context and requires some thought.

In the Biafo area, plateau-like accordance of summit areas was quite marked at high level viewpoints. The problem is to test the validity of the visual impression. One approach is to examine the 'relief' of the crestlines. The crestline or watershed may be treated as a line tracing the perimeter of a drainage basin, and its relief found from the rise and fall of the line (Fig. 9.1.). Mean watershed relief can be computed by averaging height difference between maximum and minimum altitudes per unit of watershed length. A suitable unit of length must be found empirically, since, the longer the unit the greater the average relief tends to be, while short units sample slope segments not the rise and fall of the crest-line. For the Biafo Basin, a horizontal unit of 0.06 of total water-shed length was arrived at. A datum base of 16,000 ft. was used since the watershed only descends below this at the basin's mouth. (This convention might be hard to apply in areas of lower absolute relief).

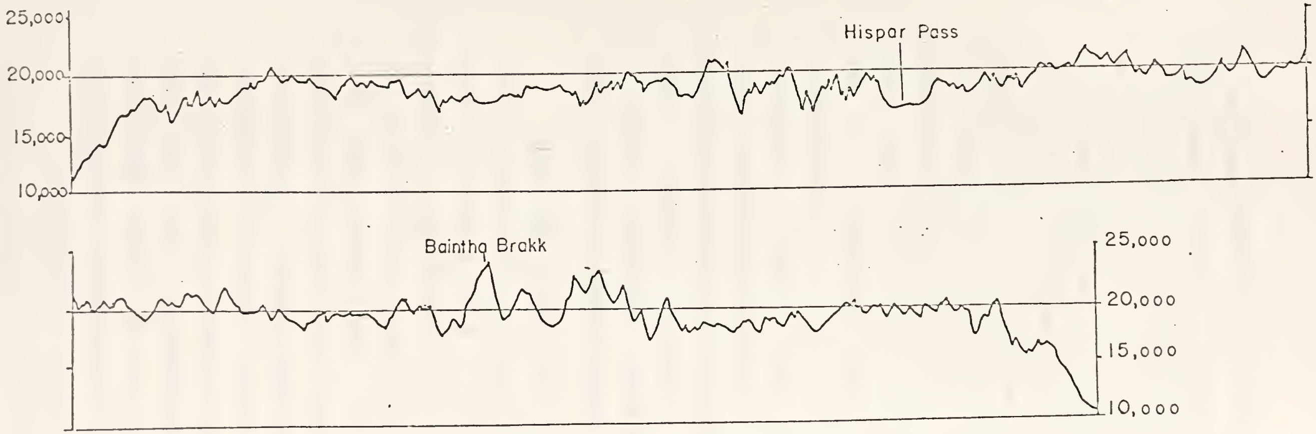


Fig.9.I. Watershed trace of the Biafo Gyang Basin.

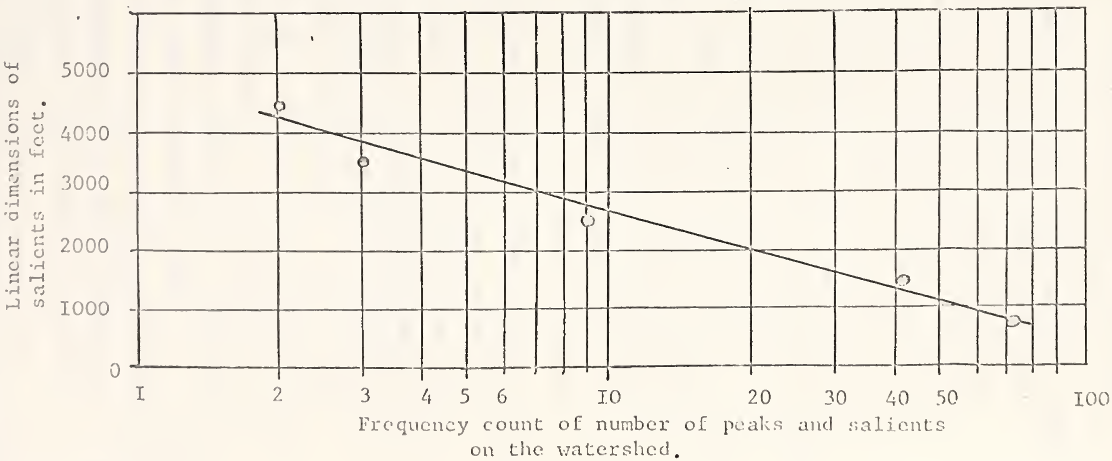


Fig.9.2.

The mean watershed relief is 3,7oo ft. This is 48.5% of the total relief above 16,ooo ft. (7.9oo ft.), and 37.5% of total basin relief (13,9oo ft.). The figures indicate considerable high level dissection.

The significance of this relates to several other points. First, in general the watershed line defines the shortest slope orthogonal from any summit, - its minimum relief component. Second, the whole Biafo watershed is knife-edge ridge, the slopes towards the drainage lines generally exceeding 45°. The visual "high level summit plain" has a relief close to the maximum available relief in Britain, and in plan is an infinitesimal part of the landscape. Thus, morphologically, it appears that, in horizontal view, the scale of the landscape deceives the eye with a planar surface which hardly exists. In a dynamic sense, the severe watershed dissection and steep, active slopes below the watershed make the existence or preservation of ancient erosion surfaces unlikely. However, the concept of regular dissection to something like the classic "Stockwerk" does not conflict with the plan-view of the landscape and would explain aggregate impressions of summit accordance.

The linear dimensions of watershed salients offer further insight into the character of dissection. As defined by mapping with 25o ft. contour intervals there are 125 salients on the watershed, and nearly as many on crestlines within the basin. For present purposes, a 'peak' will be defined as a salient within closed contours whose relief measured along the crestline is not less than 1,ooo ft. On the Biafo watershed there are 30 such peaks, and a further 25 on crestlines within the basin. A simple quantitative approach is to consider the distribution of the peaks' linear dimensions (Table 9.1). When plotted on log-normal paper the data for each class of peak lie nearly on a straight line. (Fig. 9.2.), a distribution common to many morphometric properties of drainage basins. It may be significant that, while lacking any of the largest peaks, the inter-basin crestlines have many more small ones.

The morphology of particular peaks reflects primarily the severe dissection and glacial conditions. All would be described as pyramidal

peaks," ...with steep sides formed by the intersection of three or more cirques..."; or tinds (Cotton 1958 p. 312). But there are also variations in morphological detail and mean slope angles with rock-type (7.2. and 8.3.), aspect and location. Aspect gives different character to opposing sides of the same peak associated mainly with differing snow accumulation, dependent on insolation and the direction of prevailing winds (9.3.). Locational effects may be seen for example in the different character of the drier metamorphic peaks of the Braldu and ones at similar altitude in the humid Upper Biafo. However, much that differentiates peaks in these respects can be dealt with in a more meaningful, and general manner under particular characteristics which apply to broader slope areas. In conclusion we may just note the great variety and number of minor salients picked out on slopes and crestlines in the sub-nival zone. Largely according to rock-type, these vary from squat cupola and castellated forms, to slender fingers, needles or monoliths (Plate 9.1). Intrusive sills and dykes, or flakes of more resistant metamorphic strata commonly compose these salients.

TABLE 9.1. Frequency count of crest-line salients of the Biafo according to watershed relief. (A "compound peak" is a single major salient with several minor summits.).

Relief along Crestline	Watershed Peaks		Intra-Basin Peaks		Totals
	Single	Compound	Single	Compound	
4000-5000	1	1	-	-	2
3000-4000	2	1	-	-	3
2000-3000	3	3	1	2	9
1000-2000	11	8	20	2	41
Also 500-1000	37		47		84

9.3. Perennial Snow and Ice Slopes.

Four types of surface morphology were distinguished on snow-covered

slopes:

a) Heavy covers of smooth blanket-like snow of gently concavo-convex forms. Around accumulation basins bergschrunds terminated these slopes. Elsewhere, as on the few snow-covered slopes of the lower Biafo East Wall, they would grade into couloirs and chutes filled with cones and tracks of avalanche snow. These contrasted with the absence of tracks on the snow slope feeding them.

b) Complete, and nearly complete covers of fluted snow and ice.

c) Alternating, ribs of rock and broad, snow-filled couloirs.

d) Rough walls of rock with patches and thin veneers of discontinuous snow and ice.

The smooth snow slopes were noticeably a southerly and/or windward slope phenomenon. By contrast, most snow-fluted slopes had northerly and/or lee situations. The lee side was shown by the position of snow cornices, usually on the easterly slope(c.f. Seligman 1936 p.264). Relationship to aspect was strongly defined. Strong insolation on southerly slopes induces melting and refreezing of snow and increases sublimation losses, serving to consolidate snow and remove irregularities. On windward slopes snow is packed hard and smoothed, the more so with the increasingly powerful winds of higher altitudes.

By contrast, the formation of fluting requires frequent downward movement of avalanches. In general, the avalanches derive initially from snow cornices or, to a lesser extent from rock falls making fluting a mainly north and easterly slope feature. Those southerly and windward facets on which fluting was observed lay below rock cornices and were often lined with debris.

Snow couloirs or chutes occurred in the metamorphics of the lower perennial snow zone - 16,000 - 19,000 ft.; chiefly around Lukpe Lawo and Sim Gang. From photographs taken by summer expeditions to the Upper Biafo, the couloirs seem to predominate either on southerly or windward slopes. Wind drifting and insolation again seem to be important. The couloirs range from 30 yds. to perhaps 200 yds. in width (9.5). Discontinuous snow covers occurred on exceptionally steep cliffs - greater than 60^{o} - of northerly aspect, especially in metamorphic rocks

where patterns tended to pick out structures in the rocks.

The location of snow slopes were as distinctive a feature of the granite towers as their smooth, precipitous rock-walls. The snow aprons formed lower angle segments separating the rock cliffs. The distinction between fluted and smooth snow slopes was well-defined. On the towers of the Biafo and Uzun Blakk west walls the north-facing snow was strongly fluted. The southerly slopes of the Latok Range and Uzun Blakk east wall had smooth snow aprons.

9.4. The Rock Glacier on Wat Sar.

At 17,5oo ft. on Shinlep Bluk, was a large lobe of rock waste flowing out from a cirque-like back-wall aproned with thick scree (Plate 9.2). The lobe ended above a steep couloir down which spilled a chaos of scree with massive blocks. The lobe was convex in long- and cross-profile. Metamorphic material covered the surface with compact-bladed or compact-platy boulders. Larger blocks were sorted towards the edges of the lobe. The material derived from avalanches, rock-falls, and talus creep on the backwall. The severely riven cliffs with many fresh rock-fall scars indicated a rapid rate of supply. The feature had no transverse ridges, common in some rock glaciers, and seemed to warrant the title 'Cirque Rock Glacier' (c.f. "cirque-floor type" in Outcalt and Benedict, 1965). A key question is how the coarse blocks move over such low surface gradients, and the answer was found in certain undercut edges of the feature, where outcrops of glacier ice, refrozen snow and ice-melt occurred.

The form of the cirque and 'rock glacier', the fact that it was mapped as a cirque glacier in the 1880's, and that the villagers report the disappearance of the glacier in the last 10 years indicates that the core, - and possibly the greater part of the mass - of the feature could be ice. Small glaciers close to the snow-line are very sensitive to climatic shifts, especially to a marked amelioration like that of this century. However, after accumulation ceases, the smothering by ablation moraine and mass-movement material retards the later phases of

wastage. As well as protection from the sun with such coarse debris, ventilation effects help conserve the ice (Balch 1897).

The people of Surongo paid for the 'planting' of an artificial glacier in the rock glacier cirque. This 'planting' took place in October 1961. It is a common method of trying to offset diminishing water-supplies in the Karakoram and Hindu Kush. The writer saw small cirque glaciers said to have been started in this way. However, Western scholars will hardly accept that a few blocks of 'male' and 'female' (actually Biafo) ice, and an incantation will create a glacier. The 'planter's successes may indicate that many small glaciers become rock glaciers during climatic amelioration, and return to glacial form when cooler and/or moister conditions re-appear. There are no other reports of rock glaciers in the region, though a small glacier near Baintha Camp, apart from a tiny outcrop of ice, was very similar to the Wat Sar example. However explorers rarely visit the minor cul-de-sacs where such features occur.

9.5 Chutes and Related Incisions in Bed-rock.

In a pioneering paper, Matthes noted that steeply falling channels in mountain walls were an important but neglected feature of mountain sculpture (1938 p.631). This is still largely true of the literature in English. Recently, Rapp and, more intensively, Markgren have devoted attention to the problem (Rapp 1960a; Markgren 1964a & b). The latter's work clarified terminology but his discussions have limited relevance to the Karakoram situation. Yet the number, variety and areal coverage of mass-movement channels in bed-rock clearly show their importance, and though few support a flow of water, they generally form the first three or four orders of the drainage net.

The term "chute" covers all channels cut in bedrock, and canalising mass-movement. Exclusive association with avalanche-sculpture (see Matthes 1938) is not invoked since chute areas were found where avalanching played a negligible role. Use of the regular, normal chute of Markgren as the basic type is also avoided. The type was not prominent in the area, while irregular, non-normal chutes were (c.f. Markgren 1964b p.63). "Chimney" refers to very steep chutes (i.e. greater than

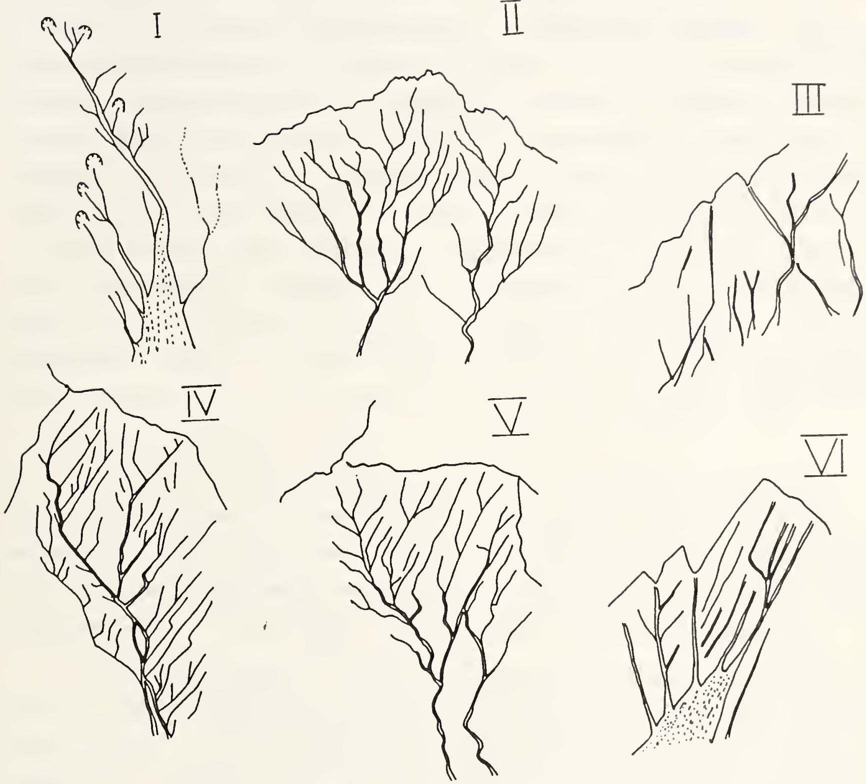
60^{o}) and "couloir" to distinctly wide, or isolated chutes in un-channelled slopes.

Most chutes in the area cut deep into the mountain-walls. Up to 17,ooo ft. their floors were generally flat, the channel trough-like (Plate 9.3), and there was usually mud plastered over the floor. Sometimes, wedges of compacted detritus formed the channel walls between constrictions. Small screes and other accumulations occurred at narrows and turns in the channel.

Some sets of chimneys reached the crest-line without significant changes of width but most chutes spread fan-wise at the head to produce wide alcoves and recesses. These included bowl or cirque-like forms, rock funnels (Rapp 1960a) and the recesses with two walls meeting at a sharp angle. The latter occurred mainly in the metamorphic terrain, one wall following the bedding plane, the other a joint plane, and were strikingly developed between 16,ooo and 20,ooo ft. The funnel and cirque-like forms occurred in the massive granites, in severely rotted rocks, and on some 'scarp' slopes cutting across the bedding planes of the metamorphics. The avalanche boulder tongues of Baintha Lukpar lay below broad, smooth scoop-shaped amphitheatres (c.f. Rapp 1959a). These faced north and narrowed from 100 yards at the top, to two to four yards at the mouth: ideal for the snow cornice and avalanche development described by Matthes (op cit.). The chutes were 1000 - 1500 ft. high and sloped at about 39^{o}. The rock at the top of the funnels was considerably riven and there were block fields above. These would provide the waste material carried by avalanches.

Around Lupe Lawo, there were sets of parallel snow-filled couloirs reminiscent of the regular, normal chutes described in other regions. The underlying rock channel was too deeply buried in snow to know its actual form. However, discussions of the origin of normal chutes, (Markgren op.cit. and Rapp.op.cit.) refer to snow-filled couloirs of this type, and infer that they have smoothly concave cross-profiles.

The branching patterns of chutes had the variety and complexity



Eig. 9.3. Branching patterns of chutes sketched in the field.

I. Dendritic -Pinnate pattern with fresh rock-fall scars in the altitudinal range I0,ooo - I2,oooft. Southerly.
II. Dendritic-Pinnate pattern in scarp slope of metamorphics, in the range I2,ooo-I8,oooft. Southerly.
III. Trellised-Rhomboidal pattern following joints and intrusions in dip-slope of metamorphics. I0,ooo-I2,oooft East-facing.
IV. Trellised-Angulate pattern with anastomosing following metamorphic joint and bedding planes. I2,ooo-I7,ooo .Northerly.
V. Trellised-angulate with divergence following joint and bedding planes in metamorphics. II,ooo-I6,oooft. Northerly.
VI. Trellised-Angulate following bedding and joint planes in metamorphics. I3,ooo-I7,oooft .East-facing.

of stream systems in widely different situations (Fig. 9.3.). Exploitation of structural weakness was the outstanding feature. Trellised patterns developed on high angle slopes in the riven granites and steeply dipping metamorphics. Dendritic patterns and sinuous channels occurred mainly on lower angle slopes of metamorphics, either where weathering was severe, or on scarp slopes. These were mainly at lower altitudes, but some dendritic patterns occurred at 17,000-20,000 ft. in the moderately riven granites of Baintha-Biafo area (Plate 9.4). Local anatomosing of channels, and divergence of different sections of channel across the nose of a spur were common, (c.f. Markgren op.cit.). Many asymmetrical systems were found, consisting of a major non-normal chute drawing most of its tributaries from where a channel normal to the mountain wall would lie.

Chute nets have not developed on most slopes on the massive granites, on slopes with heavy snow cover and the very steep cliffs in metamorphic rocks above the snow line. Massive granites below the snow line had some tracks where melt-water movement was concentrated. These consisted of lines of fresher rock, but only the barest incision.

The organisation of chutes into drainage systems raises the question of their relation to similar developments of stream channels (see Veyret 1959). A high proportion of mass-movement takes place along chutes, and, as with streams, once a channel is in existence it draws in and canalises movement from adjacent slopes. However, whereas streams mostly have more-or-less long periods of continuous flow, and a steady increase in flow with distance and stream order this is not clearly similar to the chutes. Chute transport is largely in sudden, short-lived movements. In the Karakoram chutes, the drawing in of moisture from tributary slopes is far less significant than the initial concentration of moisture in the chutes. Under the influence of wind, snow gathers mainly in sheltered recesses. The intense sunlight, low humidities and high winds soon remove the thin snow of open slopes, much of it evaporating. Snow in chutes is protected by shadowing and its extra thickness.

Cumulative 'drainage net' effects of stream channels are not quite the same as in these chute systems. Points lower down a given system may benefit from lying below chutes spreading over a wide area of slope. But this is unimportant compared to the routing of moisture from high humid areas to lower arid areas. Much moisture deposited in upper chutes fails to reach their foot and only the larger, more violent mass-movements travel the length of a major chute. The lower, high order chutes reflect rather a greater number of individual debris-flows, avalanches, etc., than down-stream increase of average through-flow common to most stream systems. Visual inspection suggests that many chutes have negligible increases in width over several thousand feet of descent.

A related feature is the overall variation in dominant processes with altitude. There is a general change of activity in chutes passing from humid down to semi-arid areas. The avalanches predominating in the steeper upper reaches tend to give way to debris- and mudflows in the lower parts. The change is less obvious in chutes that are very steep and straight throughout, and seasonal migration of the snow limit complicates the picture. Nevertheless, avalanching tends to be impeded and rarer in the semi-arid parts of chutes. In winter and spring, the middle reaches of many chutes (roughly 15,000-17,000 ft.) developed cones of avalanche snow firmly lodged among the recesses and turns. The snow would rarely form further avalanches, but it would thoroughly soak the debris in these lower couloirs and generate debris-flows. The prevalence of such a chain of events where chutes pass below the snowline was supported by the common sequence of forms: upper avalaches, trapped snow and avalanche cones; lower dejection cones and fans of debris-flow material.

A point of general interest is the rarity of chutes 'hanging' above the present valley floors. In general, funnels did not terminate high on the valley wall but at most, became single narrow chutes descending to the valley floor (c.f. Rapp 1960, p.104; and Markgren 1964b p.62). On the other hand there were several examples where branching, irregular sets of chutes suddenly became regular and normal in character

for the last few hundreds or thousands of feet of decent (Plate 9.5). In the case of the Rionpe Lung valley, examples of these lower, normal sets were cut into glacially scoured and over-steepened slopes. One interpretation of hanging chutes is that they were cut to the level of former glaciers, which have thinned more rapidly than the chutes could be regraded. It may be implied that chute sculpture has been reduced, and present processes do little more than preserve old forms. By contrast, the many chutes that reach the valley floors and kame terraces in the Karakoram could mean chute erosion has kept pace with glacial recession. This is supported by the chutes cutting deep into glacially scoured valley walls. However the single, narrow chutes and lower 'drainage densities' of the lower chute-slopes cannot be ignored. The problem is whether this sort of evidence can be interpreted to mean decreasing rates of chute sculpture since the last major ice advance. In fact, the over-all environmental changes of the last 10,000 years or so have been so radical that purely morphological evidence is quite inadequate to solve the problem. Chutes developing on over-steepened ice-smoothed walls are likely to differ from those on rough, frost-shattered cliffs. Furthermore, the picture is complicated by the original subglacial zone now being semi-arid slope. In any case, upslope morphological changes, in the area can reflect upslope environment changes as well as the legacy of past conditions. In summary therefore, while chute-cutting has generally kept pace with ice-recession in the area, the environment has changed so markedly that recent contributions to total chute incision cannot be deduced from the evidence available.

9.6. Talus.

Talus occurs in significant amounts up to about 17,000 ft, and below 15,000 ft. becomes a major element of most slopes. The slope deposits consist of broad aprons and cones mostly at angles between 30^{o} and 45^{o} with solid rock within a few feet of the surface. There is also a variety of superficial talus patterns, some of which will be considered separately (9.7.). Here, attention will be concentrated upon:-

a) Scree: aprons and cones of coarse, non-cohesive waste,

b) Taluvial slopes: the term "taluvium" being adopted after Wentworth (1943), and revised to connote steep slope cohesive deposits with a significant fines content. Note that "colluvium" is generally used for poorly sorted, poorly compacted non-cohesive slope deposits (ed. Stamp 1961).

9.6.i. Scree

This is less common in the Biafo Basin than might be expected in a high mountain environment. Of the ice-free area about 9 miles^2 is scree covered, or some 7%. Scree was less extensive than taluvial slopes. In other parts of the Karakoram it assumes a major role, the greatest development occurring north of the main watershed among friable sedimentaries (see Mason 1927; Desio 1930).

Two main groups of scree were distinguished in the Biafo area, according to altitude and setting:-

a) Large cones of typical mountain scree, 500-2,000 ft. high, mainly between 14,000 and 17,000 ft. (Plate 9.6.).

b) Small, thin aprons and cones overlying cohesive waste at the base of taluvial slopes, or below rock walls at lower altitudes. These were generally not more than 200 ft. high.

The large screes were too active and unstable to encourage lingering. Rapid reconnaissance indicated angles of repose of between 34^o and 38^o with occasional steepening to over 40^o when massive blocks or imbrication structure occurred. The material was mostly in the cobble and boulder ranges up to about 4 ft. in diameter. Two fine cones on the southern spur of Mt. Bullah at 15,000-17,000 ft., composed mainly of metamorphic blocks, (compact platy and platy), emerged from broad couloirs to terminate in arcs at the head of an alpine shoulder. Imbrication structure was quite marked in the lower part and gave a lobe-like form to the cone. On most coarse screes there was a fall sorting pattern, but also a great deal of local variation. The latter may be attributed to the action of avalanches and large rock slides which complicate the normal movement on screes.

The smaller screes lay where valley-side slopes met low-angle

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flats or terraces. Except where mudflows trimmed the end of them, the screes continued outwards to a scatter of large boulders among bump-holes, and had a strong basal concavity. Well-developed fall-sorting was found, and being thin, the screes were sensitive to local topography (Plate 9.7.)

The following characteristics were determined for scree material at the base of Choblok slope (Appendix 5):-

a) Calibre and Shape.

The bulk of the material consisted of cobbles and boulders, the range measured varying from 6 ft. to 2.5 inches long axis. There were some larger boulders and finer materials within the mass of the screes. The stones were all fairly compact in shape with average flatness indices in the range 150 to 187, significantly lower values than for material resting on the steep taluvial aprons nearby. Most of the fragments were sub-angular in contrast to the angular material of the high screes (Plate 9.8.).

b) Sorting.

Three sorting features emerge from the measurements. First, there was an increasing range of size with increasing mean grain size. Second, the mean flatness indices decreased with increasing grain size (Fig. 9.4.). Thirdly, both flatness index and grain size varied with height upslope, the former directly, the latter inversely (Fig. 9.5.). Also interesting is the bi-modal distribution of grain size for the basal area.

The bulk of the scree material was gneissic or intrusive, contrasting with the platy, metamorphic material important on the steep, taluvial aprons (c.f. 9.7.i).

c) Orientation.

In general long-axes were oriented with or across the slope, even in the basal boulders.

d) Angles of Repose.

Surface angles decrease towards the base of the slopes and with increasing grain size (Fig. 9.6.). However, since only the uppermost parts of the screes were unstable, the slope of the lower coarse material did not represent the angle of repose. Rolling and bouncing material reaching the base of these slopes need not stop suddenly with the change of slope and can build outwards well below the angle of rest.

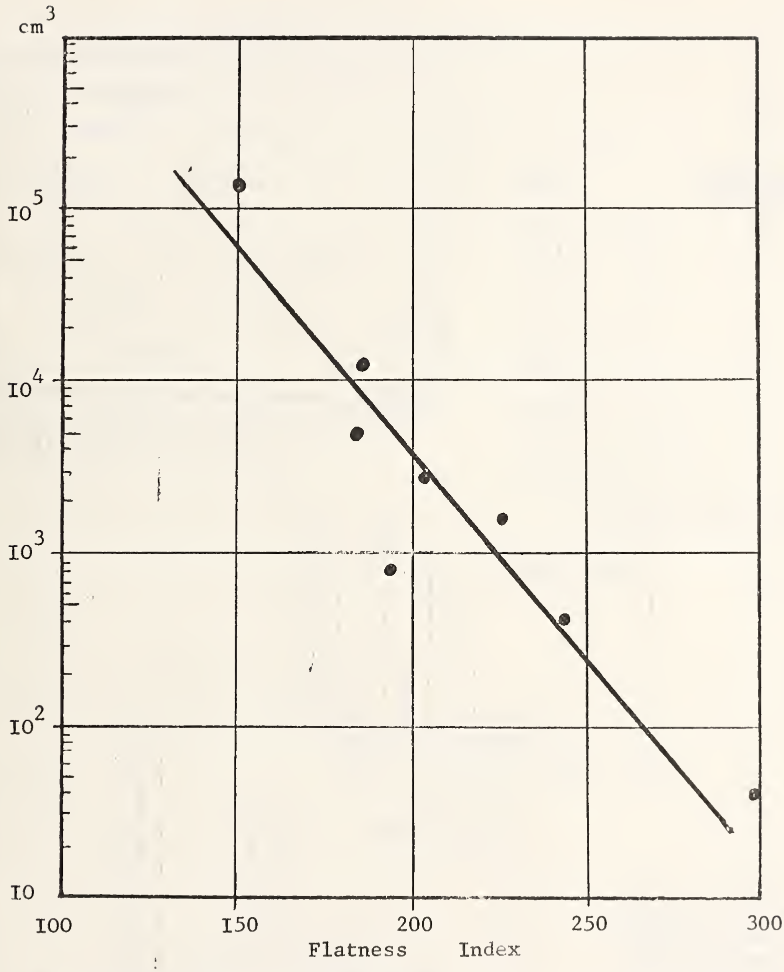


Fig.9.4.Relationship of mean grain size to Flatness Index for Choblok scree materials.

An explanation of the size and shape variations may be found in the mechanism of fall-sorting. The mobility of non-cohesive particles on a granular surface is primarily a function of the mass and shape of the particles and their relation to surface roughness.Since, for large rock particles, variations in density are usually unimportant, grain size can be substituted for mass (see van Burkalow I945). Movement over an inclined scree surface may be by sliding, rolling or bouncing.

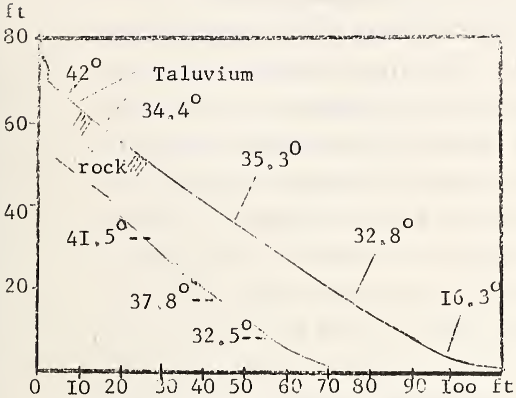
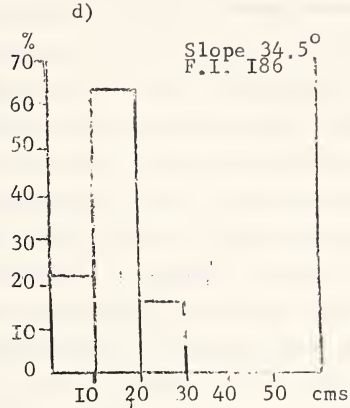


FIG.9.6. Profiles of two screes on Choblok slope at IO,5ooft.



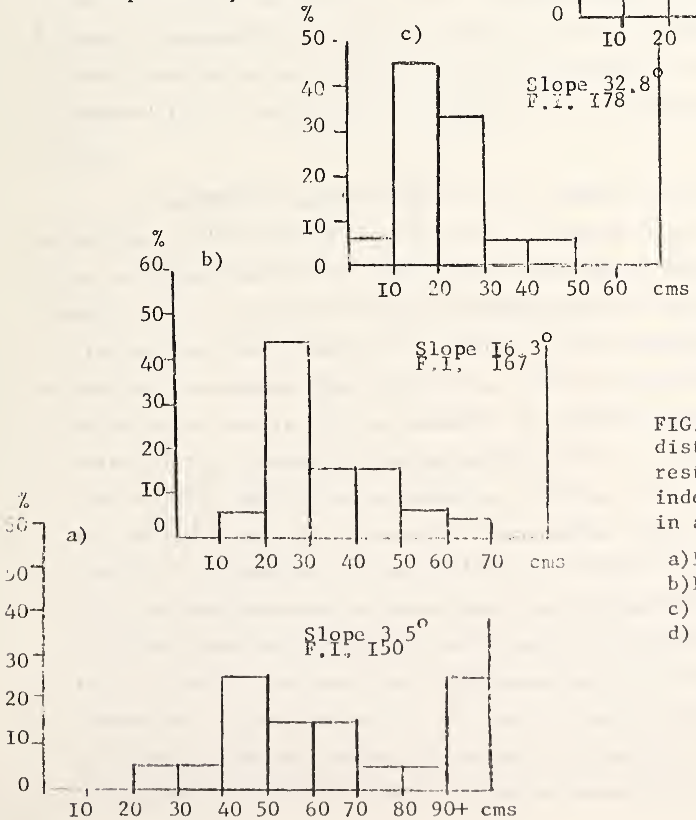


FIG.9.5. Percentage size distributions, angle of rest and mean flatness index (F.I.) of materials in a scree on Choblok.

a) Basal boulders

b) Lower part of main cone.

c) ft above base.

d) ft above base.

Size is important in two main respects: it determines the potential energy of the particle and, for fixed shape, the area in contact with the surface at any time. The larger the particle the greater the momentum it can achieve and the greater the frictional resistance (or inelastic deformation) required to stop it. The larger the particle, the smaller the ratio of surface contact to mass for fixed shape parameters. Experiments made by the writer on some Scottish screes showed that compact, bouncing or rolling particles were normally stopped whenever the scree surface material had approximately the same calibre as the particle in motion. This suggests that frictional resistance tends to equal kinetic energy when the 'wavelength' of surface roughness approximates particle diameter. For compact particles this appears to be the primary mechanism in fall-sorting found in the Karakoram screes. Rapp's explanation solely in terms of mass and radius of the moving particles omits the important process of selective checking on slope (Rapp 1960a). Furthermore, shape factors can greatly affect fall-sorting.

In general, shape acts in such a way that the less compact the particle, the less mobile it is for the given size range. This refers to movement over coarse scree, not cohesive or vegetated talus (c.f.Rapp 1960b p.97). A platy particle standing on its narrow edge is more unstable than when lying flat. Hence it will normally have the larger surface in contact with the scree. This increases frictional contact relative to mass. If the fragment is extremely large, or the scree material very unstable, sliding movement may be promoted, the scree surface acting like roller-conveyors. However, this type of movement will be checked some time before the scree grain size equals that of the particle. Likewise, if the particle is bouncing or rolling the higher ratio of surface area to mass, and the configuration of surface slow the particle down earlier than a more compact fragment. This was found to be the case in the Scottish experiments where less compact particles were concerned. Also, the points of rest for given sizes were more random in platy fragments leading to poorer fall-sorting. More patchy sorting was noted in screes of platy, schistose material in the Karakoram. In

addition, imbrication structure occurs with platy fragments increasing local surface roughness. This increases the patchiness of the sorting. Imbrication was common in platy scree in the Karakoram.

The upslope size and shape sorting of the Choblok screes appears to conform to these ideas on fall-sorting. In spite of the small range of Flatness Indices, there is a consistent upslope increase, which appears to be contributed mainly by the larger diameter particles at the sample site.

Towards the lower end of the zone of large screes, and in smaller patches down to the lowest altitudes observed were some screes with the large particles in a predominant matrix of sand and gravel material. These cones and aprons were very unstable. Some exceptionally large boulders migrated to the bottom, but fall-sorting did not affect most coarser fragments included. There was sometimes a crude downslope alignment of the patches of coarse material (Plate 9.9. These were mostly found on southerly slopes but short aprons of the type, occurred extensively along the base of northerly slopes where old taluvial slope deposits had been undercut. Many of these screes formed where extremely rotten cliffs supplied the bulk of the material. Hence there was little admixture of the old slope materials with their high silt-clay content (9.6.ii). The absence of well-defined sorting of coarse material can be attributed to the inelastic surface presented to falling stones. These sink in and are quickly checked by the yielding fines. The material moves in sliding lobes whenever instability is promoted.

9.6.ii. Taluvial Aprons and Cones.

Up to 15,ooo ft. the bulk of the talus area consists of cohesive aprons and cones of material with a relatively high fines content. In general, northerly slopes of this kind had well-developed terracettes, and southerly ones a variety of superficial patterns in coarse waste (9.7). Samples of the surface material from these aprons were analysed for grain-size and consistency limits (Table 9.2.). The sample sites involved an area of large terracettes, on a northerly slope (T.4.), an area of relatively smooth, dry, moderately compacted taluvium where

Table 9.2. Grain size and consistency limits of taluvial apron materials in the Biafo-Braldu area.

Sample			Grain	Size	Consistency Limits		
No.	Place	Aspect	Silt-Clay Fr.	Sand Fr.	Liquid L.	Plastic L	Pl.I.
E.1	Choblok	S	6%	44%	25.3	19.4	5.9
E.4	Choblok	S	19%	45%	23.5	17.1	7.4
T.4	Bakhor Das	N	26%	50%	24.5	17.5	7.

"stone-stripes" occurred (E.1.), and z aone of greyish material outcropping in the taluvial apron and merging with the normally pale yellow-brown colour of the latter (E.4). The silt-clay fractions are larger than those of in situ weathering products in the area. The dominant clay-mineral in all of these samples, as determined by X-Ray Diffraction, was illite (see 7.3.vi). The lack of swelling clays, and the low clay fraction helps to explain the small plastic range. The apparent stability and cohesiveness of the taluvium is evidently related to aridity, since the moisture level at liquid flow is quite low. Additional cohesion under the dry conditions is given by precipitated salts in the surface layers.

The taluvial deposits of the Biafo area also come into the category of "bedded slope deposits" (eboulis ordonnés). The stratification either consisted of old weathered horizons sub-parallel to the present slope but not necessarily separating strata of different composition or, more commonly, of a crude differentiation of layers of coarse and fine material, again sub-parallel to the present slope (Plate 9.10).

The fairly smooth compact taluvium of southerly slopes, with abundant migrating waste on them, resembled some features described in New Zealand (see Fisher 1952). The compact surface there was explained as due to sifting out of fines from migrating waste (ibid). This is important in suggesting that cohesive aprons may develop under dry conditions, and it may be a factor in the Karakoram examples. However, in addition to this detailed mechanism for laying down fines crusts, we need to explain the relatively thick aprons with abundant fines, and the

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[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

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bedded character. As elaborated elsewhere (e.g. 9.9.) the fines content probably relates mainly to old slope deposits derived [illegible] from glacial materials. In other areas, bedded slope deposits are mainly attributed to climatic rhythms influencing weathering and mass-movement processes (e.g. Raynal 1960). Another important factor is said to be the presence of basic rocks especially calcareous ones, (Corbel 1954). This is met by the abundant marbles of the Karakoram area, but the present writer has seen well-formed bedded slope deposits in shale areas of North Wales lacking any basic rock component. Variation in climate is likely to be a factor in the Karakoram talus development, but we should not ignore other possible agents. In the vicinity of large glaciers, base of slope condition may suffer critical changes through fluctuating ice-levels, increased pro-glacial deposition or erosion, and shift of outwash channels. These may trigger re-grading or backing-up of slope deposits. Both climatic variations and tectonic movements may, over long periods, affect slopes more by base of slope control, than changing the processes on the slopes directly. Furthermore, there was no definite evidence that bedding was uniform over large areas of slope or from one cone to another. It was generally very crude with lenses of coarse material occurring as often as planar beds. The present slopes have appreciable amounts of coarse material masking taluvium in places. It is conceivable that the random play of weathering and mass-movement across slopes could lead to alternation of slope material at a place. In the present landscape certain cornices and chutes shed abundant coarse material, others mainly finer material or little of anything (Plates 9.7; 9.9). The evidence indicates that this localisation of activities shifts from place to place on the slope as erosion proceeds. Along with the progressive re-excavation of old, fines-rich deposits this might produce irregular bedding of the kind observed. Obviously this is a subject requiring investigation, but it seems too early to attribute these depositional cycles only to climate without clearer evidence of how it will operate to organise the complex of processes on and below a slope.

9.7. Superficial Talus Patterns.

A variety of superficial patterns on the main talus elements were well-defined by colour, calibre or relative freshness of materials, by vegetation patterns, and slope micro-relief. Some of these apparently minor forms indicate geomorphic conditions more clearly than many of the bolder features.

9.7.i. The Choblok Stone Stripe Area.

The east sector of the south-facing Choblok embayment had some 25 acres of stone stripes (Plate 9.11.). In some respects the features conformed to Washburn's sorted stripes (1956 p.836), but were much longer than usual, at steeper angles; were re-inforced by vegetation patterns, and the stones were not wedged together in the way commonly described (Troll, 1944; c.f. Miller et al. 1954; Soons 1964 p. 84; Washburn op.cit.). The special interest of the features is their reflection of the Karakoram environment, when compared with other stone stripe areas. As will be shown, they are not genetically related to the stone stripes widely found in periglacial environments.

The loose stone stripes of Choblok lay between bands with a crust of packed fines, the latter having stones and pebbles embedded in it. On the bands and sometimes down the stripes grow lines of plants. The stripes were continuous for 1000-1500 ft. up the slope. Where the slope was approximately rectilinear the stripes were spaced regularly. In the lower 200 ft. coarse material built up and formed broad stone streams, stone lobes and scree-like aprons. These were 5-15 ft. across.

The slope profiles showed a considerable range of angle in detail, but over the central 800-1000 ft. were very uniform with mean angles between 35° and 36°. The head of the slope, close to the rock cornice steepened up to between 41° and 44°. Here, however, were only incipient stone stripes, defined by lines of artemisia bushes. The stones were in scattered patches or individuals, lodged on an irregular compacted surface. At the base of the slope a marked concavity was associated with modification and disappearance of the stripes into a complicated

pattern of lobes, patches and streams of waste, small scree-like aprons, and large fall-boulders. The downslope increase in depth and width of the stripes contrasts with a downslope narrowing reported in many periglacial examples.

The stripes were slightly incised, and except near the base of the slope, their surface was level with, or slightly below that of the packed fines. The basal streams and lobes, however, were up to a foot higher than surrounding parts and spilt out laterally as well as downslope. Vegetation growth was intimately associated with the talus patterns. Plant cover densities were low but increased upslope. Across the slope nearest shrubs were 1-3 ft. (head of slope) and 4-7 ft. (base of slope). In an upslope direction they were more closely spaced, usually 1-3 ft., the outer branches almost touching. In the lower 500 ft. of the slope the individual bushes stood up to 3 ft. high and 2-4 ft. in diameter. Artemisia was the dominant plant of the upper 500-1000 ft., growing on broad strips of finer material (Plate 9.11). These strips became narrower downslope ending in rows of single plants. In the lower parts, there are two other plants: a tussock grass in clumps 1-2 ft. across and 2 ft. high, and an aromatic shrub (related to Artemisia?) often growing in the stone streams and forming large bushes (Plate 9.12). In addition, patches of closely spaced Ephedra occurred on some outcrops of fine, grey mud. The grass tussocks grew in arcs, convex downslope, and with radius between 6 inches and 1 foot (Plate 9.13). The aerial growth sprouted from the downhill side of a tough clod of old roots. The arcs formed traps of loose waste; the downslope side was often undercut several inches. In winter, little snow patches survived several days longer in these arcs than on the rest of the slope. The same plant was seen to form complete rings on the flat valley floor. This growth form and the other features reflect adaptive advantages for coping with superficial movement of waste, and general slope aridity. (But compare some apparently similar lunes and rings of plants in the Turkish Uludagh interpreted as frozen ground phenomena by, Pfannenstiel, 1956).

The plants come mainly into the category of 'Scree-dammers' (Schuttstauer), the crust of fines serving to protect the more delicate roots from superficial movement (See Schroeter 1925; Harshberger 1929 p.16). Furthermore, the bushiness of the shrubs, and growth pattern of the grass also produces a local microclimate favourable to moisture conservation. These are important points, since there is certainly reciprocity between plant growth and the mass movement pattern, rather than one-way control.

The area was notable for the variety of talus material evident at the surface. At least five components could be distinguished by their differing composition:-

a) Taluvial apron material.

The superficial patterns lay over a surface of packed cohesive taluvium whose composition was described above. (9.5.ii).

b) "Outcrops" of grey mud:

Characteristically, there were patches of distinctly grey material of fine composition emerging through the main taluvial apron (see 9.5.ii).

c) Fine waste streams.

Associated with the stone stipes, especially near their lower ends, were streams of fine, non-cohesive waste. Almost all of the material was either predominantly sand or small pebbles (Fig. 9.7).

d) Stone Stripe Materials (Appendix 6).

These are primarily cobble particles with some pebble and small boulder size fragments. In an upslope direction the stripes decreased in mean grain size, and increasedin mean Flatness Index (Fig. 9.8).. In this respect they resemble the screes examined in the area (N.B. Examples of periglacial, sorted stone stripes frequently show upslope increase in particle size). The long axes of the stone stripe particles also tended to point downslope (Fig. 9.9).. Since the particles examined were loose and unstable the downslope alignment must reflect scree-like movement rather than, say, lateral pressure and sorting by ice. However, platy fragments at many points were standing on edge, wedged between other stones and oriented parallel to the slope. This is a common feature of frost controlled stripes.

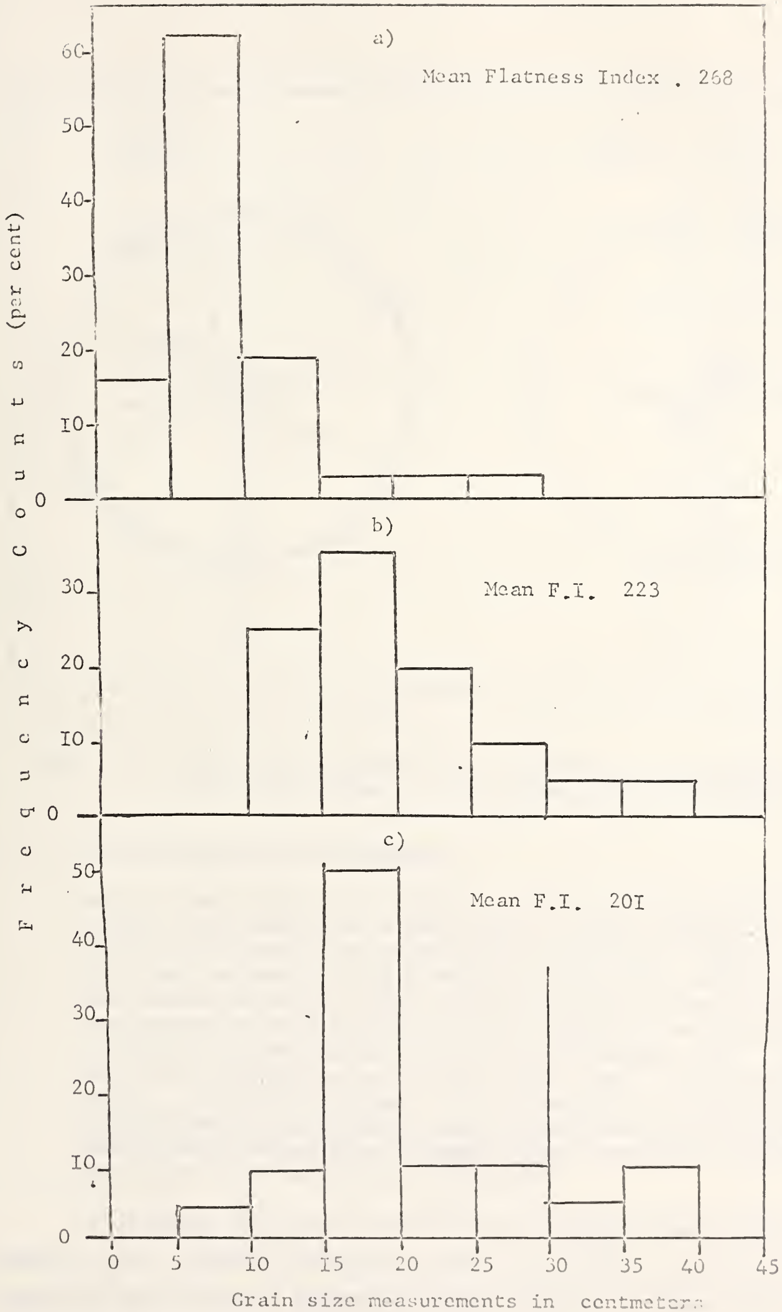

Fig.9.8.Size distribution of stone stripe materials :
a) near base of stripes, b) I00ft above base, and c) 250ft above base.

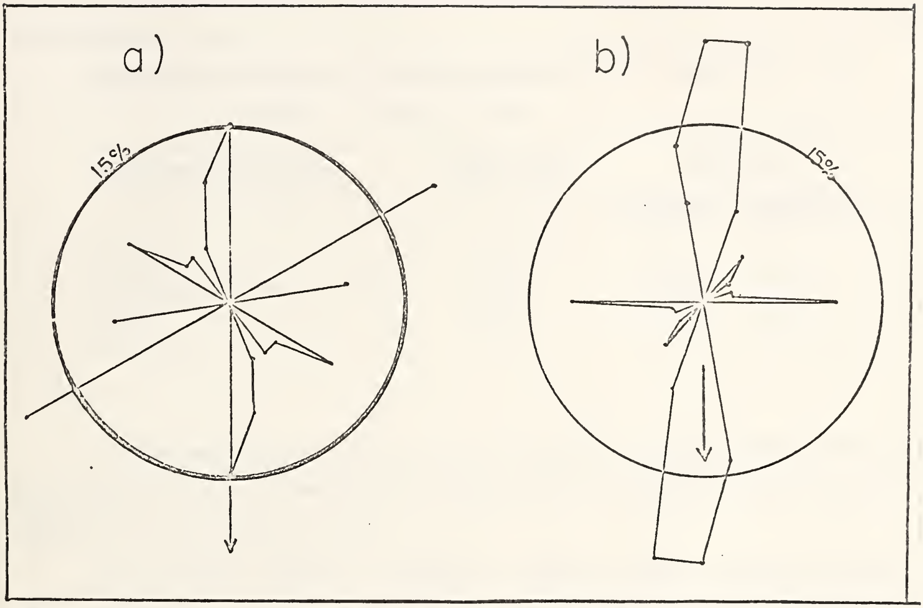

Fig. 9.9. Percentage orientation of particles at two points along the stone stripes, a) near base, and b) mid-slope position.

e) Basal Stone Lobes and Patches.

On the lower part of the slope in addition to the stone stripes proper, were many patches and lobes of coarse material. These consisted of cobble and small boulder grades but even the eye can pick out distinct sorting between one patch and another. Apart from being generally coarse, these materials did not conform to the upslope sorting patterns of the stripes. The platy fragments tended to cluster together separate from compact ones. The result is also a segregation according to rock type. The platy fragments here, - and in the stripes - were primarily schistose, with darker colouration and marked imbrication structures. The compact fragments, which, apart from in plant traps, occurred at the base of the slope, were intrusive or gneissic.

In addition there were collections of massive platy blocks at the head of slope, checked immediately below the cornice. A few such blocks were seen lower down as Wandering Blocks that had ploughed distinctive tracks down the slope.

Local slope angles varied with calibre of material over a broad range (Table 9.3.).

Table 9.3. Local slope angles associated with particular size grades on Choblok slope.

Dominant Constituent	Mean Angle	Extremes	
		Maximum	Minimum
Cobbles	34°40'	42°10'	30°
Pebbles and Coarse Sand	34 10'	35 50'	32 30'
Sand	30 20'	32 50'	21
Taluvium	35 40'	42 10'	24 40'

Variations within calibre sizes related to local banking and spilling effects, to the occurrence of vegetation or embedded stones; and to position on the overall slope.

The greatest amount of movement on these slopes occurred on mornings following snowfall. In addition, considerable activity was set off by herds of Makhor and Ibex in winter, and domestic herds at the beginning of the summer transhumance. Small spontaneous movements on sunny days appeared to be due to insolation (c.f. Anderson, et.al. 1959). With the intense solar radiation on these southerly slopes, thermal expansion and contraction of particles could be a major factor in persistent talus creep of loose stones. Owing to the dryness of the winter no marked wetting of the taluvial material occurred. But, since the fines crust became greasy, and more erodible when wet, scouring by sliding stones is likely to be important in wetter years. Finally, there was much triggering of secondary movement by initial falls and slides. The abundant superficial material moved downslope in "queues" normally at the angle of repose, and quite minor build-up of material gave instability.

The obvious omission from these active agents is frost. In the field only minor, poorly-developed needle-ice was found in the taluvium - mainly around the grass tussocks. The restrictive condition is poor moisture supply since temperature and talus materials would favour effective

frost growth (see 10.6). In wetter years, however, needle-ice growth may be important in breaking up the taluvial crust, promoting loss of strength, and even sorting stones. But if this is so, the effects are masked by the other, more vigorous activities. At least, the stone stripes are in certain key features unlike those controlled primarily by frost.

The looseness, downslope sorting, particle orientation and imbrication structures of the stripes suggest a scree-like movement of debris; the arrangement of vegetation is an adaptation to rapid streaming of loose debris over a compacted surface. At the base of the stripes, the build-up of streams and lobes of waste also reflects rapid downslope migration of debris. The controlling factors seem to be:-

a) Rapid supply of coarse weathering products to the slope.
b) An underlying taluvial apron, relatively hard for most of the year but capable of some erosion by moving superficial waste.
c) Low vegetation cover adapted to and assisting in the confinement of waste-movement to well-defined paths.
d) An arid slope free of channels coming through from high wetter areas and without much secondary relief. Hence, there is little to disturb the sensitive forms developed in the thin skin of superficial waste.

9.7.ii. Granular Disintegration "Streams".

In numerous localities of the Biafo-Braldu sub-nival area, sets of waste "streams" were noted consisting largely of coarse sand. They ran down from small outcrops and cornices of rock exhibiting granular disintegration (7.1.ii). These features were also seen along most of the Braldu, in all cases on southerly slopes, and normally on taluvial slopes with low knobs and cornices of rock and irregular slope profiles. No examples were seen where the sand streams were more than 150 ft. long. A fine set of them observed on Laskam will be described in more detail.

At 13,ooo ft., on the south-facing flank of a shallow dry valley, nine individual sand streams descended from a low, rounded cornice of crystalline limestone. The streams were irregularly spaced over a distance of 100 ft., and varied from 2 ft. to 7 ft. in width. Each stream was 50-60 ft. long, broadly convex in cross-section, and concave in downslope profile. The upper part rested at 32°, decreasing to 25° in

the central region, and 21^{o} in the lower, lobe-like portion. The streams rested on a compact taluvial slope with a slight suggestion of terracette development. In the upper part the streams were very slightly incised into the slope.

Mechanical analysis of samples of the stream material showed a dominant coarse sand fraction - 73% (Fig. 9.10). Inspection of the material coming off the cornice suggests that the silt-clay fraction, (nearly 9%) is introduced from the taluvial material. Perhaps the main fact was that the sand grains were pure calcite crystals. All the other instances of these streams which were inspected also consisted of calcite crystals. This suggests that we are dealing with water-starved processes.

The controlling conditions for the formation of these features seem to be aspect, erosional situation and rock-type. The sand streams are produced where rock responds to weathering by intensive granular disintegration. But the importance of low outcrops suggests that in larger exposures of rock, disintegration into larger fragments, possibly joint-bounded, masks or over-rides granular products. The short, only moderately steep slopes reflect the lower angles of repose of sandy fragments, and the pre-requisite for their accumulation in large amounts. Finally, and of more general interest were the southerly aspect at moderate altitudes, where rapid drying of surface moisture inhibits slope wash, that could sluice away the sand, and an erosional situation where more violent mass-movement processes are rare or absent.

9.7. iii. Downslope Patterns in Aprons of Loose, Fine Waste.

The downslope patterns described thus far depend on the presence of compacted taluvium. Elsewhere, there are aprons and cones of talus of largely non-cohesive fine material. Individual examples are not normally more than a few tens of feet high, but they occur repeatedly on and below stream terraces and breaks of slope throughout the subnival zone. The three main components of the downslope patterns are sorting into sifferent size fractions by adjacent "streams"; downslope lines of vegetation; and distinctions between "fresh" and dull coloured materials. Vegetation lines were irregularly spaced and con-

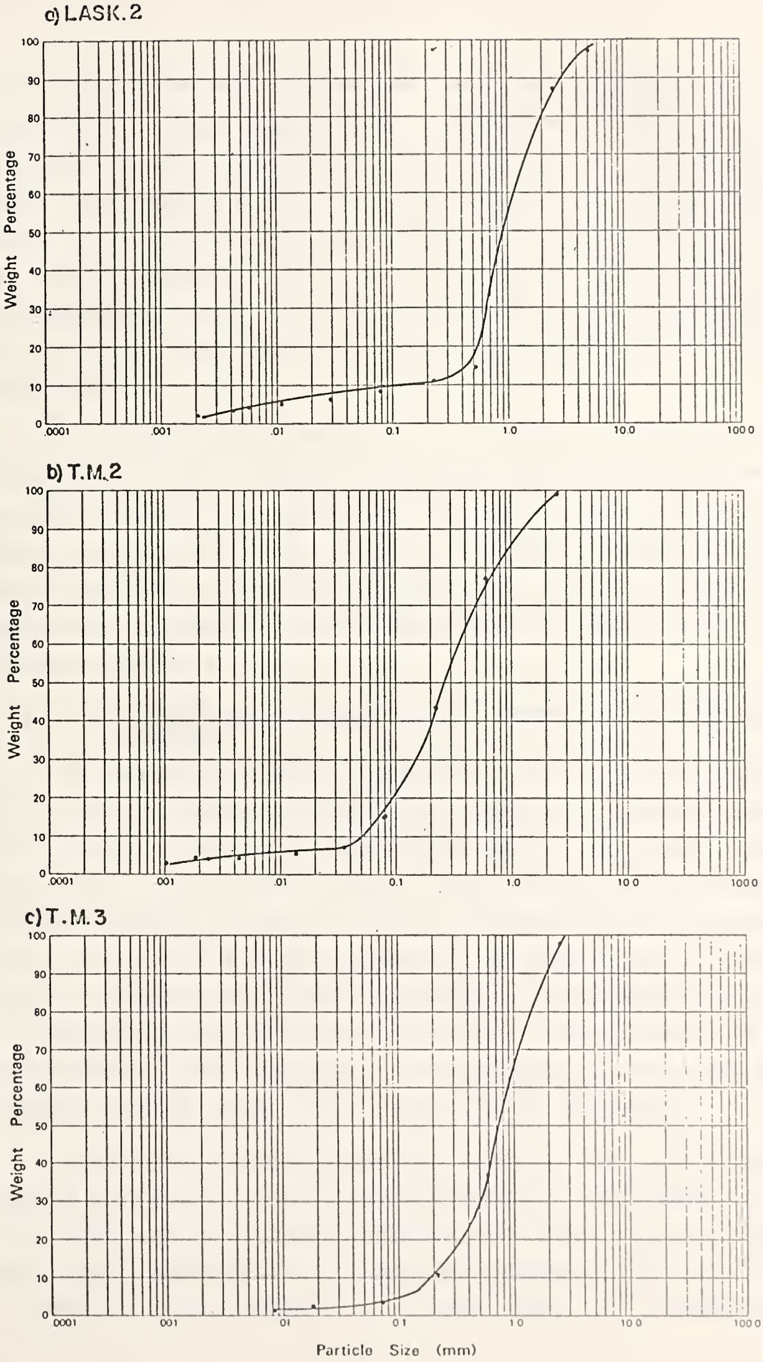

Fig.9.IO. a) Cumulative percent grain-size curve for granular disintegration stream on Laskam at I3,oooft.
b) & c) Cumulative percent grain-size curves for the fine matrix of loose, at two localities on Choblok at II,oooft.

fined to the lower middle reaches of the aprons. *Ephedra* was a common plant, and occasional *Ribes* bushes. Cobbles and boulders were scattered over these cones and aprons but most material was smaller than gravel. Two samples of the materials from distinct streams indicate similar composition to the granular disintegration streams but with a less severe restriction to one narrow size range (Fig. 9.10b and c). The samples were taken where the material was mainly derived from rock directly. Other cases have some old, re-excavated slope deposits intermixed.

The patterns arise where there is differential movement in a cross-slope sense, movement probably reflecting differences in the inter-granular friction of the materials, damming by plants, boulders or outcrops, variable sub-surface friction and moisture seepage, and the impact of rock-falls. The fine differences in sorting of the two samples suggest that differential creep under these dry conditions is a very sensitive process.

9.7. iv. Downslope patterns on active cones and aprons of northerly slopes.

In addition to new and old gullies, and debris-flow tracks, some active cones on northerly slopes had a superficial downslope pattern. It was defined by downslope rows of vegetation with 'tracks' between (Plate 9.14). The 'tracks' did not contain obvious stone stripes, but irregular patches, streams and lobes of material and long stretches of 'crust' with coarse material embedded in it (Plate 9.15). Slope angles on examples from Stokpa LungValley were predominantly about 36^{o}, steepening up at the apex of the cones. The vegetation of the plant lines was mainly *artemisia*, but *ephedra*, *ribes* and some *juniprus* occurred, forming larger plant traps than the *artemisia*.

The cones in Stokpa Lung Valley lay below long, steep cliffs reaching practically to the snow-line with only minor breaks of slope. At the lower end of the chutes supplying the cones were outcrops of grey, clay-rich material with some earth pyramids. It seems that the cone patterns relate closely to the latter fact, and to avalanches

moving down from high up. The silt-clay matrix of the cones, gives them moderate cohesion. Small streams of water from high up, persist through the summer cutting a gully down one side of the cones. Mudflow and debris-flow activity seems largely confined to these gullies. The main parts of the cones are affected by winter and spring avalanches which spread over them on a broad front (See 9.8.). The environment is moister than the stone-stripe areas, but the accommodation of plant growth to active mass-movement again results in down-slope lines of vegetation with movement tracks between.

9.7.v. Terracettes.

These were the only widespread form of cross-slope pattern, best developed on northerly slopes, but with poorer examples over large areas of southerly slope. Between 13,ooo and 15,ooo ft. moister southerly slopes along the glacier margins had well-developed terracettes. The pattern had the greatest extent of all the superficial talus patterns, a reflection of the importance of cohesive taluvium.

Few terracettes were strictly horizontal, most ramifying across the slope like a net stretched laterally. The longest individual steps were on relatively dry slopes with low vegetation cover (Plate 9.16). Here the vertical profile was smoothly concave between vegetation strips. On better-vegetated slopes steps were markedly angular. In general, the denser the vegetation cover, the more complex the terracette pattern (Plate 9.17). The largest terracettes observed were at 14,ooo ft. on a north-west facing of slope of Baintha Lukpar. Here steps were 2.5-3 ft. high, and cracks continued into the ground from the back-face. There was a closed vegetation cover of tall grasses, and the taluvium consisted of fissured clays. The dense vegetation and unusual concentration of reddish brown clays depend on the moistness and weathering of metamorphosed limestone. Elsewhere associated with moderately dense artemisietum on northerly slopes were extensive developments of sharp terracettes in rhomboidal patterns (Plate 9.18). Steps were generally between 1.5 and 2.5 ft. high.

On well-developed examples, slope profiles were the steepest of all extensive taluvial areas. There were some instances of very poor terracettes on southerly slopes at 30^{o}-35^{o}, but most cases exceeded 35^{o}, and areas with sharp steps exceeded 40^{o}. On a northerly segment of Choblok, with steps of 2-2.5 ft., terracette slopes lay at angles of 45^{o} - 45^{o} 50'. Slopes between 43^{o} and 45^{o} were measured on the terracette slopes of Stokpa Lungma Valley. The Baintha Lukpar examples were on slopes between 38^{o} and 43^{o}. These values should be compared with Behre (1933), who described limiting angles for his 'contour patterns' as being 30-32^{o}, while downslope patterns occurred at steeper angles.

Material composing the terracette slopes is that of the cohesive taluvial slopes (9.6.ii), with relatively high silt-clay content giving cohesion, and large fine- and medium-sand fraction (See Table 9.2).

Terracettes are common in a wide range of mountain environments with moderate to dense ground vegetation and steep slopes covered by predominantly fine material. They appear to develop by a combination of creep and small-scale rotational slip, the size of the slippage blocks being a function of slope angle and depth of taluvial cover. Their widespread occurrence in the Karakoram between 10,000 and 15,000 ft. relates to the taluvial material on these slopes, in turn related to the glacial legacy. Their predominance on northerly, and higher southerly slopes reflects the importance of local moisture supply and vegetation cover. Their absence or very poor development on many southerly slopes is sometimes a reflection of low moisture and vegetation; sometimes of the over-riding effects of streaming superficial waste.

9.7.vi. Boulder Festoons.

On the south-facing taluvial aprons of Baintha Camp Embayment (13,500-15,000 ft.) and Choblok (11,000-13,000 ft.) were areas with several hundred superficial lines of boulders arranged in curvilinear, cross-slope patterns, rather like pearl necklaces (Plate 9.19). They covered otherwise cohesive, moderately vegetated material at angles be-

between 32° and 36°. The features, all lay below short, wide and active chutes. The writer has found no previous description of such features, and coins the provisional term "boulder festoons" for them. The festoons consisted of small boulders and cobbles plastered with fines. The material was similar to that of debris- and mudflow levees. Clearly the bouldery material had flowed into these strange forms and in many cases, had actually moved round into the arcs and therefore across the slope. The process was not seen in action but a mechanism is suggested here.

The festoons seem to be formed by debris-flows that have failed to cut a channel in the taluvium when they leave the chutes. The short open chutes probably fail to canalise the debris-flows into narrow tongues. The cohesive, taluvial aprons with slight cross-slope convexity tend to further disperse the flows. Rapp described sheet-like mud-flows moving over talus without even moving his stakes and painted cobbles (1960 p. 155). Dispersed, sheet-like flow is evidently a prerequisite for the formation and on-slope checking of the festoons. But a thin sheet of saturated debris flowing down a steep slope is unlikely to remain in one piece. Irregularities in the material, the slope surface, and moisture loss should stagger the flow. Since it is fanning out over a slightly convex surface it might form a series of 'trains' analogous to "rain wave trains" (see Horton 1938). Flow may continue if the slope itself is slippery or snow-covered but intermittent checking of "waves" is also likely. Once in existence the festoons promote their own development by creating temporary dams and deflecting debris across the slope. The normal aridity of the slopes and rapid drying would help preserve these rather fragile forms.

Festoons were not seen on north-facing slopes but occurred over a large range of altitudes on southerly ones - 10,000-15,000 ft. They depend on the erosive conditions in southerly chutes, and the compact taluvial aprons of the talus zone.

9.8. Mass-Movement Dejection Cones, Fans and Tongues.

The flow varieties of mass-movement - avalanches, debris-flows, mudflows, etc., - create deposits that are a major element of the

Karakoram landscape. Even the enormous fans below high cirque glaciers in the main valleys include large amounts of debris- and mud-flow materials (see Chapter 14). The general term dejection features is adopted to cover these deposits. Some consider a term like dejection cone synonymous with alluvial cones (ed. Stamp 1961 p. 119). But the term "dejection" usually refers to mountain deposits which include many mass-movement materials with or without torrential stream deposits. In general, it implies rapid efflux from a steep gorge or chute, and piling up through sudden loss of momentum. Like alluvial cones and fans, mass-movement dejection features imply channelling, but of slopes, and lie below chutes or gullies.

In the Central Karakoram, most of the dejection features are in some degree complex, containing materials introduced by a variety of processes. However, one particular process was often dominant, and there was a general variation of the dominant process with altitude.

9.8. Avalanche Deposits.

These mainly occur above 13,ooo ft. and fall into four main categories, that can be called the supra-glacial, chute-trap, cone, and boulder tongue forms. The incidence of the particular type relates strongly to the position of the climatic snow-line.

a) Supra-glacial forms.

At the base of cliffs surrounding firn regions are innumerable cones and tongues of avalanche material. The cones lay below chutes, recesses and snow-flutes that canalise movement. They consist mainly of snow but with more-or-less abundant patches and tracks of debris. The fact that these are essentially part of glacial accumulation should not make their importance as mass-movement features. Though incorporated relatively quickly into the glacier; the material is constantly renewed and a perennial feature of the high altitude landscape. (For some magnificient photograph of the features - See de Filippi 1912, Pananamas C.S. and O).

b) Chute trap forms.

These occur in chutes passing below the snow-line (see 9.4. and 10.4.i).

c) Avalanche Cones.

Between the snowline and about 14,ooo ft. occur many dejection cones with few tracks scoured by wet flows. Their surface is covered with large blocks, and they show poor fall-sorting and a crude downslope pattern. Many reach hundreds of feet up broad chutes and couloirs at angles somewhat less than 40°. Another variety is the perfect half-cone below narrow, very steep chutes. These are built mainly by avalanching with an important free-fall component in the movement.

d) Avalanche Boulder Tongues.

Along the north-facing flank of Baintha Lukpar Gl. at 14,5oo ft., were some large 'roadbank' tongues running down from a sheer rock-wall, they continued 50 yds. across on ablation valley, rose 40-50 ft. over a high lateral moraine and plunged down to the glacier 100 ft. below. The tongues were 15 -30 yds. wide, 20-30 ft. high in the ablation valley, and 80-100 yds. from rock-wall to moraine crest. Some 30 ft. above the apex of each cone was the narrow mouth of a funnel-shaped chute (see 9.4. and Rapp 1960a). The material composing the tongues was mostly boulder sized and angular. There was a crude sorting of larger boulders towards the flanks. These features conform to Rapp's description of avalanche boulder tongues (Rapp 1959). There seemed to be more on the south side of Uzun Blakk Gl. but the writer did not visit them.

9.8.ii. Debris-Flow Deposits.

A transitional zone was apparent where avalanche cones had debris-flow tracks running down them. However, debris-flows form fans rather than cones and these became important below 14,ooo ft. Some fans were very large even along the glacier margins. An example near Baintha Camp was ½ mile across the base, of similar length, and 800 ft. from base to top (Plate 9.20). This fan was compound. Like other debris-flow fans it had a concave long-profile, the apex lying at about 29°, the outermost fringes at between 1° and 4°. There was only a slight suggestion of convexity in cross-profile. A maze of old and fresh tracks covered the surface with the typical levees of coarse material (see Sharp 1942). Individual flows had somewhat straighter tracks than those of the mud-flow fans. The periphery of the fans consisted mainly of finer material, especially washed sand, and the distal tongues and lobes, ("snout" in Sharp op.cit.) of more vigorous flows.

In the upper parts of chutes feeding the debris-flow fans avalanche activity predominated, but it was stifled by channel irregularities lower down. Avalanching gave way to debris-flow activity as the chief depositional agent approximately between 12,000-14,000 ft.

In addition to large and small fans there were innumerable debris-flow tracks ravaging talus slopes around the Biafo and leaving levees and small distributary tongues of waste. The features were common to slopes of all aspects in the sub-humid belt below the snow-line (See 10.5.i.).

9.8.iii. Mudflow Deposits.

Below 12,000 ft. were more mass-movement deposits with a significant silt-clay content. While mudflows occur frequently on north-facing slopes, extensive and fairly pure mud-flow deposits are mainly a southerly slope phenomenon. At the western end of Choblok embayment were two large fans consisting of mud-flow material. They formed what Rickmer Rickmers graphically called "Lion's Paw" Fans (1913 p. 201), with tracks of recent mud-flows like irregular sinews over the surface, and a truncated and notched fan front (Plate 9.21). These two examples had a frontage of ½ mile each and were ½-¼ mile in length. The western one had a perennial stream running through it and cutting a gully 10-30 ft. deep, but alluvial deposits were minimal on the fan itself. The stream had shifted its channel from time to time through mud-flow jams. However, two secondary fans running out from the present, and a previous, stream gully indicate that most mudflows follow the stream channel. Hence, there are fewer ramifying, fresh tracks which cover the other example. The mud-flow channels were 10-15 ft. deep with sharp walls in the cohesive materials. The beds of these gullies had signs of stream action including pot-holing, but were generally very irregular. The levees were typically 3-8 ft. high, consisting of boulders and cobbles, with a noticeable amount of fines between or adhering to them. As with the debris-flow areas, there were also innumerable minor mudflow tracks with attendant bouldery levees and

distributary tongues of fine material.

The eastern fan was 900 ft. from base to apex, its lower part convex in cross-profile and roughly straight in long-profile, the latter falling at between 6^{o} and 10^{o}. The upper half steepened reaching 18^{o} near the apex giving an overall concavity. The western example did not have the steepened head, (probably due to the stream's activity), was only 600 ft. high, and convex downslope in the lower part. Some samples of the material in the easterly Choblok fan were examined for certain key properties. The samples and results were:-

a) Boulders exposed on levees 30 yds. below the apex of the fan.

These were measured to obtained size and shape parameters (Appendix 7). The boulders were sub-rounded and ranged in size from 1.5 cu. ft. down to 38 cu. inches, the mean of the long axes being 12 inches. Flatness Indices varied between 122 and 282, with a mean value of 160. Since the source area was ¼ mile in radius the sub-rounded condition and low flatness index appear to reflect rapid abrasion by the mud-flows.

b) Fine matrix of the levees in the same area (S4).

The silt-clay fraction was 10% with 6% clay-size; 50% was sand and the remainder small pebbles (Fig. 9.11a).

c) Mud-lobes deposited on the fan. (T.3 & F.3).

Grain size frequency curves were similar to the levee matrix (Fig. 9.11b and c) but with somewhat higher silt-clay contents. Clay-size material was 12% and 10% for the two locations sampled. Consistency limit tests were also performed, giving a Liquid Limit of 27%, Plastic Limit of 13.5%, and Plastic Index of 13.5%. Of all the slope deposits, this P.I. was most closely paralleled by material gathered from the earth pyramids (9.9.) and it is important to note that in the area of provenance of these mud-flow fans there were several suites of earth pyramids (c.f. de Filippi 1932, p.293).

d) Sandy material washed out beyond the main mud-flow fans, (S.1.2.3.)

These had negligible silt-clay fractions and consisted primarily of sand. (Fig. 9.11d and e). One location contained 40% small pebbles. The low angle flats (1-3°) where the samples were collected were composed of material washed out beyond the lobes and levees of the mudflows, and strikingly reveal the effect of ephemeral streams of water in sorting material; rejecting the coarse debris and sluicing away the very fine.

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[illegible]

[illegible]

[illegible]

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A feature of the fans characteristic throughout these mountain regions is the sharp truncation of their distal parts. Recent down-cutting is responsible for the truncation; the preservation of a steep cliff reflects aridity and the cohesiveness of the mud-flow deposits. The surfaces of the main fans were evidently graded to the highest of the recent terrace levels, but the fans were set back from the rivers above other terraces on which minor mud-flow fans and tongues occurred. In the Choblok examples the main deposits washed beyond the fans were sand flats. Other than the perennial stream of the westerly Choblok fan, headward erosion from the new base-of-fan levels was very irregular. However, the truncated fronts had short, deep notches cut in them, (Plate 9.22) and the mud-flows have begun to re-excavate the fans. Compared to the old fan surface untouched by recent flows, the present mud-flow tracks seem less random with two or three deeply incised gullies which carry most of the flows. The notching of the terminal cliff isolated small tabular and finger-like masses of mud-flow material forming earth-cones (See Wood 1922; Rickmers 1913 p.205; Durand 1900 pp.33-34).

9.8.4. The Biafo Complex Cones.

At the base of steep, glacier-smoothed cliffs along Biafo Lungma occurred some perfect half-cones (See Plate 12.6) at the mouths of narrow, steep chutes descending between 2,000 and 8,000 ft. without a break. In detail the surface of the cones was broken by patches of enormous blocks and debris-flow tracks. Debris-flows, avalanches, stream action and rock-falls all contribute to the formation of the cones. They owe their perfection of form to the steep funnelling of debris which resembles vertical feeding from a hopper. The complex variety of processes reflects the uninterrupted chute channels, northerly aspect and large altitudinal range of source areas. There are many cones of this type along the Braldu and tributary valleys. In nearly all cases they lie below northerly cliffs oversteepened by glacial action.

9.9. Earth Pyramids.

Suites of earth pyramids occur throughout the Upper Indus Basin (Note 9.1.). In general, the pyramids have few protective boulder caps,

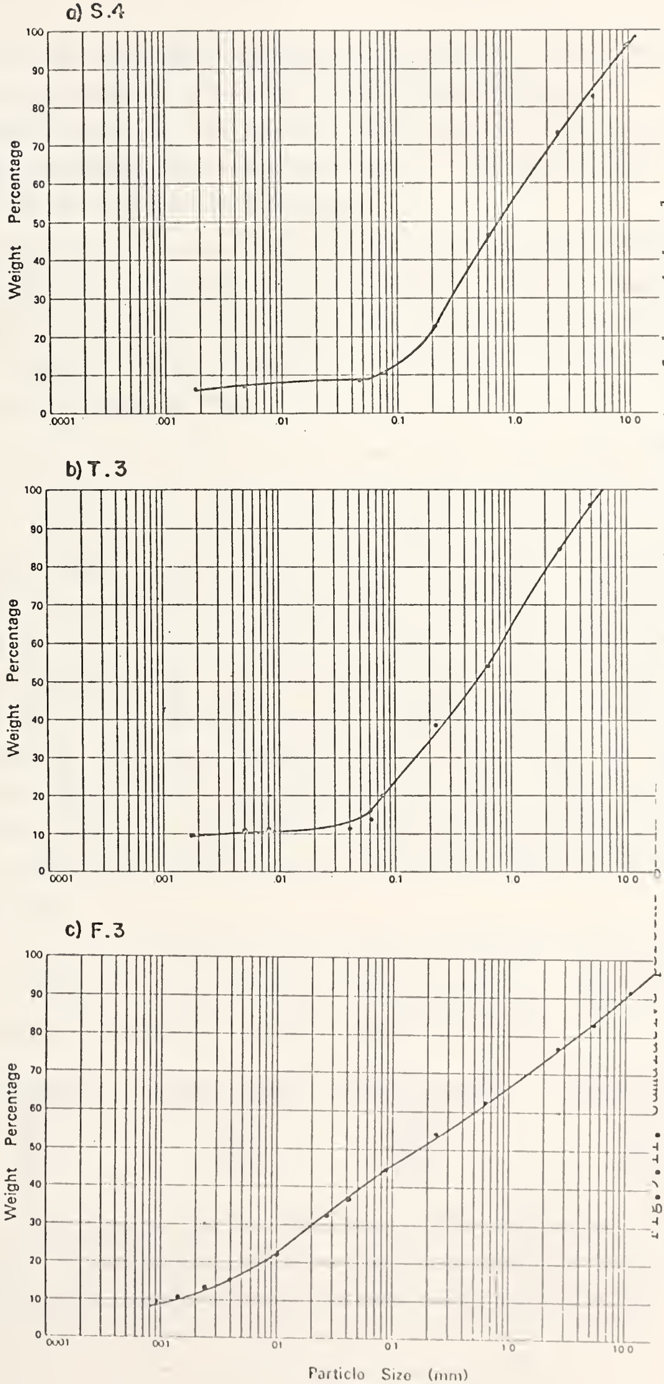

Fig.7.11. Cumulative

a) Matrix material of mudflow levee. b) & c) Fine matrix of depositional lobes on mudflow fan. d) & e) Sandy material washed out beyond fan.

and are not strictly earth pillars ("Demoiselles", "Erdsaulen"). According to Becker's terminology they are earth cones, - "Erdkegeln", while the few examples with capping boulders may be false earth pillars "Erdsaulenahnlicher..." (See Becker 1963). The distinction is genetically important.

The earth cones in the Biafo area rest on the surrounding slopes rather than being carved in them (Plate 9.23). But the impression of resistance to erosion is tempered by the fact that the earth cone suites have the highest "drainage densities" of all talus slopes, and the appearance of badlands (Plate 9.24).

Most of the cones are broad based and finger-like rather than strictly conical. The upper and middle parts show signs of sludging and washing. The base is undercut on the lateral and downslope sides. This seems common to most earth pyramids (c.f. Becker op.cit.). The basal parts and immediately surrounding slopes have multiple, closely-spaced rills cut into the grey cone material. In the close-packed pyramids narrow gullies sever individual cones and show signs of rill incision as a minor formative agent. However, most channels, and all the large ones have rough, broadly convex beds. These are full of embedded and superficial stones plastered with mud, and are mud-flow, not stream, gullies. The heads of the channels sometimes form shallow bays or amphitheatres hemmed in by, and often undercutting the walls of the cones.

The earth pyramid materials show relatively high silt-clay fractions - 50%, 64%, and 88% (Fig. 9.12 a, b and c). Consistency limit tests on these materials gave the following values:-

Sample	Liquid Limit	Plastic Limit	Plastic Index
TM 4	29%	18.5%	10.5
TM 1	20.7	10.1	10.6
T 1	22.5	11.9	10.6

These limits and the Index are rather higher than for other slope deposits. In conjunction with the high silt-clay fraction they help to explain the erosional resistance of the earth pyramid areas. The near

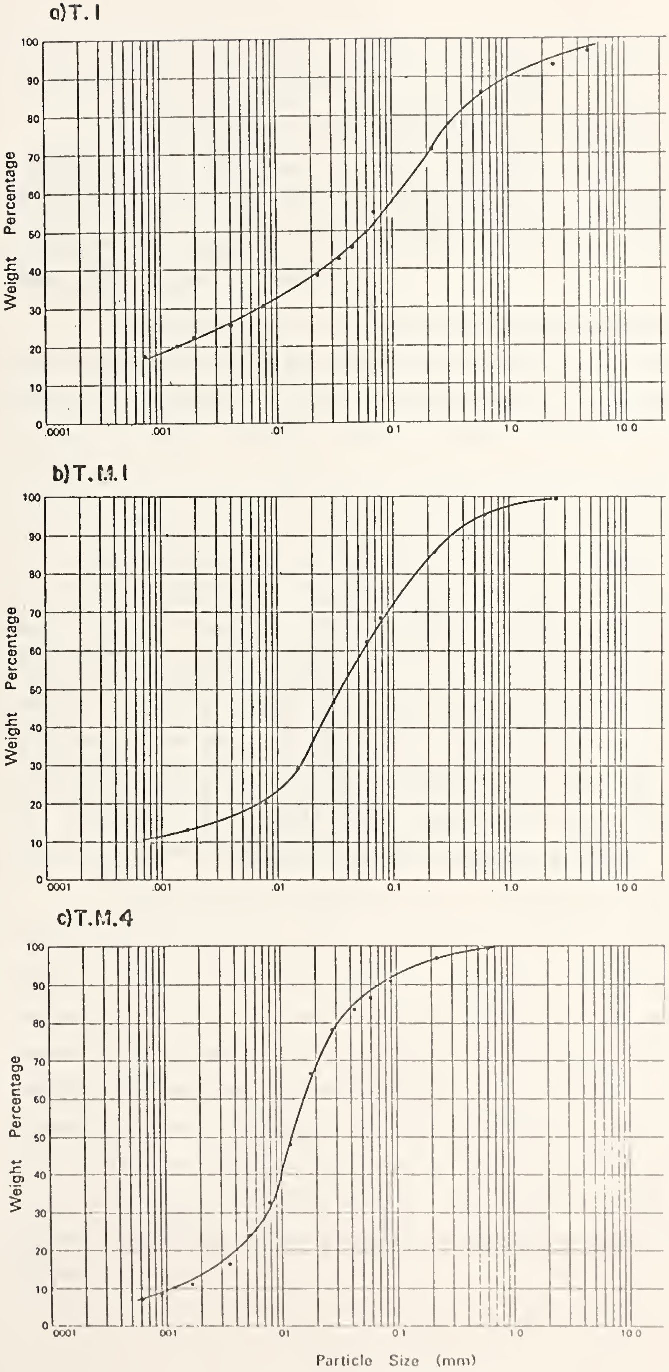

Fig.9.I2. Cumulative percent grain-size curves for earth pyramid materials at three localities on Choblok.

vertical slope and normal hardness of their walls is an expression of cohesiveness given by high silt-clay content.

The earth cones are interesting for two particular reasons. Firstly, their forms and the fact that they are not earth pillars reflects the nature of the present erosional environment. Secondly, the type and origin of the material of the earth cones throws light upon other taluvial features.

The pyramids are not primarily the products of rain-beat on soft materials with protective caps (Note. 9.2). The chief factor is relatively effective linear erosion between the cones and ineffective erosion on them. Between the cones snow collects and lasts longer. On the cones snow collects with difficult and usually evaporating directly and causing very little wetting and rilling of the surface. When the snow in the hollows and gullies melts it is able to thoroughly wet the surface material. Sapping takes place and some of the runoff cuts small rills. However, removal is mainly effected by mud-flows occurring when a sufficient quantity of the earth-pyramid material becomes soaked. In late spring and occasionally in summer there are periods of rain in the area and these give some rain-beat erosion. This may explain the fact that, while protecting boulders are not necessary for the formation of pyramids where they are present the cones are slightly higher and more tapering than the examples without.

Turning to the problem of the origin and localisation of the earth-pyramid material, it is significant that the only contemporary deposits with these quantities of silt-clay are the pro-glacial lake sediments (12.8). The earth pyramid materials are not however hydraulic deposits and in most cases are not till either. There were several bedding planes trending sub-parallel to the present slope surface, and a few structures indicative down-slope sludging of the original material (c.f. Bonney on similar features of the Alps, 1902 p. 12). The materials seem to have been slope-deposits. The problem is how the fines-rich materials originated and remained localised at particular places on the slopes.

The locations of the principal earth-cone suites conform to a pattern. If we reconstruct ice movement at levels 3,000-4,000 ft. above the present valley floors, they would be in relatively protected areas tucked away in the lee or stoss side of obstacles the ice would have moved round. The Choblok suite lies in the upstream angle of a pronounced knoll, the three Bakhor Das suites on the downstream side of a spur or bastion rock (e.g. Plate 9.5.). The Laskam cones lie in the angle between the (ancient) Panmah and Biafo glaciers. In the ablation zones of present-day glaciers it is in such protected localities that small kame-terrace lakes form and considerable quantities of fine material accumulate. At many places of this kind along the Biafo, present or recently-dried lake beds occur with thick deposits of mud, rich in silt-clay particles (see 12.5.).

Under the wetter conditions which probably continued during the early phase of recession of the large glaciers, the pro-glacial materials would have suffered solifluction, slope wash, and sludging moving them downslope and building aprons of taluvium. With increasing aridity the slope deposits with higher silt-clay content would show increasing resistance as in the present earth-cone areas. This reconstruction fits in with other lines of enquiry. Meanwhile, at the present time the earth cones like other areas of excavated old slope deposits provide greater quantities of silt-clay material than current weathering in the semi-arid zone. This material plays a significant role in the forms and processes acting over other parts of the taluvial slopes.

CHAPTER 10

SLOPES AND MASS-MOVEMENTS III

SURVEY OF PROCESSES AND CONCLUSIONS

10.1. Introduction.

Here the processes observed on slopes or inferred from other evidence are described and their role in the landscape suggested. As a basis for the terms employed a system of classification of movement processes is given (Table 10.1). The classes derive mainly from a U. S. Highway Research Board System, but some changes and terms more common in geomorphology are introduced (H.R.B. 1958).

10.2. Mass-Movements Actually Observed in the Field.

While more activity was seen in the Karakoram than in most regions, many movements had still to be inferred from circumstantial evidence. Usually, as with mud-flow levees, slump-blocks or bump-holes, this is done with confidence. Nevertheless there must be an element of deduction which needs to be qualified by stating the actual movements observed. (Table 10.2). Except for lack of direct observation of creep, other evidence suggests that the movements seen are representative of the Central Karakoram. In a wetter year debris- and mud flows should occur in greater numbers, but with a corresponding increase in all activity.

10.3. Mass Movements I : Falls, Slides, Glide and Creep of Rock

10.3.i. Movement Features and Distribution.

Everywhere the rock walls of the area showed the effects of slide and fall transport. Material moved in this way lay at the base of all slopes. Closer inspection revealed innumerable slide and percussion marks over rock surfaces. Cracks, and countless small rupture scars recorded points of release, and the many active localities where shown by "freshness" of surface material. The multiple bump-holes in talus and alluvium and large number of movements actually observed show the processes are fully active at present, - though one might be deceived by

Table 10.1 CLASSIFICATION OF MASS MOVEMENTS

Type of Movement	Type of Material (N.B. Prior to movement)			
	Bedrock	Rock Fragments: Large ——▶ Small	——▶ Fines Predominant	Other
FALLS (clear or with bouncing) Increasing Velocity ↑	ROCK FALL (Hig) Boulder Fall (Ra2)	Stone fall Pebble fall (Ra2)	SOILFALL (Hig)	ICE-BLOCK FALL (Firn-, Glacier-, "Black"-)
SLIDES Few Units ↓ Many Units r^x rotational p^x planar	(ROCK-) SLUMP (r^x) (Hig) BLOCK GLIDE (p^x) (Hig. Bal.) ROCK SLIDE (p^x) Boulder Slide	DEBRIS SLIDE (p^x)	"BLOCK"SLUMP (r^x) (Str. Hig.) "Slump Earthflow" (Jo) EARTH SLIDE a) Bowl Slide (r^x) b) Sheet Slide (p^x) (Ra2)	SNOW SLIDE (p^x) "Slab Avalanche"
	ALL UNCONSOLIDATED			
	Coarse Rock Fragments	Sand ——▶ Silt	——▶ Mostly Plastic Materials	
FLOWS Increasing Velocity ↓ Dry ↓ Increasing Water/Ice Content	ROCK CREEP TALUS CREEP (Shl) ROCK FRAGMENT FLOW (Hei. Ken. Mu.) ROCK GLACIER FLOW (high velocity)	DRY EARTH FLOW (Jo) SANDRUN (Hig) LOESS FLOW (CM. Hig.) RAPID EARTH FLOW (Shl) SAND-FLOW SILT-FLOW (Hig) DEBRIS FLOW (Hig. K.) - - - - - - - - - - Bouldery Mudflow (K) "Mountain Mudflow"	SOIL CREEP SLOW EARTH FLOW (Hig) QUICK-CLAY FLOW (TP) SOLIFLUCTION (An) "Failure by Lateral Spreading" (TP) - - - - MUDFLOW BOG BURST (Bow)	AVALANCHES (See Sect. 8.6) SLUSH FLOW (WG)
SUBSIDENCE	CAVERN COLLAPSE	SETTLING OF DEPOSITS		KETTLE FORMATION
COMPLEX MOVEMENTS	(= Various combinations of the above types)			

NOTES
1. Terms in Large Script = Major Classes
2. Terms in Small Script = Sub-Classes
3. Terms in Quotes = Synonyms or Ill-defined Classes
4. For references see Table 8.7

TABLE 10.2. Mass-Movements Observed in Action or Shortly After Known Occurrences, September 1st 1961 to May 15th 1962.

Type	Incidence	Comments
FALLS		
Rockfalls	Very many	Perhaps fifty seen many more heard.
Stonefalls	Very many	They were concentrated during intermittent melting in late autumn and winter, and in spring.
Soilfalls	Three	In January and April, from terraces in of the Braldu.
Iceblock falls	Many	From glacier carapaces or hanging glaciers of Baintha-Latok region and along the flanks of the Biafo.
SLIDES		
Rockslides		
a) Very large	Five	Near Baintha Camp, late September (2); Biafo West Wall near snout in January and February (2); Braldu Gorge in April (1).
b) Small	Very many	Concentrated as in the case of rockfalls.
Debris slides	Many	Concentrated as in the case of rockfalls. Often mingled with stonefalls or followed rockslides.
(Block) Slumps	Four	From kame terrace of Biafo west side in November (1), from Braldu terraces in January and April (2), and from Shigar Valley terrace near Braldu entry in April.
Earthslides	Three	From old lateral moraine of Baintha Lukpar in October (1), and from Braldu terraces in April (2).
FLOWS		
Dry earth flow	Several	From Braldu terraces. Examples at all periods.
Sand run (small)	One	Braldu terrace.
Debris flows	One	A small one near Baintha camp in November.
Mudflows	Nine	Upper Shigar Valley (2), Braldu Valley (2 supercharged streams, 3 true mud-flows), Dumordo Valley (1). All in late March and April except last which was in January.
Avalanches	Very many	Literally thousands over the period and at all seasons, but extending to lower altitudes in late winter.
Frost heaving	Some small patches	Minor irregular growths of needle ice disturbing superficial material, but never extensive. Seen in February, March and April.

the calm of summer conditions in the sub-nival zone. Throughout winter and spring small rock falls were the most frequent movements observed in that zone.

Two main slide situations were seen; slides canalised by chutes, and those following slip planes provided by rock structures. The examples in chutes were generally small and, unlike the many falls, seemed unimportant compared to avalanches and debris-flows. It may be that the platy rock masses of metamorphic slides do not move easily down confined channels. Also, the best developed and largest slides, of the second type, occurred especially where the slope coincided with the dip of the metamorphics where chute development is poor. Throughout the metamorphic areas of the Braldu, Lower Biafo, Panmah and adjoining valleys were vast areas of rock wall formed of segments cut along steeply dipping structural planes, mainly bedding-planes. Many had typical slide masses piled up at the base. Frequently, the slip surfaces allowed slides with little deformation or reorientation (Plate 10.1). Most of the large rock-slides occurred under these conditions. Commonly there were predominantly slide-slopes and fall-slopes on opposed sides of crest-lines, salients, and valleys (Plate 10.2). The slope angles of the opposed flanks need not differ greatly but the steeply dipping metamorphics provide good slip surfaces on the dip slope, and rugged surfaces on the scarp slope preventing efficient sliding. However, vertical and overhanging segments were more common on the scarp slopes. Creep and glide phenomena are not so conspicuous. With the very steep slopes, loose material is soon propelled downwards. Slower forms of movement were largely observed where immediate descent was barred. A typical example was the rock creep on medium altitude crest-lines and spurs (Plate 10.3). The close relation of erosion and structure was brought out here too. Small examples of bending and tilting of strata split along bedding planes occurred at the base of rock cornices, along most shattered crest-lines at moderate altitudes, and around minor salients. True glide phenomena were only seen where metamorphics dipped at low angles (less than 30^{o} as on Shinlep Bluk) or where a resistant mass checked the development of a slide.

The observations of frequent and widespread falls and slides in the Biafo area applies to most of the Karakoram and surrounding ranges. Examples were seen in profusion along the whole Braldu valley, the Shigar valley and Basin of Skardu. While flying up and down the Indus Gorge from Skardu to Attock area, the writer identified innumerable slides of the structure-guided types described at the Biafo. There are abundant references to these processes in the literature. Unfortunately most descriptions treat all falls and slides together as 'avalanches', or when large, 'landslides'. The terms 'mud avalanche' or 'stone avalanche' sometimes help to distinguish movements from those involving snow.

A notorious area is the Hunza Gorge and adjoining valleys. From there come numerous reports of large slides which begin thousands of feet up and continue for many hours and sometimes several days (see Cockerill 1922 p.104; Shipton 1940 p.412; E.S.Williams in 1957 p.com.; Miss F. Azhar in 1961 p.com.). These slides show considerable progressive and retrogressive growth (see Kjellman 1955). The Hunza,and Indus Gorge at Nanga Parbat are well-known for slides of magnitude sufficient to dam the main rivers.

10.3.ii. Incidence of Rock Falls and Slides in the Sub-nival Zone

The strong variations in intensity corresponded to seasonal change. In August and September 1961, movements were rarely observed below 15,000 ft. However, from the first light falls of snow at these altitudes, and the beginning of freeze-thaw cycles, there were spates of minor falls and slides. A definite lessening of activity occurred in mid-winter, though sporadic movements continued on most days. The greatest amount of movement between 7,000 and 15,000 feet occurred in late winter and spring. This seasonal pattern is well-known elsewhere (see Heim 1932; Rapp 1960 p.106 and Bjerrum 1963 p.81). Yet, the contrast of intense activity in late autumn and spring with the dormancy of the second half of summer was exceptionally strong. (The expedition Base Camp was sited at the mouth of a sheltering gorge at about 10,500 ft. It was peaceful until late November. From then until it was abandoned in late May hardly a day passed without small rock falls coming off the cliffs above, persuading us

to move all activities and tents beyond the gorge mouth.)

There were smaller variations within the broad seasonal pattern. In winter, activity varied sharply with time and type of day. There was always a sudden increase of activity when the sun reached any slope. Most falls and small slides were concentrated on sunny days and in the first few hours of sunshine. A typical sequence is shown by a series of rock-fall counts made at Baintha Camp during changeable weather in October (Fig. 10.1) On the other hand three of the largest rock slides occurred at night, two of them in January during a very cold period.

In addition to temporal variations, there was marked spatial variation in activity. With the onset of winter, a definite progression downslope took place, not very marked in the Braldu valley, but well-defined between the middle and lower Biafo. The change followed the lowering of the precipitation belt. There was also a definite aspectual variation. While activity was generally reduced in mid-winter, it was greater on southerly slopes. These maintained an active zone below 14,ooo ft. throughout the winter, rapid removal of snow by winter sunshine being related to considerable small-scale movement.

10.3.iii. Initiating Factors.

While most of the possible initiating factors of mass-movement are in some measure present in the region, certain ones are specially important or peculiar to the Karakoram situation. The over-riding features are deep dissection exposing large areas of steep, bare-rock cliff; great variation in temperature and moisture availability; glacial over-steepening of slopes, and frequent and varied 'trigger' mechanisms.

The distribution of slope angles, and altitudinal range are eloquent of great relief energy (8.2). While many rock cliffs at middle altitudes descent to dry, low-angle terraces, the over-steepened slopes effectively behave as though basal removal were taking place. Along the main river valleys, recent down-cutting has produced a new generation of active slide and fall slopes. The large slides of the Hunza and Indus Gorges reflect several thousand feet of river incision since the mid-Pleistocene (see Paffen et al. 1957).

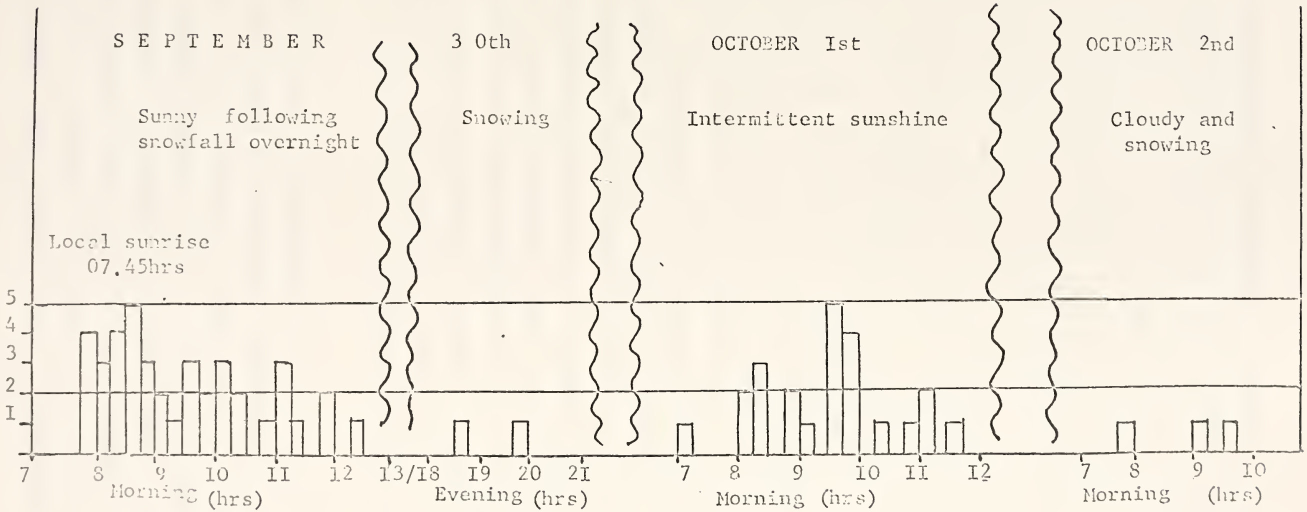

Fig. IO.I. Rockfall count in ten minute periods for some days in October 1961 at Baintha Camp. The slope involved was about I mile long and 3,500ft high.

The gravitational component, by providing for the rapid removal of loosened rock, emphasises surfaces of mechanical failure that follow structural lines. The role of rock-type in the development and sculptural effect of mass-movements is very marked. Failure occurs along developing fractures or weathered surfaces in the rock fabric. In particular, rock units defined by bedding planes and joint systems are major elements in rock-falls and slides (c.f. Keller 1964; 7.2 and 7.8). The joint-bounded block is a major component of the Karakoram falls and slides. In metamorphics, stress minerals arranged in planes, especially mica have relatively low shear resistence parallel to those planes. Along the Lower Biafo and Braldu valley, micaceous surfaces in the metamorphics are a prime factor in the provision of slide-planes for rock-slides (see also Heim and Gansser 1939 p. 71 and Bhaskaran 1962 p.80 on other parts of the Himalayas). A related factor is the tendency for tensile strength in rock to be lower normal to the bedding planes in laminated rock (Hobbs 1964 p.394). Oversteepening and undermining of rock gives axes of low tensile strength an important role in the geometry of mass-wasting. The outwards tilting of platy masses on cliffs in the metamorphics, rock-falls from overhangs (Plate 10.4.) and rock-creep (Plate 10.3.) are largely responses to tensile stress. Also, the 'unloading' features of the massive granites and many metamorphic cliffs, - exfoliation and sheet-structure - are special but important examples of tensile fracture parallel to erosional surfaces (see Balk 1939, p.307-310). In all of these cases, the rapidity of removal gives full expression to the effects of structural diversity.

The strongly varying temperature and moisture regimes are chief factors in initiating rock movement, emphasised by long, steep slopes, which increase the incidence of 'chain reaction' movements triggered by already falling or sliding rock. In addition, seismic activity probably plays an important initiating role. Earthquake triggered movements may only affect any particular spot at long intervals. However, when shocks do occur they can initiate a vast amount of movement in a short time, and provide the extra energy needed to set off the really massive landslide.

On the Kondus Glacier (August 25th, 1912) the Workmans experienced a seismic tremor after which "...the thunder of avalanches and rock-falls continued for forty minutes..." The effects were more severe in the lower Kondus and Saltoro Valleys where the air remained "...murky with dust..." for several days, and secondary landslides continued to occur for some days, one lasting nearly 10 hours (Workman 1917 pp.215-216). Cockerill reported the "coming alive" of slopes following earth tremors as a frequent occurrence and described an example near Tirich Mir (1922 p.110). Examples are also recorded by Mason (1914) and Coulson (1937). The most spectacular single geomorphic event on record for the region, the 1841 natural dam burst originated from an earth-quake triggered landslide of enormous dimensions (Becher 1859 p.226; Drew 1875 p.417). There are numerous descriptions of enormous slides following earthquakes in the mountains surrounding the region (see Auden 1935 pp.78-79; West 1935 p.203; Suslov trans.1961 p. 532).

The rhythmic micro-seisms that occur during periods of high river flow are thought to induce subsidence and slides (Bhaskaran 1962 p.81). These micro-seisms are due to the movement and percussion of boulders on the river bed, a marked feature of Himalayan streams during peak flows. Probably the mechanism could act as the final trigger of certain landslips, but must depend on other factors to bring the slip area close to failure condition.

10.3. iv. Concluding Remarks.

The frequency, size, and numbers of slides and falls indicate the importance of short-lived, rapid movements in slope erosion. Also, high rates of erosion are suggested for these processes, field evidence indicating much more intensive activity than the writer has observed in mountain areas of Britain, Norway, Switzerland or Cyprus. The importance of seasonal variations in activity, associated with temperature fluctuations and snow-melt is evident here as in most mountain environments. Spring and early summer are the outstanding phases in the subnival zone.

The fierce erosion by these processes does not, however, lessen

the importance of structure as a factor in landform morphology. On the contrary, the intensity of processes often emphasises structural detail. In particular the form of slope salients, and of snow-free peaks reflect stripping away of rock along planes of weakness occuring in the bedrock.

10.4. Mass Movements II. Avalanches.

The term 'avalanche' is restricted here to movements with snow the major constituent. There is not much geomorphological literature on avalanche activity in English and most of the Continental writers deal mainly with technological and safety aspects. Nevertheless, the belief of Allix (1924 p.544) and Matthes (1938 p.633) that avalanches have a major and much under-estimated role in mountain sculpture seems valid, and certainly applies in the Karakoram. To aid description the varied terms in the literature have been rationalised into a formal classification, based primarily on Continental usage (Table 10.3).

10.4. i. Spatial and Temporal Distribution of Avalanches in the Karakoram.

The interrelations of seasonal climatic fluctuation, and great relief produce some clear variations of avalanche activity in time and space:-

a) The zone of avalanching expands (downwards) and contracts (upwards) in the cold and warm seasons respectively. This represents a seasonal avalanche belt of 5,000 - 8,000 ft. in the Biafo-Braldu area, but reaches some 12,000 ft. in the whole Upper Indus Basin. The zone of erosionally vigorous damp, ground avalanches migrates in sympathy with freeze-thaw belt (Fig. 5.4). The great height range sustains an avalanche belt at some altitude throughout the year. Probably, mid-winter is the only time when avalanching is geomorphically insignificant, being restricted over most altitudes to dry snow types. Spring and early summer avalanches are primarily important in the sub-nival zone below 13,ooo - 14,ooo ft. But the spring avalanche season seems to be less dominant than in the Alps. In the Karakoram the major zone a severe avalanche action lies one or two thousand feet below the snowline, and above it. Here, the main phase of vigorous sculpture by dirty avalanches extends from late June until October. We have many descriptions of the incessant avalanches at

	COMPOSITION	THERMAL STATE	MODE of MOVEMENT	GROUND INTERFACE	TRACK
WHITE (Rap)	Dry, New Snow "Neuschnee..." "Av...sèche" "Trockenschnee..." (Hӧl. Gode. Qu.)	'COLD' (Al)	Airborne: "Powdery", "Dust" (Rap) Wild: "Av...poudreuse", "Staub..." (Qu.)	SUPERFICIAL "Surface" (Rap) "Ober..." (Qu)	Open, even (Qu) Channelled (Qu) a) In snow b) Rock chute. c) Gully.
WHITE (Rap) / DIRTY (Rap)	Damp, New Snow	'WARM' (Al)	Flow Fall . Slide. "Slab ..." "Schneebrett..."	GROUND "Av...du fond" (Gode.) "Boden..." (Qu)	
DIRTY (Rap)	Old Snow "Altschnee..." (Hӧl.) Mixed "Mischnee..." (Hӧl.) "Av...humide" (Gode.)	'WARM' (Al)	Flow Fall . Slide. "Slab ..." "Schneebrett..."	GROUND "Av...du fond" (Gode.) "Boden..." (Qu)	
SLUSH (Rap)	Clean Dirty	'WARM'	Flow (c.f. "Slushflow" Table 8.7)	GROUND	
ICE-BLOCK (Hӧl.)	Firn Glacier Ice Frost Ice	'COLD/WARM'	Fall. Slide	GROUND	

TABLE 10.3. Classification of avalanches according to characteristics of importance in their geomorphic role. The sources quoted are : (Al) Allix 1924; (Gode) Godefroy 1948; (Hӧl) Hӧllermann (1964); (Qu) de Quervain (1958); (Rap) Rapp 1960b.

these altitudes through the second half of summer (e.g. Conway 1894; Visser 1926 p.467; de Filippi 1932). In late summer 1961 sets of new avalanches could be identified on high snow slopes almost every day.

b) A fundamental spatial division exists between avalanche activity above and below the snowline. That below the snowline is not only seasonally restricted and decreasing in incidence downslope. Except close to the snow line, the movements are restricted to small dry powder avalances immediately after snowfall, or relatively few, large, chute-confined avalanches of great erosional power. These are sometimes composed of 'second generation' snow already avalanched down from higher altitudes. Above the snowline avalanching is a perennial phenomenon, frequent in occurrence and continually strengthened by snowfall at all seasons. In winter, and after summer snowstorms cold dry snow avalanches predominate. During fine summer weather there is massive release of new and old damp snow avalanches. Slush flows can occur at least as high as 20,000 ft.

c) Both above and below the snowline, there are differences between northerly and southerly slopes. In the sub-nival zone the belt of frequent avalanching descends lower. Along the Braldu Valley, avalanching was quite frequent down to 10,000 ft. on some northerly slopes. On southerly slopes it was unimportant below 14,000 ft. Above the snowline, linear avalanching down snow-flutes is less common on southerly slopes. Exceptions are where slush avalanches or melt-water cut channels into the snow. However, a related factor here is that of prevailing wind direction.

d) At altitudes above the snowline, the prevailing wind mainly determines the deposition of snow, and formation of cornices. Apart from some topography-controlled eddies, the prevailing movement of snow is from the west or south-west in the Biafo area (see 9.3). Most cornices overhang easterly and northerly slopes. The breaking-off of these cornices is the major initiator of avalanches, and indirectly, of the formation of fluting (e.g. Workman 1910 p.116). By contrast smoother snow-slopes tend to occur on westerly and south-westerly slopes. As a result avalanches developing on southerly and westerly slopes commence on a broad front. Many local variations occur mainly due to slope angle. Very steep windward

cliffs may still develop fluting. Gentle lee slopes show blanket-like deposition where slab avalanches occur.

e) There is regional differentiation related to mass-of-mountain, and precipitation variations (see 5.3.iii). There is more snow, and many more avalanches on the main Karakoram Range than to the south, and this differentiation can be seen between the Upper and Lower Biafo crest-lines. The occurrence of snowstorms on the Greater Karakoram throughout the summer helps sustain avalanching there. In the firn region of the Biafo, avalanching was a predominant and frequent mass-movement agency down to 15,ooo ft. throughout the summer. No avalanching was seen below 17,ooo ft. from the end of August until November in the mountains around the Lower Biafo and Upper Braldu.

Local erosional situation plays an important part in complicating the broad picture. Steep, normal chutes descending several thousand feet without appreciable breaks of slope or channel irregularities, canalise avalanches far into the semi-arid zone. It is a feature of such chutes that they have the typical avalanche cone of debris below (9.8). At such places patches of avalanche snow may persist far into the summer. (c.f. Conway 1894 p. 321).

Along the Biafo West Wall, the Sim Gang South Wall, and the Upper Baintha Lukpar and Uzun Blakk there was a chaotic mixing of avalanche types and glacier ice. New and old snow avalanches, ice-block falls from hanging glaciers and ice aprons, white and dirty avalanches occurred in adjacent localities within a few hours. Along the base of slopes they would become inextricably mixed. At the same time, within the summer and autumn period, day-to-day weather would produce differences in the type and frequency of movements.

A classic description of the flanks of the "Golden Throne"-Chogolosia on the Upper Baltoro - characterises summer conditions in the high glacial areas:-

"....Avalanches fell continually from the wall.... not so stupendous as those from Broad Peak, but more frequent....The first ray of sunshine was sufficient to dislodge the snow and it fell in cataracts and cascades...down all the ravines and

> crannies of rocks...The heavy rumble of the falling mass was punctuated with the sharp knocks and cracklings from rolling stones...or drowned...(by) a rock breaking off....In the warm part of the day it seemed as though the whole mountain were falling apart, so huge were the masses of ice, rock and snow that hurled themselves down..." (de. Filippi. 1912 p. 296)

The same writer also noted a point observed in the Biafo sub-nival zone in winter, that a phase of numerous avalanches would cease overnight if the temperature remained below freezing (op.cit.pp.245-6) (c.f. also Conway 1894 p. 369 on summer avalanching from the Hispar Wall).

Chute-sculpture has mainly been attributed to avalanche action (Matthes 1938). In the Karakoram, for the most part avalanching seems the main agent of chute-sculpture. From close to the snow line up to high altitudes its importance was apparent in the large numbers actually seen descending chutes, and the numerous fresh cones and patches of avalanche debris in them. In the lower accumulation zone in warm weather, slush avalanches are common, rushing out, especially from south-facing chutes, and leaving tongues of debris on the firn. Above 14,ooo ft. there were more dejection cones lacking the linear tracks and levees which cover most examples at lower altitudes, and reflecting avalanche deposition. However, in the sub-nival zone debris-flows gradually become more important downslope under present conditions.

10.4.ii. <u>The Incidence and Erosional Significance of Avalanches.</u>

The frequency and erosional power of avalanches at higher altitudes cannot be doubted. Indeed, any form of rock failure or movement becomes involved in, even when not triggered by, an avalanche. Conway, who had extensive experience of mountain areas stressed the greater size and number of avalanches in the high Karakoram as compared with other regions (Discussion in Visser 1926 p. 471).

Adequate assessment of the role of avalanche erosion is difficult both because they are hard to examine closely and because in slopes descending below the snowline they give way to other processes, - debris-flows especially, - which nevertheless depend upon them for moisture supply. Even so, circumstantial evidence suggests that avalanching

effects tremendous erosion. Above 14,ooo ft. chutes are mainly carved out by avalanches. The deep incision of these in areas where other processes - rock-slides and falls particularly - fiercely attack adjacent buttresses seem to indicate great erosional power. Along the glacier margins above the firn-line and reaching up to 19,ooo ft. in late summer, the large areas of cones and tongues of thoroughly blackened snow pre-suppose rapid denudation. All steep snow-slopes showed fresh, dirty tracks of avalanches on most days. Further, there is the evidence of the vast amounts of debris melting out on the glaciers below the snow-line and away from the influx of material from valley walls. If the Biafo is compared with the Baltoro where avalanche feeding is a major factor, the earlier and more rapid build-up of ablation moraine on the latter must be attributed to the avalanche effect.

As further support for the importance of avalanches we must consider:-

a) The fact that the main avalanche zone coincides with the heaviest precipitation belt in the region.

b) The main avalanche zone coincides with the steepest average slope angles of the area, (8.2.i and v.).

c) That many of the avalanche slope areas are trimmed at the base by glaciers, (see 8.2.iv).

d) That avalanching is the most frequently observed of all mass movements, and occurs over a broad altitudinal belt at all times of the year.

With these points in mind it seems reasonable to suggest that avalanching may achieve more erosion than any other, and, for the high glacial basins, perhaps all other slope processes. Some of the possible implications of this will be discussed in the conclusion of the chapter.

10.5. Mudflows and Debris-flows.

Throughout the sub-nival zone of the Karakoram rapid flows of saturated waste are frequently reported and affect a large area of the landscape. They have been described by many visitors to the region (Austen 1864 p. 27; Tanner 1891 p.407; Dunmore 1893 vol. I. p.190; Conway

1894 esp' vol. I. pp. 323-4; Curzon 1896 p.20; Durand 1900; Guillarmod 1904; Rabot 1904; de Filippi 1912 pp. 147-9; Hedin 1917-1922 vol. IV p. 177; Dainelli 1922-1934 Ser.II. vol. 4). Many of the flows are "Mountain Mudflows"; bouldery masses rushing down steep gradients and leaving incised tracks and levees of boulders. However, all gradations in composition occur. A distinction between mudflows and debris-flows is made on the basis of fines content (H.R.B. 1958 p.36), and further subdivision into "Pure" and "Bouldery" mudflows.

10.5.i. Debris-flows.

These mainly occur in the higher sub-nival zone, (12,ooo - 16,ooo ft.). They consist of wet flows of mainly coarse material with a small amount of fines. There is more free- water action than in true mudflows, and they may develop from slush avalanches. There were countless fresh debris-flow tracks and deposits along the Biafo, but only one small one was seen in action, in the Baintha area. This began as part torrent, part debris-slide in a steep chute. Only on the depositional fan did it develop the typical debris flow characteristics - a tongue of saturated waste ploughing in rapid bursts down an old track. The jerky progression seemed due to the formation of boulder jams, helped by intermittent depltion of water content. Cobbles and boulders were shed to the side adding to an existing low levee. The flow petered out half way down the fan but a small stream reached the bottom and washed some sand out onto the ablation valley floor.

Larger debris-flows, which may begin in an old track, generally alter course and scour out new tracks, evidently through the formation of boulder james in the old channel. The termini of these large flows often split into series of "bird's foot" tongues of washed cobbles and boulders. There is more fines in these flows when they commence than appears in the bouldery deposits they leave. The fine material is easily washed out from the debris-flow tongues, often forming sandy flats beyond.

10.5.ii. Bouldery Mudflows.

On lower slopes, generally below 13,ooo ft., mudflows predominated.

These are saturated waste flows with a sufficient quantity of silt-clay material to surround coarser debris - generally more than 10% by volume. In the Karakoram most of these contain large boulders and are distinguished here as "bouldery" mud-flows (c.f. Tricart 1957; Dollfus 1960).

The examples of bouldery mudflows seen in action were of moderate size (Plate 10.4a). They progressed in small and large pulses of movement. Every ten minutes to half-an-hour, over periods of a couple of hours, large tongues of material including boulders and quantities of damp earth in clods and crumbs, would surge down. Having left the confining chute or gully, the waste spread laterally forming broad levees until it gave way to a narrower flow of liquid mud. The latter would continue to flow exhibiting regular small pulses until the next large surge. The distal ends degenerated into a series of tongues of slowly spreading mud (Plate 10.4b). Unlike the debris-flows, and mountain mudflows described in Temperate and sub-Artic regions (e.g. Lewis and Baird 1957) the small mudflows frequently did not give way to muddy streams of water.

10.5.iii. Pure Mudflows.

In many localities there were broad areas of slope deposit containing little or no coarse material. In April, 1962, on a broad terrace of the Lower Braldu, and again on an alluvial fan in Shigar Valley, vast quantities of liquid mud were seen gently spreading out along a front of ½ mile to a mile. The mud was almost pure silt-clay, and ran down from gullies in "Badlands" of till-like material plastered along the valley walls (c.f. 9.9). These flows obviously occur in most years. When dry, the mud became very hard and was broken up into building blocks by the local people. Other smaller examples were seen along the Braldu.

10.5.iv. Super-charged Streams.

Several north-bank tributaries of the Braldu were heavily charged with mud and were more like mudflows than streams. Rocks splashed by them had thick films of mud, while the gorges in which they flowed had

mud plastered many yards up the sides. At times very large mudflows course down these gorges. On July 17th, 1956, E. S. William's party was nearly engulfed by a large mudflow in one of these tributaries of the Braldu near Chongo (p.com.). DeFilippi also described these streams (see 1912 p. 148).

10.5.v. Large, Catastrophic Mudflows.

The writer only saw the after-effects of very large Karakoram mudflows, but they are a frequent feature of sub-nival mass-wasting, whose action has been described first-hand by several competent observers. These flows transport vast quantities of debris and endanger life and property in the local villages. Conway described an example in the Hispar Valley at approximately 7,ooo ft. as follows:-

> "...The weight of the mud rolled masses of rock down the gully turning them over and over like so many pebbles, and they dammed back the muddy torrent and kept it moving slowly but with accumulating volume. Each of the big rocks forming the vanguard...weighed many tons; the largest were 10 ft. cubes. The stuff that followed them filled the nala to a width of about forty, and a depth of about fifteen feet. The thing moved down at a rate of perhaps 7 m.p.h. ... Looking up the nala we saw the sides of it constantly falling in and their ruins carried down....." (1894 vol. I. p. 323).

While he was there Conway reports that the nala yielded three of these "frightful offspring".

When crossing Skoro La, the pass between Shigar valley and Askole, Godwin Austen encountered a huge mudflow at 12.5oo ft.:-

> "....a black mass.... moving rapidly over the broad slope of boulders which formed the bed of the valley.... it consisted of a mass of stones and thick mud about 30 yds. in breadth and 15 ft. deep, a great mass of stones and rock, some....measuring 10 ft. x 6 ft. all travelling along together like peas shot out of a bag, rumbling and tumbling one over the other and causing the ground to shake ....(and).... shortly after, another body of stones not so large as the first but travelling much faster. ....These 'shwas' are of frequent occurrence in the ravines...." (Austen 1864 p. 27).

As with the smaller examples the large boulders are bull-dozed along in front or rolled by the thick, viscous mud which forms the body of the flow. The rolling mechanism may be compared with that of flash floods in

in ephemeral streams (Leopold and Miller 1956, p.6). The occurrence of several distinct surges is also a characteristic of these flows.

When the mudflows leave the gorges and pass onto lower angle fans and terraces the larger boulders are pushed aside to form levees and the flow becomes progressively less burdened with coarse debris and spreads steadily over the surface. Near Skardu, the writer visited a village which had recently been buried by one of these catastrophic mudflows. By the time the flow had reached the village it had deposited nearly all coarse material and consisted of sand-rich mud. This had gently flooded the buildings and fields burying them to a depth of 5-10 ft. (Plate 10.5). The situation was exactly comparable to that described by Sharp and Nobles (1953 p. 558.and their Plate 2).

10.5.vi. The Controlling Conditions in Mudflow Activity.

The fact that mudflows occur so frequently indicates they are an important reflection of the geomorphic environment. Mud and debris-flows are a feature of many mountain regions of the world, and as Cailleux and Tricart have pointed out, these "coulées boueuses" are generally of greater importance in the Mediterranean climate (1950). The sub-nival zone of the Karakoram has features in common with Mediterranean areas. However, few regions have large numbers of mudflows as a regular feature of each year's erosion.

Four factors encourage the development of mudflows:-

a) Sudden short-term increase of surface water in spring (see Sharpe 1938, and Beatty 1963 p. 534).

b) Considerable supplies of moisture from higher altitudes descending to arid areas.

c) A generally sparse vegetation cover.

d) Large quantities of rotted rock and slope deposits in the sub-nival zone.

e) Steep slopes.

Although most of the mudflow areas are sub-humid to arid in climate, available moisture occurs over short periods and in correspondingly high concentrations. Melt-water from patches and banks of snow that collected

in gullies and chutes is the chief source. The sharp upward curve of annual temperature, with superimposed, large diurnal variations produces rapid short-term melting of these snow patches. Old and new slope deposits floor or clog drainage lines with reservoirs of waste to be saturated during phases of snow melting. In the higher sub-nival areas where debris-flows predominate, rock-falls and avalanching from above provide much of the debris in chutes and on talus slopes where the flows form. In the lower sub-nival zone, contemporary weathering provides abundant large and small waste materials. However, an important factor is the presence of ancient till and slope deposits. These contain much more silt-clay material than is found in contemporary weathering products (9.9). The bulk of the silt-clay material in the mudflows of Choblok, Laskam and Bakhor Das slopes comes from old slope materials (9.8 iii). The situation parallels that described by Bonney (1902) in the Alps, and his interpretation, stressing the importance of ancient slope and till deposits seems substantially correct for the Karakoram area. Rapp found old till-covers important sources of materials in mass-movement processes (1960b p. 154).

For the initiation of small mudflows melting in gullies and chutes is sufficient to saturate superficial waste and cause failure. The large mudflows require additional factors. The usual and most likely explanation is the formation of dams in narrow ravines. This was suggested by Godwin Austen for the example quoted above. Bonney quotes this happening in the Alps (op.cit.p.9). Rock-slide and earth-fall dams are quite common in the narrow ravines, chutes and gullies of the Karakoram and may even be triggered by the early stages of melting and mudflow movement. Meanwhile, the characteristic surges of mudflows themselves indicate that they block their own course with accumulated debris or through secondary bank failures. At the same time, unusually large rises of temperature, especially following heavy snowfall late in spring may release sufficient quantities of moisture to set off large mudflows without the aid of a dam. In the lower parts of the Upper Indus Basin, occasional heavy rainstorms create large mudflows as they do in the Alps and the mountains of Britain (c.f. Baird and Lewis, 1957; Rapp, 1960b, p. 162).

Mudflows also occurred on the flanks of river terraces where springs were thrown out. There were a number of examples along the Braldu which formed at the end of the winter in 1962, involving large masses of old till and valley train. Some built fans of debris fifty yards across, spreading thirty yards into the stream. They were completely removed when the higher river discharges began (c.f. also "Glacier Mudflows", 12.7).

10.6. A Discussion of the Role of Freeze-Thaw in Mass-Movement.

Under suitable conditions, freeze-thaw can play an important role in the preparation and initiation of mass-movements. Frost bursting may trigger rock falls and slides. Freezing of soil moisture can initiate movement through volume increase, weaken soil by disaggregation, and concentrate moisture at centres of ground ice formation. Melting may lubricate slide surfaces, release ice-wedged blocks and start movement of soil through saturation and loss of strength. All these processes play a part in the Karakoram. Films and crystals of ice were found in some slide masses, and soil-frost occurred in taluvium between 10,000 and 15,000 ft. at least. Most mass-movement occurred in periods of thaw. Nevertheless, the actual relations between freezing and thawing were not always clear; partly for reasons noted in connection with the problem of frost weathering (see 7.7).

It was hard to disentangle the importance of frost-cycles from their association with the precipitation season. Melting following falls of new snow seemed more significant in initiating movement than melting following periods of sub-zero temperature without recent snow-fall. The massive, nocturnal rock-slides of mid-winter could have been triggered by frost-bursting, or, perhaps, the creep-response of ice in fissures to loading (see Haefeli, 1939). These slides were also on northerly slopes where ice-formation is better favoured. On Choblok a small rock-slide occurred from a southerly cliff in February, where, though the cliff was thoroughly dry, films of ice and ice crystals were found under the slide. The dryness of 1961-62 may have limited this action more than usual.

The part played by ground ice in the regolith is also hard to define. Patterned ground due to frost action is known to occur rarely and only at very high altitudes in the semi-arid mountains of Southern and Central Asia (Troll,trans. 1958 pp.7-8 and 89-90). The only significant areas of patterned ground reported from the Karakoram occur in the eastern plateau areas at over 17,ooo ft. (Hedin 1922 vol. IV. p.25; de Terra 1940 pp. 101-102). This contrasts with the large stone rings found at 10,5oo ft. in the Pir Panjal (de Terra and Patterson 1939). The main factor is moisture availability, as is shown by the lower patterned ground areas with favourable moisture-bearing winds in the Afghan and Middle Eastern mountains (e.g. Rathjens, 1965).

The frost growth in 1961-62 in the Biafo area was meagre compared with those described, say in the Andean or Southern African Highlands (Troll op.cit pp.34-49). Rather than the well-known cellular needle-ice it consisted of irregular needles mixed with amorphous films of ice. These were distributed irregularly in the upper skin of talus and derived from superficial snow-melt rather than the upward migration of moisture from damp, silt-rich soil as in the classic cases. Although the composition of the Karakoram taluvium would often favour that kind of needle-ice growth its moisture content was never high enough. However, such ground ice as there was effectively broke some taluvium, and in a wetter year should do more of this. Again, the situation is rather ambiguous. It cannot necessarily be inferred from the absence of patterned ground that ground ice is geomorphically unimportant. A process, however active, will only dominate landform character if other processes do not mask or over-ride its effects. In the present case, it is not simply a question that aridity limits frost action. During the main period of frost-cycles, there is temporary abundance of moisture.but the incidence of moisture, particularly as it becomes available to the regolith gives greater impact to processes due to melting than those due to freezing. There are two main reasons. Firstly, there is the actual relationship of frost-cycles to moisture availability. The period when the freezing phase of frost cycles is predominant comes in the first half of the precipitation season; roughly from November to March. This follows the

driest season of the year, autumn, which thoroughly desiccates the soil. Hence, frost growth, except at a few favoured spots, will depend upon water from intermittent snow-melt during the winter. If snow cover is thin little moisture is liberated. If it is thick little of the winter melting will penetrate to the soil. On the other hand, in spring when more moisture is present at the surface, the freezing phase may be large but it is generally subordinate to the melting-phase of diurnal frost cycles. Thus, when frost action is best provided for, it is likely to be masked in its effects by thaw phenomena. This introduces the important second reason: that frost-action in soils only produces relatively slow movement while thawing in soils on steep slopes can cause rapid and violent movement. The tendency of frost action to produce well-defined patterns will be masked by the over-riding importance of fierce mass-movements on these predominantly very steep slopes. Most well-developed patterned ground does occur on gentler slopes (see Washburn 1956; Tricart 1963 p. 90).

The significance of these points is that in freeze-thaw action it is the results of thawing that dominate the mass-movements and superficial character of talus slopes in much of the area. However, frost-action may be important in certain years, but primarily as a preparation for the more vigorous thaw-triggered processes.

10.9. Conclusion.

Many of the conclusions emerging from the examination of slopes take on greater meaning in relation to the overall geomorphic situation and will be treated in the final chapter. Here only a brief summary is given.

The principal dynamic aspect of mass-movement is the way climate, slope angles and available relief combine to promote short-lived, high energy processes. Large and rapid temperature shifts, where precipitation is mainly snow, encourage sudden, vigorous movements. Steep slopes give pre-eminence to the more rapid movements due to thaw and wetting of waste, rather than the slower frost controlled movements. Below the snowline,

winter precipitation partly offsets aridity by concentrating available moisture in a short spring snow-melt season. Above the snowline the predominant avalanche erosion is maintained with varying effectiveness throughout the year. Steep slopes and high relief serve to route moisture and mass-movements rapidly down from humid upper slopes to lower arid ones. The effect of decreasing moisture and increasing temperature downslope favours swift, large movements since smaller ones tend to be stifled by moisture loss. Relatively slow erosion on lower arid slopes most of the time, and perhaps over periods of many years can be compensated, because of poor vegetation cover, by rarer humid periods since these slopes have relatively small resistance to mass-movement scour and run-off.

In the absence of measurement we must consider carefully the grounds for giving so much importance to brief, high energy processes. The direct pieces of evidence are:-

a) Processes observed show the high energy types to be very active.

b) Base of slope condition is generally a sharp angle even away from present axial drainage which would not be expected if slow mass-movement (creep) were important.

c) Base of slope deposits are dominated by large volumes of rock-fall, rock-slide, debris- and mudflow and avalanche materials.

d) Large quantities of avalanche and rock-fall debris on glaciers.

e) The true slope areas which show the actual land surface to be mainly at angles exceeding 40^{o}; angles much steeper than those of areas where slower mass-movement processes are important in controlling surface form and removal of material.

However, perhaps the most convincing argument is to consider under what circumstances the more gentle mass-movements can dominate erosion. In calculating rates of erosion on slopes we normally consider volume of material and vertical distance through which it moves in a given time. In the sense that rapid and slow mass-movements compete to remove material we have a hare and tortoise situation. The slow movements must compensate by continuing longer and by involving a much larger area of landscape. As slope angle is increased a balance may be maintained initially by a relative increase in rate of the slower movements. However, it

seems that an increase in relief must always tend to favour the rapid movements, since a single slide, flow or fall is able to travel much further down-slope. The other variables are moisture supply and existence of an extensive vegetated regolith responding by slow movements. Poor moisture supply seems to be more inhibiting to slower movements than decrease in slope. In mountains this can be offset by insolation-induced creep and gravity rock creep. But regolith conditions which promote slow movements at lower angles here produce large failure and rapid movement. Very steep slopes prevent regolith development by exceeding the angle of repose of the material. In the Karakoram, rapid mass-movements normally travelled through several hundred feet of altitude and many avalanches, rock-falls and mudflows travelled more than a thousand feet. Most of the reports of large rock-slides, avalances and mudflows involve the translation of hundreds and occasionally some millions of tons of rock down five to ten thousand feet of relief.

Under the conditions in the region, it is unlikely that slow movements in cohesive regolith are greater than those found in wet environments - somewhere in the range .2-.4 foot per year (Rapp 1960; Washburn 1967). Let us assume that dry creep, solifluction and any frost heave in the talus zone, amount to .3 ft. per year and act to a depth of 1 ft. What is the slow movement equivalence for a fall carrying a million cubic feet of rock one thousand feet downslope? (Two rock-slides at the Biafo in 1962 were of this order). Creep, etc., will take about 3300 years to move the same body of material - ignoring the difference in density of granular material. Alternatively the slow movements must act over an area of 3,3oo,ooo,ooo sq. ft. (roughly 1¼ sq. miles) for one year. The latter may not be a prohibitive requirement in a subdued landscape. Where less than 30 per cent of the snow-free landscape has a regolith it becomes so. Meanwhile, we have seen that the talus areas themselves are subject to vigorous transport and erosion by rapid mass-movements. Finally, it seems unlikely that rock creep in areas without regolith can be a large factor. Evidence of it in the Karakoram was restricted, and quite small shifts on these steep rock-walls tend to promote failure and rapid movements. Thus, it would infer that the bulk of the erosion on

slopes in the area is being achieved by rapid, short-lived mass movements. A serious, outstanding problem is how to begin to obtain measurements of such activity. The methods of Rapp do not seem adequate for really high relief mountains. Possibly audio-monitoring and time-lapse photography would be a way to guide field inspection of size and location of movements.

While the landscape would generally be called "Youthful" deposition within it was an important factor. Along rivers and glacier ablation zones there were commonly large depositional terraces forming sharp breaks of slope. On these terraces mass-movements from large areas of slope are checked and leave considerable deposits. On the high river terraces aridity further promotes deposition through moisture loss, and helps the preservation of deposits. Main gullies cut deep slots through the terraces and do not ravage the deposits on them (Plate 9.3). The overall result is the strong "hour-glass" pattern of slope form with lower depositional cones and fans, and upper erosional phases concentrating movement lines towards the heads of these (c.9 Plate 9.21.). While not uncommon in mountain areas this pattern is strongly emphasized by the scale, the vigorousness of processes, and lack of vegetation. Perhaps more important is the large discontinuity in the chain of denudation. At least 50 per cent of the sub-nival slopes descend to depositional terraces where vigorously derived slope materials are isolated from removal by normal axial drainage. However, recent deep incision of streams make it unlikely that erosion is "winding down". It will be suggested that in an environment of this kind extreme erosional events are controlling agents in the removal of lag deposits of slopes and from other processes (Chapter 16).

CHAPTER 11

GLACIAL GEOMORPHOLOGY I : THE GLACIERISATION OF THE KARAKORAM, and THE BIAFO GLACIER SYSTEM

In this section we describe the area coverage and types of glaciers in the Karakoram Range to give a perspective on the particular glacial basin chosen. The problem of classifying glaciers is reviewed with the particular types found in the Himalayas given prominence. Finally the size and organisation of the Biafo glacier system are examined.

11. I. Karakoram Glacierisation.

The Karakoram Range has an extensive ice-cover (Fig. 11.1). For the whole range von Wissmann has calculated a glacial area of 5,850 square miles (15,147 sq.km.) covering 37 per cent of the mountain area (1959 p. 1125). This may be compared with 17 per cent coverage for the Greater Himalaya, and 2.2 per cent for the Alps. The concentration of ice on the southern flank of the Karakoram east and west of the Biafo is much higher again (Table 11.I.).

TABLE 11.I. Glacial cover of the Karakoram Range and Upper Indus Basin. (partly after Visser, 1938, and von Wissmann, 1959)

Region	Total Area sq.miles	Ice-Cover	
		sq.miles	per cent
Biafo Basin	331	202.5	61 (73)[x]
South Flank of Central and Eastern Karakoram	2,800	1,650	59
Karakoram Range	15,900	5,850	37
Upper Indus Basin	66,250	8,550	13

[x]According to von Wissman the glacier area of Biafo is 242 sq. miles (see Note 9.2.)

[illegible]

Fig. 11.1 GLACIERS of the GREATER and LESSER KARAKORAM

Within the main glacial area of the Karakoram occur several glaciers which, with the Fedchenko in the Pamirs, constitute the largest valley glaciers outside Polar Regions. The Biafo is one of these. Twenty-four of the Karakoram glaciers are larger in area than the Aletsch, (Table 11.2). They all occur within a belt 250 miles long and about 40 miles wide following the main Karakoram Range: roughly the area of the High Alps from Haute Savoie to the Stubaier Alpen. Glacially, the Karakoram is distinguished from surrounding ranges by greater ice cover, longer valley tracts subject to contemporary glacial action, and lower penetration of large glacier tongues. The largest glaciers descend well into semi-arid areas. They are distinguished from smaller ice-masses in tapping the heavy precipitation of the main range (5.3.), and form the upper reaches of the main drainage channels. Like the major river valleys, they have long sections of gentle (ice-surface) gradient contrasting with the surrounding, precipitous slopes (Note 11.1).

By contrast, smaller ice-masses in minor valleys are tributary to deeply incised main valleys and descend very steeply. Many glaciers with lengths up to about 12 miles have three distinct sections: an upper zone of ice-falls and avalanche-walls; a middle portion of relatively gentle gradients, and an outlet tongue or lower valley falling away steeply again (Plate 11.1). Examples include the Minapin, Silkiang, Garumbar, Yengutz Har, Paiju-Burdomal, and Khumdan Glaciers. Significantly, most of these names are associated with glacier "surges" (See 16.2). Rates of movement in the lower ablation zones of these glaciers may often exceed 1000 ft. per year (See Pillewizer 1957). In addition these glaciers are striking in the ferocity of their normal erosional activity. The melt-water torrents, ice-block avalanches and mud-flows which descend from them in summer effect tremendous erosion in the arid valley walls of the main rivers. They have cut deep narrow gorges and built enormous alluvial fans across the main valley floors (Plate 14.3).

TABLE 11.2. Area and length of major valley glaciers in the Karakoram (after Wissmann, 1959).

Name	Surface Area (sq.miles	Length (Miles)
Siachen Gl.	456	46.6
Baltoro	292	38.6
Biafo	242	42.2 *
Hispar	240	33
Rimo	197	28
Skamri ("Crevasse")	165	25.5 (Shaksgam Drainage)
Panmah	185	27.3
Chogo Lungma	128	29.2
Kondus	120	19.9
Te Rong	114	17
Batura	112	37
Khurdopin	108	25.5
Sarpo Laggo	89	20.5 (Shaksgam Drainage)
Braldu	78	21.8 " "
Virjerab	73	22.4
Kero Lungma	58	13
Bilafond	58	14
Yazghil	56	18.7
Riong	54	
Barpu	52.5	21
K2 ("Depsang")	52.2	II (Shaksgam Drainage)
Karambar	51	17
Staghar	50 (?)	18 (Shaksgam Drainage)
(Aletsch Gl.	44.5	16.8)

*See Note 9.2

11.2. Typology of Glaciers.

An important question concerns the morphological types represented by the Karakoram glaciers. Apart from occasional references to "Himalayan" or "Turkestan"type - the avalanche-fed glacier, not well represented among the larger Karakoram glaciers,- the problem has little currency in Anglo-Saxon writings. The best-known classification of glacier types in English, that of Ahlmann, does not cater for the Karakoram situation; his Type III ("Himalayan") only applying to some of the smaller ice-masses (Ahlmann 1948 pp.59-63).

However in the Germanic literature there is much debate concerning

TABLE 11.3. Morphological Classification of Ice Masses.

General Class		Glacier Type	Examples
A. Minor Ice-Masses		Ice Apron (G.G.) Ice Carapace (Sharp) Well-sided Glaciers (Ahl.) Niche Glacier (Groom), Cirque or Corrie Glacier (G.G.,), Glacieret (Hobbs).	
		Turkestan Type I. (c.f. Wissman's "Extreme form").	
B. Valley or Alpine Glaciers	1)	Turkestan Type II. ("Avalanche-fed Gl.") (Vis. Wiss.)	Minapin Gl. (W. Karakoram)
	2)	Firn Caldron Type ("Firnkessel")	Baltoro Gl. (C. Karakoram)
	3)	Firn Stream Type ("Mustagh Gl.") (Kleb.Wiss.)	Biafo Gl. (C. Karakoram)
	4)	Firn Basin Type I. (def.= Firn Basin less than twice outlet tongue) (= Ahl. Type I, see Kleb. Wiss.)	i) Vedretta del Forno (Alps) ii) Siachen Gl. (Karakoram)
	5)	Firn Basin Type II (def. Firn Basin more than twice outlet tongue) (= Ahl. Type II)	Grosser Aletsch (Alps)
	6)	Firn Basin Complex (= Ahl. Type IV)	14th July Gl. (Spitsbergen)
	7)	Transection Glacier (Ahl.)	Löwenskiold Gl. (Spitsbergen)
	8)	Piedmont Glacier (Hobbs)	Malaspina Gl. (Alaska)
C. Valley Glacier Complexes	9)	Fringing Glaciers (Hobbs)	Keriya Darya Glaciers (Kun Lun)
	10)	Radial Glacier Complex ("Radiating Type") (c.f. Hobbs)	S. Nanga Parbat Massif (Himalaya)
	11)	Parallel I. "Longitudinal"	
	12)	Parallel II. "Transverse"	
	13)	"Anastomosing" (=Eistromnetze) (Tri. Wiss.)	i) C. Karakoram Complex. ii) Clavering Is Complex (Arctic)
D. Ice Sheets	1)	Ice Cap (<50.ooo km^2) (G.G.) (sub-types. "Plateau..." "Highland..." "Lowland...")	Vatnjökull (Iceland) Columbia Ice Field (Rocky Mts)
	2)	Continental Ice Sheet (>50.ooo km^2) (G.G.)	Greenland Inland Ice.

References. G.G. (Armstrong et.al. 1966). Sharp (Sharp 1960). Ahl. (Ahlmann 1948). Vis. (Visser 1935/38). Wiss. (von Wissmann 1959). Kleb. (von Klebelsberg 1948). Tri. (Tricart 1962). Hobbs (Hobbs 1911).

Central Asian glacier types associated particularly with Oestreich (1911), Visser (1933/34 and 1938) and von Klebelsberg (1926 and 1948). More recently, Pillewizer (1956), von Wissmann (1959) and Kick (1964) have reviewed the situation and revised the older typologies. With the aid of their work a general glacio-morphological classification is prepared here with a view to placing the Biafo in a descriptive context (Table 11.3.). The arrangement emphasises landscape form, giving equal weight to shape of ice-mass and relation to the local topography. The nature of accumulation, particularly important in Central Asian types, is built into this scheme. Pillewizer and Kick also stress climatic relations and mode of flow, especially the existence or otherwise of "blockschollen" movements. While it is desirable to incorporate these factors in a dynamic classification, too little is known about most of the glaciers for it to be feasible at this time. Von Wissmann has listed the larger Karakoram glaciers according to morphological type (1959 p. 1146). His results indicate the great variety present. Many, including the Biafo, are either in some degree intermediate between two main types, or have tributaries which differ from the main glacier.

11.3. The Biafo Glacier System.

Sixty-one per cent or 202.5 miles of the Biafo Basin (projected area) is covered by perennial snow and ice (Note 9.2.). Of this area, only a small fraction is made up of extra-glacial snow slopes, though their true area exceeds 40 square miles (c.f. 8.3.v).

The Biafo is largely Firnsteam Type (Fig. 11.2.). This type has a large firn area composed of extensive ice-streams rather than compact basins. In the case of the Biafo, considerable crest-lines and peaks occur between the firn-region ice streams (i.e. most "intra-basin peaks" of 9.2) However, the relative areas of valley wall and ice stream give a greater direct precipitation onto the glacier than avalanche accumulation. The type is clearly intermediate in terms of accumulation between the Turkestan and Firm Basin Types.

In detail, the relations of main glacier, surrounding topography and form of accumulation are complicated. Conway's christening of Lukpe Lawo "The Snow Lake" (1894), though he did not know of the great tributary system above,emphasises the openess of the firn area (c.f. Tilman in Shipton 1938). But the Uzun Blakk tributary and several others are <u>Firn-Caldron Types,</u> while Biantha Lukpar is <u>Turkestan Type II.</u>

The main glacier originates in Lukpe Lawo and the Sim Gang. Of the ablation zone tributaries the largest, Baintha Glacier makes little contribution at the moment. Three right bank tributaries add small ice-streams. From expedition reports, the distribution of moraines on the 1939 Map and observations in autumn 1961, the relations of accumulation and ablation areas have been mapped (Fig. 11.2.). On the main glacier, the firn line has been encountered between 14,250 and 15,000 ft. by summer expeditions over the past seventy years (Note 11.3.). In December 1961, wind removal of new snow revealed glacier ice up to 14,500 ft).. Height of firn lines varies with aspect and between the Upper and Lower Biafo. Along the Lower Biafo the main West Wall tributaries had firn lines between 15,000 and 15,750 ft. East Wall tributaries of the Lower Biafo had firn lines at over 16,000 ft.,(i.e. 16,500 ft. on the Phorosarig and at 16,000 ft. on the Baintha Tributaries). In the Sim-Gang and Lukpe Lawo area, the firn line on both aspects was below 15,500 ft. if we exclude minor areas of concentrated melting such as along the Sim Gang North Wall. Concentrated snowfall on the Upper Biafo leads to marked lowering of the firn lines there, as on the adjacent Hispar Glacier (Note 11.4.). The total accumulation area of the Biafo, excluding disconnected tributaries is about 120 square miles, the ablation area 47 square miles; a ratio of nearly three to one. Mason stated that "...the ratio of supply area to waste area is as large as 3 : 4. ...." (1930 p.221). While the newly determined values hardly fit his explanation of fluctuations in the Biafo snout - suspect anyway (ee Note 15.4), - they do help to explain how the large ice tongue survives far into semi-arid areas.

The survival of the glacier down to 10,200 ft., is also assisted by the shortness of the ablation season. In 1961, outflow decreased

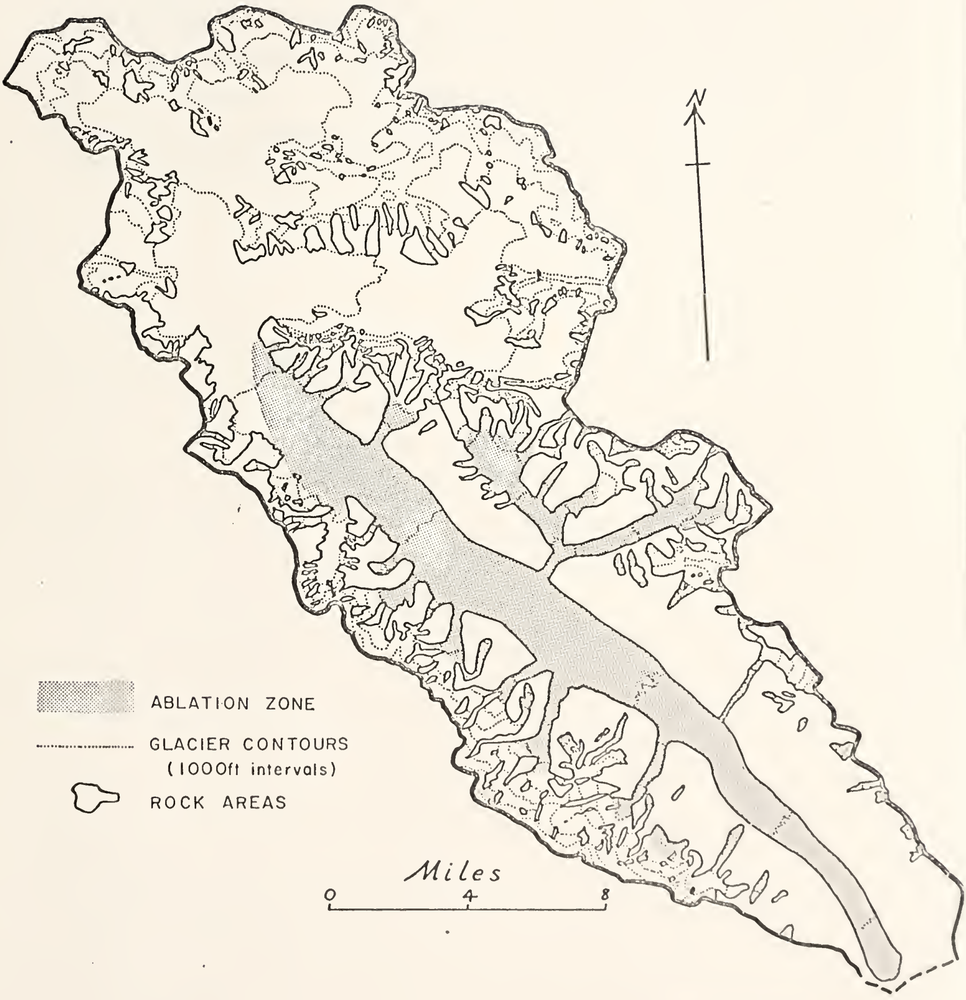

Fig. II.2. The Biafo Glacier System showing ablation and accumulation areas, and contours accoring to the Shipton 1939 Survey.

markedly in September, and little melting occurred over most of the ablation zone after mid-October. In early May, it had barely recommenced. To judge from all reports, ablation is concentrated between mid-June and early September, the sharp peak of discharge at this period reflecting the massive contribution of the 12,000-14,000 zone; with its broad, moraine-free ice-streams, coursed in summer by wide rivers of melt-water. The hydrological importance of these high glacial basins is reflected in the concentration of most run-off from the Upper Indus Basin in the same period (See Chapter 15).

CHAPTER 12

GLACIAL GEOMORPHOLOGY II: CONTEMPORARY GLACIAL FEATURES AND PROCESSES OF THE BIAFO GLACIER

12.1. Introduction.

In this chapter the detailed features and processes on and beside the Biafo are described. First the glacier surface and transport of debris are considered.

12.2. The Accumulation Zone (Plate 12.1).

Above the firn limit debris is rarely seen on the glacier. The only important exceptions are the cones and tongues of dirty avalanches which line the margins in late summer, and a large belt of moraine localised beneath the north wall of the Sim Gang. The wide, snow-covered basins act as heat traps in summer, shade temperatures in the fifties (^{o}F) occurring as high as 18,ooo ft. (E. S. Williams, p.com.). Pools and lakes are found in the snow of Lukpe Lawo up to 16,5oo ft., and ten miles from the firn line. Steeper snow slopes develop parallel sets of runnels where melt water drains, though it rarely breaks out as surface streams. Strong and varied wind action redistributes snow, creating "dunes" in some places, and revealing hard ice 'pans' where percolating melt-water has refrozen.

The large area of clean accumulation zone is not typical of most Himalayan glaciers, and reflects the minor importance of avalanching as a source of ice (c.f. 11.3.). Even the heavy moraine of the Sim Gang disappears again beneath firn. There must, however, be large quantities of englacial and subglacial debris to explain the great increase of ablation moraine on the lower glacier away from additions by tributaries.

12.3. The Upper Ablation Zone (Plates 12.2. and 3.).

From the firn line down to 12,5oo ft. clean ice-lanes predominate, medial moraines gradually increasing in height and width, lateral moraines broadening as belts of debris-covered mounds and ridges. Material com-

posing the moraines is coarse and angular generally ranging from a few inches to over ten feet in diameter. Stones are spread thinly over the protected ice-ridge of the medial moraines. These ridges are generally flattened on top with sides sloping at between 15° and 25°. Their surface has few irregularities. Small glacier tables form in summer and shed debris, usually towards the flanks; but the increasing disarray of ablation moraine below 13,ooo ft. is absent. Ice-pinnacles left by the tables melt away rapidly. Smaller stones, up to 10 inches in diameter, melt into the ice where they are set like rough mosaic. The most massive boulders, and very large glacier tables occur in the depressions which run beside the medial moraines. The first 'dust-wells' and 'dust-basins' occurred here (Sharp 1949); and increased in number downstream. They occurred where there was a relatively small amount of fine detritus on clean ice,- a point recorded in the German name Kryokonitlocher drived from Polar examples where the dust was attributed to cosmic or volcanic origin (see Wagner, 1928). Most of the Biafo examples were dust wells, "...small vertical, cylindrical depressions filled nearly to the brim with water and containing a layer of dark bottom silt..." (Sharp op.cit. p. 305). A few elongated basins occurred - Agassiz's 'trous meridiens'. A large Krykonit Pool occurred on the Baintha Lukpar Glacier. It was some 70 ft. wide, nearly circular with water 4 ft. deep and surrounding ice-walls 9-30 ft. (c.f. Ogilvie 1904 p.703). These features are relatively common on Karakoram glaciers (see Workman 1913/14 pp. 306-314; who called them "...thin-debris pools or pocket variety...").

There were few sharp irregularities over the whole main Biafo stream. However, in summer melt-water drainage shaped the glacier surface, a pronounced feature being a pattern of longitudinal ridges and depressions that deepened downstream and as the ablation season advanced (c.f. Conway 1894 v.2 pp.398-9). In September, between 13,ooo and 14,ooo ft. the ridges were 150 ft. wide and up to 45 ft. high. Generally, the slope of the flanks was convex falling sharply into deep, incised meltwater streams. The pattern was intermittently broken where the streams plunged into glacier mills. Apparently the

pattern records regular development of meltwater drainage under intense ablation and without much disturbance from differential ice movement. The drainage on the ice effectively sluices away any fine material, and the frequent disappearance of large streams indicates englacial drainage of a complex and widely ramifying kind.

During winter the topography cut by meltwater was steadily levelled by ice movement and drifting of snow into troughs. From mid-November until May there was virtually no movement of debris apart from the flow of the ice itself. The silence which descended on the ablation zone was good evidence of this. The 'scoriated', rapidly melting ice surface of summer gave way to hard smooth ice through re-freezing and sublimation. Considerable wind action, evidenced in violent "snow-devils" whirling across the glacier, assisted the smoothing effect, drifting snow into depressions.

Below 13,000 ft. the effects of melting and gravity on the volume and spread of debris intensified. Medial moraines became much more uneven forming lines of sharp hillocks and troughs (c.f. Workman 1914, on Siachen moraines). Several medial moraines merged as smaller ice-streams pinched out. At the glacier margins were broad zones of wasting, sometimes stagnant ice covered with unstable moraine (Plate 12.4.).

12.4. The Lower Ablation Zone.

Below 12,500 ft. progressive smothering of the ice by debris was so extensive that clean ice soon disappeared from the surface. Steepening over two small ice-falls, narrowing of the glacier, and a gradual turn to the west helped speed the spread of ablation moraine. Boulders released from the ice in the area between Jahan Par and Mango were observed to roll as much as 200 yds. This was aided by height difference of the order of 150-180 ft. between the crest of medial moraines and last narrow tongues of clean ice (see Plate 12.7.). Most material rolled downstream and the net effect of collapse of glacier tables and general debris instability was to accelerate the speed of surface transport. Clean ice disappeared completely at 11,800 ft. and ablation

moraine thickened markedly. Processes which rework surface debris had a further 5 miles to act before the terminus.

The moraine-covered lower glacier had a chaotic surface whose general appearance was of many irregular grey waves. Most slopes were covered by coarse moraine and varied in angle from 15° to over 40° according to thickness and type of debris cover. Crests of ridges were generally flattened and sharply interceped by steep melt-faces veneered with fine mud. The latter were invariably steeper than the debris slopes. Fine material was more common than higher up and many dirt cones occurred (Plate 12.5). Some of these high conical features had slopes of 40-45° (c.f. Workman 1909 and 1910a p.263). Relief of the surface varied but was usually between 30 ft. and 50 ft. Such topography reflects a crude pattern of differential protection of ice by debris, with progressive inversion of relief as lower parts are buried and crests or certain slopes exposed to rapid melting (see Sharp 1949; Swithinbank 1950). Such an environment works on erosional material in various ways. Sliding, falling and rolling induces comminution. The many percussion marks, slightly rounded edges and chipped corners of stones revealed the less spectacular aspect of communution. There seemed to be few of the large boulders common on the middle glacier. However, reworking also gives ample opportunity for fines to be sluiced away.

Despite the local concentration of fines in dirt cones most ablation moraine fines is probably washed out before the terminus. The net result of all the processes is a reduction of material in both the upper and lower calibres, and ablation moraines mainly consisted of cobble and moderate sized boulder grades.

Weathering may also modify ablation moraine. Sudden large changes in temperature occur often as rocks shift from the sunlit surface to being packed against ice, and this is associated with alternate wetting and drying. It is difficult to conceive of a natural situation closer to the second set of insolation experiments made by Griggs (1936).

When on the glacier, no order could be seen in the ridges and melt-faces. However, from a high level viewpoint, sets of melt-faces had a distinct alignment transverse to the glacier and slightly up-stream. They seemed to preserve a pattern of transverse crevasses on the ice-fall above. Much broken longitudinal ridges and depressions could also be traced. Such features might be used to indicate whether a glacier is still active, something difficult to decide under summer conditions without a programme of difficult measurements. The fully stagnant area on the east flank of the terminus showed no patterns (see also Sharp 1949, on the stagnant Wolf Creek Glacier).

The well-known 'ice-ships' or ice-pyramids, common on the nearby Baltoro and many other Himalayan glaciers were absent (c.f. Workman 1914; 1913/14b; and Visser 1932). According to Visser (1935-38), and more recently Fisher (1950), these features represent avalanche snow. Ice formed from this is more resistant to melting than ice from firn, and stands out when the latter has melted. Such an explanation accords with the dominant accumulation of the Biafo and the decision to call it a <u>firn-stream</u> glacier (II.3.).

In terms of volume, ablation moraine from the glacier surface dominates terminal deposits. Hence the effect of the ablation moraine environment on composition and distribution of moraine immediately behind the ice-front is important. At any one time there is a variable concentration of debris across the glacier, but the random nature of reworking tends to give a relatively even distribution through time. Which of these facts is more important will depend on the stability of the ice-front position. A significant outcome of ablation moraine processes is an overall levelling of the glacier surface. The height difference between flanks and centre becomes relatively small and this assists in giving more even distribution of debris across the glacier. The heavier actual cover on the flanks must be weighed against the more rapid movement of the central areas.

While emphasis on ablation moraine is warranted in terms of surface observation and volume of material, englacial moraine plays an

important role at the terminus. Cut-banks of old moraines, ice-contact lake sediments and the ice emerging at the foot of the terminal ice-cliff in winter, contain large quantities of fine material. Since much of the sand, silt and clay is sluiced from the ablation moraines, englacial fines is important here. Primarily, it is material incorporated in terminal thrust planes but there is also fine matter in the body of the ice (See Hewitt 1967, and Appendix 8). At the terminus there are therefore converging routes of debris transport with coarse ablation moraine being brought down and mixed with upward moving, predominantly fine material. This has significant effects on terminal deposits (ibid).

Finally, ablation moraine is important in the mass-balance of the glacier. Although details of protection by debris are complex (see Ward, 1952; Ostrem 1959), the net result in a case like the Lower Biafo is to reduce ablation. Where debris is abundant it both shields the ice from insolation and creates a humid micro-climate under the stones. With some 8 miles of the glacier largely protected in this way, the extension of the Biafo well into semi-arid areas depends to a significant degree on ablation moraine. The same is probably true of most of the other large Karakoram glaciers. One would expect this also to have a conservative effect in relation to climatic change. At the Biafo the delay in the spring rise of run-off until melting reached the middle glacier was well-marked. Insofar as runoff yield is greater from higher levels its incidence will also be more sharply peaked (see 5.5.).

12.5. The Glacier Margins I:"Ablation Valleys"

In the ablation zone the Biafo is flanked by a series of large lateral moraines and kame terraces. The ice-edge takes a direct line between rock spurs leaving broad embayments between glacier and valley wall. Here are found typical Himalayan "ablation valleys", a term used by travellers and mountaineers which serves well to define the complex of deposits in this distinct environment (Plate 12.6.). Re-

cent thinning of the Biafo has left the terrace surfaces well above the ice level and they create sharp discontinuities between valley slope and ice margin processes.

Along most of the ablation zone there was a depositional terrace between valley wall and ice-edge, and in some cases several distinct terrace levels (Plate 12.7). Generally there was one main terrace with only minor ridges or steps on the flank (c.f. Ahlmann 1941 pp.199-202 and 1948 pp.72-73; Sharp 1951 p. 107). Some ablation valleys were two miles long and up to half a mile broad, though usual widths were 50 -100 yds. The finest examples occurred between 11,5oo ft. and 14,ooo ft., over a distance of 15 miles. Many ablation zone tributary glaciers also had small but well-defined ablation valleys. The main examples were walled off from the glacier by high morainic ridges so that most slope processes terminated with disposition on the terrace. Outwash from small glaciers and snow patches was canalised along the ablation valleys for long distances depositing its load before plunging to the glacier (see Visser 1928 pp. 182-191, on the Batura "ablationstäler"). Northerly slope streams were generally more successful in cutting deep notches directly through the terraces.

The ablation valley sediments are a complex mixture of mass-movement materials from valley walls, outwash from disengaged tributary glaciers, and of ice-contact deposits and moraine from periods of higher ice levels. In the recent past the ice stood high enough to shed moraine and outwash onto the terraces. Photographs from the beginning of this century show ice falling steeply to or overhanging the kame terraces (e.g. Workman 1910a opp. p. 190). Workman described the situation in our area in 1909:-

> "The Hispar...and also the Biafo at certain points, are ...actively building lateral moraines. At the edges of these glaciers great, ragged, perpendicular ice-walls rise high above the glacier bed their summit as well as their substance heavily loaded with debris, which is constantly showered down...upon the moraines at their bases. At some points the moraines can be seen to grow day by day.... As these walls move downward they....apparently exert no lateral pressure on their moraines so that there is no question

> as to their forming moraines by pushing or ploughing up ....(old lateral deposits)...and I saw no evidence that such was pressed out on their sides by their weight. The moraines appeared to be built up by deposition of the debris borne on the glacier surface, as well as in crevasses and the substance of the ice-walls". (Workman 1910a p.123).

The description agrees with the Workman photographs though he may have been misled by summer conditions into under-estimating effects of lateral pressure. Observations in winter 1961-62 indicated regeneration of ice movement in the lateral margins. Like old terminal moraines, lateral moraines usually have compacted cores with an important fines matrix which would hardly form under the conditions described by Workman (c.f. Hewitt, 1967). Preferential lodgement was found in the till fabric of lateral moraines in Switzerland; which suggests deposition is less crude than mere dumping (Portmann 1960 p. 6.). Also, from the nearby Panmah we have observations of glacier thickening causing erosion and pushing of lateral moraine (Austen 1864 p. 15).

Some large lateral moraines had secondary ridges built on their glacier flank below the kame terrace level. Examples were found at Mango and Baintha Lukpar, and occur along the Hispar (E.S. Williams p.com.). They were discussed by Workman (1901 p.232). There was no sign of secondary ridges forming in the deep trough beside the present glacier and they seem to depend on phases of ice thickening, albeit minor ones.

A striking feature of lateral moraines at Hoh Bluk and Baintha Camp was the arrangement of sets of them <u>en echelon</u> (Plate 12.8.). The ridges were 20-50 yds. long, rose 15-30 ft. above the ablation valley floors, and lay at an oblique angle pointing down-valley. Tributary glaciers entered just above each example and they probably record fluctuations in these, the main glacier forcing the short ice tongue towards the valley wall.

At times of advance the ablation valleys appear more like typical kame terraces, with outwash streams running along them and draining to their lakes. There are also larger numbers of ice-margin lakes in them at these times. Currently there are at least five dry lake beds that

were filled during high ice levels of the last 60 years at Jahan Par, Mango, Hoh Blukk, Baintha Camp and Dongbar. Sedimentation in these lakes is a complex affair with steady hydraulic settling and showering in of coarse moraine (see Drew 1875 p. 365). Accumulation of fines in these lakes is an important factor in the cohesiveness and persistence of the terraces. The break in transport from slopes to axial drainage which occurs on the terraces, also helps accumulate fines. A small lake, deriving from the slopes above Baintha Camp had at least three feet of sticky red clay covering an area of about an acre. The resistance of the terraces to erosion is important in short-term geomorphic developments, allowing ablation valley features to develop with a large measure of independence from changes of ice level. When the glacier thickens pro-glacial deposition adds to the terrace. Otherwise the lateral moraines are slowly buried and non-glacial deposits predominate (see Plate 9.20.).

The height and thickness of lateral moraines and width of embayment mainly decided the completeness of the break between valley wall and glacier. Avalanches along Baintha Lukpar cross the narrow terrace, ride up over the lateral moraine and plunge to the glacier. At Hoh Blukk, Mango, Baintha Camp or Namla substantial valleys have no through movement to the glacier. Between Chaunpisha and Baintha Camp a tributary stream flowed in the opposite direction to the glacier for a mile and fed a small lake at the upstream end of an ablation valley (c.f.Ray 1935 p.303). In the same area, two ablation valleys are joined by a stream which cuts through the narrow rock spur between ,forming a gorge 80 yds. long, 20-30 ft. deep and 10-15 yds. wide in the bottom (c.f. Tarr 1908-9 p.100)

The terrace slope falling to the glacier was generally steep but varied with the cohesiveness of the material. Till slopes with coarse debris were generally unstable with frequent slides and falls of waste. They sloped at less than 40°. The cohesive terrace flanks, which occurred particularly where much or all of the lateral moraine had been eroded away, often stood as cliffs as steep as 60°. Many cohesive

terrace slopes had suites of parallel gullies cut in them. On northerly slopes with higher local humidity, some block slumps and earth slides occurred in the terrace material.

12.6. The Glacier Margins II: The Ice-Contact.

In most of the ablation zone, the glacier slope of kame terraces plunged steeply under the ice and there was a deep narrow trough between it and the steep or overhanging ice-edge. In the trough small ice-contact lakes formed and drained in a few days or weeks and there was continual movement of debris, and change of ice forms. Streams rarely ran along the trough though there were large torrents hidden under the ice. With its abundant supply of debris washed in from ice and terrace wall, this trough promotes movement of debris to lower levels of the glacier where melt-water, moving with great force, can transport it more effectively.

In the lowest few miles of the glacier it was sometimes impossible over short periods, to identify the edge of the glacier. The presence of the ice was only shown by cracks, slumps and subsidence in a mess of earth and boulders. However, the occasional tributary streams excavated deep funnels revealing ice against the old kame terrace slope. Deposition under these conditions is evidently complex, (see Tarr 1908-9, p. 98).

There is a large seasonal variation of activity at the ice-contact and winter plays an easily under-estimated role. At that time most melting and release of rock from the ice ceases. Loose debris becomes set in refrozen melt-water and snow fills in the hollows. There is a small winter 'surge' at the margins raising their level and tending to smooth irregularities. At the end of the winter there was far less of an impression of stagnation and wastage, an important point in relation to the transporting efficiency of the glacier near its margins.

Places recently exposed by recession revealed the nature of ice-contact erosion on rock. Many surface features were present including micro-pitting, striations, polishing, streamlining, pot-holes,

fractures and angular cavities. The complex relation of ice and water action was evident in the changes over a few feet from water-scoured, pot-holed rock to striated bosses and angular unpolished niches.

Near Baintha Camp, Mango and the Snout, crevasses revealed the existence of tunnels or "tubes" along which meltwater coursed, one wall being ice the other rock (Plate 12.9.). Incisions into the rock of up to two feet occurred and included strings of half-potholes and cavities with smoothly polished walls. Sets of smooth holes and grooves on rockwalls several hundred feet above the present ice must have originated in such a way. On rock walls there were smooth channels of a similar sort falling at steep angles, even vertically, and crossing one another. These suggest the existence of other "tubes" descending to deeper levels under the glacier. Pot-holes and channels were also observed to commence and stop abruptly. This fierce erosion by melt-water raises some problems. The high summer discharge armed with abundant debris should give effective fluvial scour, but this would not be expected to cut deep channels in one or two season. Yet, it is unlikely the ice will throw the streams out at the same places each year. The many crossing paths of streams support this belief. In connection with pot-holes and related forms it has been suggested that cavitation attack may allow extremely rapid excavation (Barnes, 1956 and 15.2.iv.). It is believed that this type of erosion should occur particularly with high speed flow in sub-glacial tunnels (Hjulstrom 1935 and Barnes op.cit. p.503). At the Biafo, the long period with little or no melting, - about 8 months - and sudden increase in run-off with the ablation season, produce meltwater streams in early summer moving at great speed through compressed and nearly destroyed drainage tunnels (c.f. Hewitt 1967). Featherstone described great fountains of water welling up at the Biafo snout (1926 p.100). It is highly probably that the critical velocities for cavitating flows would develop under these conditions. When acting alone cavitation attack produces rough pits and jagged edges, but since it is combined with normal abrasion by transported debris smooth surfaces can result

(see Dahl 196.5 p.137).

Another significant feature of the ice-contact was the abundance of fine material squeezed into holes and cracks in the rocks. It is believed that such plastically deformable material under the influence of ice pressure will also produce smoothly-molded forms in rock (Gjessing 1965).

Striated surfaces occurred on convex areas indicating scour by debris-laden ice (Plate.12.10). Removal of large pieces of rock also reflected action of ice and transported moraine. Some blocks were dislodged in sub-horizontal directions which suggest plucking or frictional loading by boulders moving with the ice. Others, however, must have moved downwards or laterally at right angles to ice movement (Plate 12.11.). This might be explained by loading due to heavy wedges of moraine at the ice margin resting on overhangs of rock. There was also much movement of large boulders jammed between the ice and rock. These, or boulders from the ablation moraine above would suddenly drop to lower levels with great force and break off pieces of rock.

12.7. Direct Movement of Debris from Tributary Zones to the Main Glacier

At the upper and lower ends of the ablation zone where ablation valleys were small or dissected, mudflows, debris-flows, rock falls and avalanches descend to the glacier directly. Outwash streams from the larger disconnected tributary glaciers carried great quantities of debris down the steep intervening slopes to the main glacier, and some massive glacier mud-flows added to this transport. Few of these processes deposit material out on the glacier surface. The material plunges into the deep ice-edge troughs. Mass-movement debris became lost in the confusion of ablation moraine there; tributary streams, opaque with alluvium, plunged into deep amphitheatres cut into the side of the glacier. Examples near Mango and Namla were 100 ft. across and 100-150 ft. deep. The streams introduce large amounts of already water-worn debris into the glacier over a distance of 25 miles, and help to explain the great volume of well-rounded debris issuing from the snout in summer.

Glacier mudflows arise in a number of ways. The termini of the tributary glaciers were more-or-less buried in thick ablation moraine, flanked by high ridges of lateral moraine and floored with deep ground moraine (c.f. Heim and Gansser 1939 p.233). Normal, torrential discharges and outbursts from small glacial reservoirs easily become super-charged with debris and form mudflows. Mudflows also begin on these glaciers where nearly stagnant ice saturates and provides slide surfaces for overlying ablation moraine (see also Sharp 1942 p.225 and 1960 p.332). Glacier mudflows are common in the ablation zones of many glaciers in the region and some of the catastrophic mudflows described elsewhere are due to bursting of glacial reservoirs (Longstaff 1910 p.636 and 10.5.v.). The characteristic mudflow levees and dispersed tongues of debris covered the retreat paths of the tributary glaciers of the Biafo.

12.8. <u>The Glacier Margins III: The Terminus.</u>

In a separate article the writer has described the conditions and behaviour of the glacier terminus in 1961-62 (Hewitt, 1967 and Appendix 8). Only a short summary will be presented here.

The characteristic features of the terminus are, heavy cover of ablation moraine, steep ice-front, thick aprons of unstable <u>melt-talus,</u> pro-glacial lakes and large, changeable outlet rivers (Plate 12.13). These have also been noted by many visitors (Austen 1864 p.13; Conway 1894 v.2. p.409; Workman 1901 p.105; de Filippi 1912 p. 163; Featherstone 1923 p.253; de Filippi 1932 p.86; Auden 1934.). Several observers also commented on the rapid seasonal change of the snout (Note 12.1.). What has not been observed previously is the powerful modification of the terminus by the winter surge. Dainelli crossed the terminus in December 1913 but only noted the general position (de Filippi 1932 p.86.). The writer's observation in 1961-62 covered the period of maximum seasonal advance and retreat. The alternate back-melting and large debris release in summer, and advance with reworking of moraine in winter are complimentary factors in determining form and composition of terminal deposits.

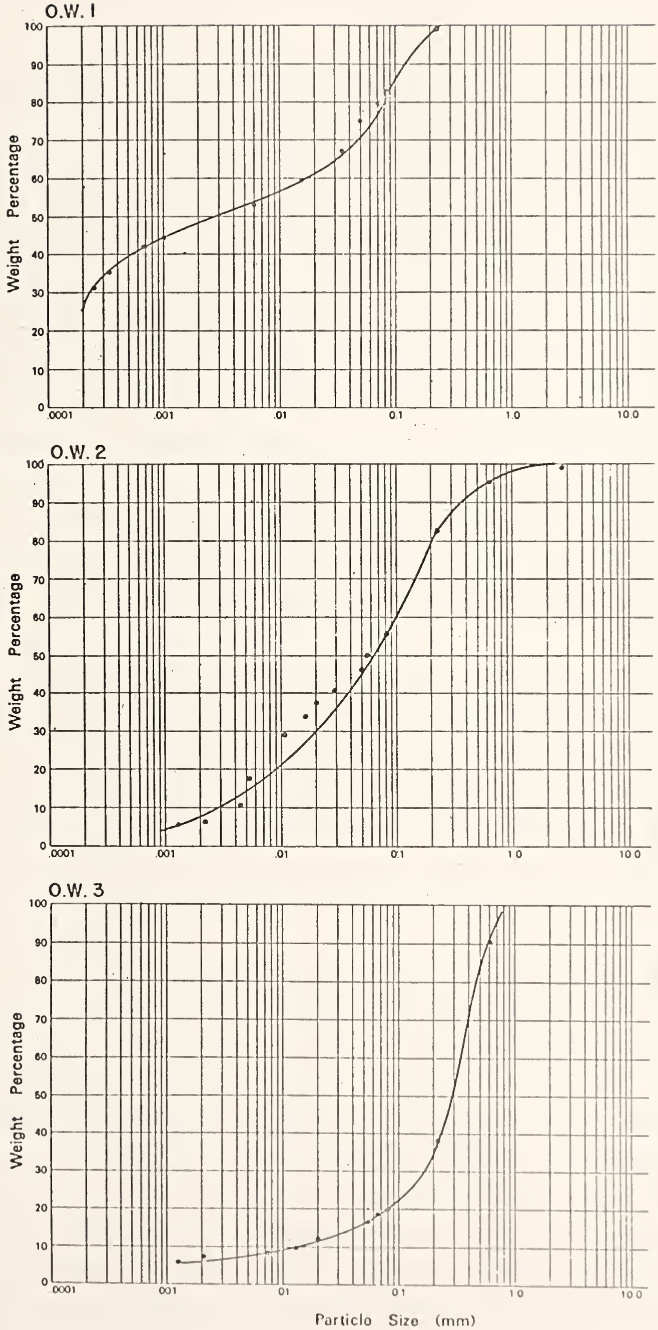

Fig. Cumulative percentage grain-size curves for samples taken at three levels in pro-glacial lake sediments of the Biafo: O.W.I. from the uppermost, O.W.2 from the middle (8inch depth); and O.W. 3 from the lower (I2½inch depth) layer of one year's deposit.

Ice-contact lakes have more than local significance in the frontal deposits of the glacier. Along with the kame terrace lakes these seem to be the only places where significant amounts of fines are accumulating in the present environment. The material shows seasonal stratification with predominantly sandy deposits of early summer giving way to predominantly silt-clay deposits in late summer. Samples from this sequence in the large ice-contact lake of the 1961 ice-front indicate the changing composition (Fig.12.1.). The importance of silt-clay accumulation away from the outwash torrents is that it can be reworked and re-incorporated in the terminal ice during the winter surge, and more especially, during secular advance. Thus, substantial amounts of fine material become available to be worked into the coarse ablation moraine, forming a more cohesive terminal deposit. This helped to explain the greater cohesion of older moraines, than either outwash deposits or the superficial terminal moraine forming at present (Plate 12.14).,

Beyond the present ice-front lies a wide crescent of old terminal moraines, dry pro-glacial lake beds and old outlet channels (Plate 12.15)., Many of the features can be identified with glacier positions in the period of recent exploration (see 13.3.). West of the outermost old moraines lies a broad flat covered with large water-worn boulders, which the writer explains as the result of flood(s) from Biafo ice-dam(s) across the Braldu (Hewitt 1964 and 14).

12.8 Conclusion

The overall impression of glacial activity is of massive erosional transport and efficient reworking of moraine and removal of it as outwash. The former is inferred from the large amount of debris on the ice and the probable rapid movement of the glacier. Unfortunately, the writer's theodolite measurements of movement on the middle glacier were lost in transit from the mountains. Checks of the figures in the field are recalled as indicating movement of several feet in four to five days. Measurements of glaciers in the rest of the region, even those large ones of relatively low surface gradient show rapid movement compared to most Alpine or Polar examples in similar situations

(see Supan 1911 p.197.; Finsterwalder et.al.1935; Pillewizer 1957; Desio et.al. 1961 and Kick 1964). Although the Biafo is a firn-stream glacier much of the debris transported by it must be attributed to vigorous avalanche activity in the main and tributary glacier accumulation zones. During the present phase of thinner ice, erosion of lateral deposits of the glacier makes a contribution though it is hard to assess. The importance of it relates to vigorous melt-water action along the margins rather than ice erosion. At high ice phases deposition along the lateral margins predominates. The effectiveness of outwash transport is attributable to the short, intense ablation season with correspondingly high stream discharges in and beyond the glacier. There are some grounds to suppose that much of the sediment yield of the Upper Indus derives directly from present glacial areas as does the water (see Chapter 15.). The fact that the glaciers commence where moisture is most abundant, have much of the steepest slope area concentrated around them (8.2.iv.), slopes with the most frequent of all mass movements, avalanches (10.4.ii.); as well as supplying most of the run-off, gives some strength to the argument. Corbel has shown the superior sediment yield of glacial streams (1959). In the Upper Indus Region and the Himalaya generally it would be a useful piece of research to discover whether, in fact, the bulk of the great erosional rates must be attributed to the high nival and glacial basins as compared to the river gorges and snow-free slopes.

CHAPTER 13

GLACIAL GEOMORPHOLOGY III: RECENT SECULAR CHANGES OF THE BIAFO AND THEIR GEOMORPHIC EFFECTS

13.1. Introduction

Fortunately, the Braldu Valley has been visited by many travellers since the first description by the Schlagintweit in 1857, and we have a fairly good record of the fluctuations of the Biafo Terminus. Related thinning of the glacier and behaviour of its tributaries have not been reported. Nevertheless, it is possible to deduce information on these matters by relating photographs and comments of past explorers to present conditions. The fluctuations over the past 110 years have involved a net loss of over one cubic mile of ice within the basin, and changes in certain critical relations of the glacier to its tributary slopes and to the Braldu River. These fluctuations are of considerable geomorphic significance. Since they can be attributed to short secular changes within the contemporary climatic environment they are of central interest to the present investigation.

13.1. Magnitude and Effects of Thinning

Thinning is expressed in general lowering of the ice surface and disengagement at those points in the glacier system less than, or only marginally thicker than the depth of thinning. Disengagement may occur in the main ice-tongue leaving a stagnant mass in the lower valley or between tributary glaciers and the main ice-stream (see Flint and Demorest 1942). Only minor masses of stagnant ice seem to have been stranded by thinning of the lower Biafo (Note 13.1.). However, at least seven ablation zone tributaries of the Biafo have become disengaged during recent secular changes, to judge from comparison of the Conway, Workman and Shipton Maps and present-day conditions.

13.1.i. Thinning of the Main Glacier

Apart from direct measurement, the best evidence of glacier thinning is the presence of extensive and well-defined kame-terrace

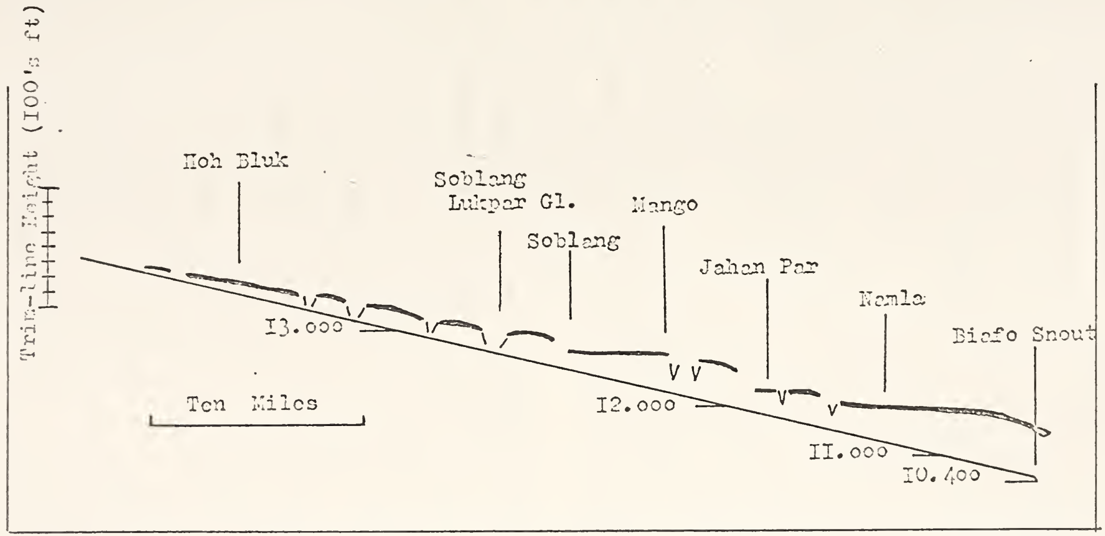

Fig. 13.1. Diagram showing the general relation of the west flank, main kame terrace level to the Biafo ice level in 1962. The ice-edge is stylised and vertical scale greatly exaggerated.

trim-lines (Flint and Demorest, op.cit.). Such evidence is amply supplied along the Biafo and will be used to calculate the order of recent thinning, (see Plate 12.7.). Nevertheless, the limitations of this information must be recognized. The value of the trim-line depends on the rate and magnitude of the thinning, and the relative rates of moraine-building at high ice levels. The kame terrace surface generally represents a minimum value for high ice levels over the period concerned. Lateral moraine ridges of the Biafo showed the ice had been several hundred feet higher than the kame terraces in some places. Theoretically, the ice could also have stood a further 150 ft. or so higher than the large moraine ridges without flowing into and destroying the terrace deposits. Lateral moraines are generally fewer and less well-preserved than the kame terraces. Hence, estimates of thinning based on kame terrace levels will tend to be conservative. In the case of the Biafo, estimates could be 30 per cent too low.

The height of the main trim-line varied from 300-500 ft. near the terminus, to 20-40 ft. at 14,000 ft. (Fig.13.1.). Since the visit of the Schlagintweits there has been thinning of at least 600 ft. at the site of the present ice-front (see Shlagintweit 1861-66. Vol II p. 462.). Godwin Austen's map showed "The Nose", - a feature on the west flank of the present ice-front, - completely buried under the glacier, although its summit is nearly 100 ft. higher than the nearby kame terrace level. That author also travelled five miles up to the Biafo but made no mention of a trim-line, which would be surprising, in view of his other careful observations, had it been apparent (1864 pp.25-26.). There was some active lateral moraine construction along the middle Biafo early in the present century when the glacier was less extended and thinner than in the mid-Nineteenth Century. It therefore seems reasonable to conclude that the glacier has thinned at least from the height of the main kame terrace in the past 100 years.

The loss over 100 years approximates a wedge of ice 22 miles long and 1 mile wide tapering in thickness from 600 ft. at its lower

end. Ignoring irregularities, and assuming the glacier has thinned parallel to its present surface, this represents a net loss of about 1.3 cubic miles of ice: equivalent to 4.05 million acre-feet of water. There has also been an intervening phase of advance, so that two-thirds of the net reduction since the 1860's has occurred in the last 40-50 years. (Note 13.2 a and b).

These losses are equivalent to a precipitation deficit over the whole Biafo catchment of 230 inches precipitation in 100 years: an average annual reduction of 2.3 inches per year. Actually, the equivalent loss in the past 40 years exceeds 3 inches per year. Losses of this order have also been reported in the Alps (Flohn, p.com.). Unfortunately it is not possible to say whether an actual decrease in precipitation took place, or an increase in melting, or both. We do know that the run-off from the whole Upper Indus Basin has been higher, on average, for the period 1909-1959, than the corresponding period 1869-1908. In particular, run-off for the period 1929-38 shows eight out of ten years with above average discharges. The run-off depends largely on the melting of snow and ice, and therefore on the length and/or intensity of the summer melt season. There is no evidence of increased precipitation in the second period. Meanwhile, phases of higher snowfall are likely to reduce melting through associated greater cloudiness, and shorter melt-season at higher altitudes. The evidence from the Mediterranean Belt and Western Eurasia generally is of rather higher temperatures this century, (Lamb et.al. 1966.), and since the Karakoram weather is primarily westerly it may reflect the same tendency. Hence, we assume provisionally the retreat and thinning of the glaciers generally, and of the Biafo in particular during this century reflect higher average temperatures and probably lower precipitation, especially for the summer accumulation season at high altitude. (see Lamb op.cit. on the association of recent phases of climatic amelioration with reduced summer storminess and rainfall).

13. I. iii. Effects of Thinning on Ablation Zone Tributaries

In additon to thinning of the main glacier, there has been wastage of tributaries, several of the ablation zone ones becoming disengaged and retreating considerable distances. Conway showed the large Baintha tributary without an extensive cover of ablation moraine and joining the Biafo as a broad ice-stream. He visited Baintha Lukpar but made no mention of its lower part being a moraine-covered, near-stagnant mass as in 1961 (Conway 1894 Vol.II.p.398.). A photograph of the Mango tributary in 1899 shows it reaching the main glacier (Workman 1901 opp.p.114.). By 1939 it had receded over 1½ miles the snout lying 1,750 ft. above the Biafo. It was in the same position in 1961. They also photographed two other West Bank tributaries in 1908, which have thinned 100-150 ft., one example becoming disengaged since then (Workman 1910, opp.p.190 and p.192.). (Note, 13.3.).

13. I. iii. Some Geomorphic Effects of Thinning

Thinning has a number of locally marked geomorphic effects. The results of isolating kame terraces above the ice level have been noted earlier.(12.5.). Some striking effects of ice level changes occur in the belt of landscape subject alternately to glacial and sub-aerial conditions. In the lower ablation zone this belt is several hundred feet in height. Much of the rock exposed by recent thinning is stained and rotted by weathering which, in view of the heavy scour in sub-glacial areas, probably occurs sub-aerially or under protective coverings of moraine. In the lower few miles of the glacier where kame terraces are absent or largely destroyed, rock falls and slides commencing below the trim-line level are very common. In the same areas the glacier margins are now covered with thick moraine, probably underlain by stagnant ice. The absence of ice-contact marginal lakes and drying out of many on kame terraces during the present phase of thinning must reduce the occurrence of sudden floods from the draining of these lakes and the violent flushing and scouring which result. The degeneracy of the ice and dependence of most vigorous activity on melt-water, at least in

the visible zone of the ice-margins, contrasts strongly with the conditions during higher ice stages when the glacier rapidly builds lateral moraines and modifies its margins. The landforms and deposits of the ablation zone margins depend strongly upon the secular variations of the glacier.

13. 2. Magnitude and Effects of Terminal Fluctuations

Changes in the Biafo terminus are much more fully recorded than those for the rest of the glacier. (Table 13.1).. There are maps, which, though rarely accurate in detail, give a clear picture of changes in plan at approximately 30 year intervals since 1861, and numerous descriptions and illustrations at much closer intervals. The period 1929-1939, one of marked recession, is particularly well documented. (Figs. 13.2 a & b).

Within the broad pattern we may note some detailed variations. Firstly, at given mean positions there have been differences between the size and degree of advancement of the east and west parts of the two lobes with a recessed part in the central area. In 1961-62 the western half of the snout was higher, more advanced and more active. In 1937 this half seems to have been the thickest part of the terminus. However, in 1933 Auden's map shows the eastern half much more advanced, and in 1909 de Filippi remarked on the much greater height and steepness of the eastern lobe (1912 p. 165).. There is insufficient information at present to say whether these changes reflect the distribution of a mass, and lines of movement in the lower glacier at different ice levels; or changing contributions of ice from different sections of the accumulation areas. One would expect the eastern side of the glacier to be the least conservative, both because it receives greater insolation, and because it has the enormous Baintha tribut ry entering in the ablation zone; a tributary subject to large fluctuations (13.1.ii.).

A second variant, identified in terminal morainic ridges and some maps, is the tendency of short sections of the ice front to have a measure of independence. Over the past forty years sections

a)

b)

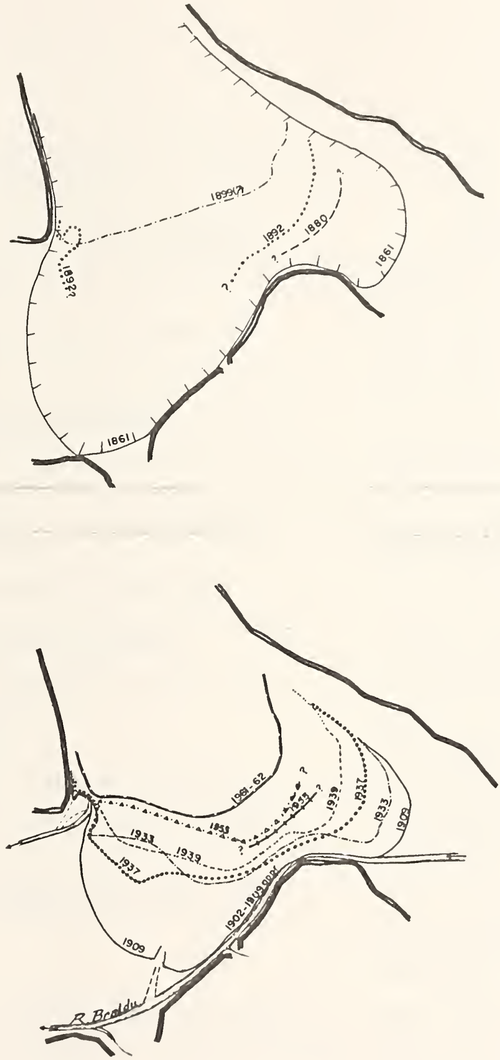

Fig.I3.2. Positions of the Biafo Gyang Terminus:
a) I86I-I899 , b) I902-I962

TABLE 13.1. Summary according to date, of observations of the Biafo Snout with published sources.

Date	Type of Information	Source
1857	Thickness of terminal lobe in Braldu Valley.	Schlaginweit (1861-66). Vol. II.
1861	Map and description of terminal lobe.	Godwin Austen (1864).
1880	Map	Lydekker (1881).
1892	Description, map and watercolour sketch from Korophon-Laskam Path.	Conway (1894).
1899	Map, description, and distant, ill-defined photograph from Skoro-La Path.	Workman (1901). (see also Note 13.4).
1902	Description, and position relative to Braldu River.	Guillarmod (1904). Pfannl (1904).
1905	Position relative to Braldu River.	Penny, in Mason (1930).
1909	Description and photograph from Skoro-La Path (The Sella photograph).	de Filippi (1912).
1913	Position relative to the Braldu, and photograph.	de Filippi (1928 & 1932).
1922	Description.	Featherstone (1923 & 1926).
1923	Position relative to the Braldu.	Egeberg, in Mason (1930).
1929	Map and relation to Bakhor Das cliffs.	Savoia Aosta and Desio (1930 & 1936).
1933	Map, description, and photographs from Korophon-Laskam Path and Skoro La Path.	Auden (1936).
1937	Map	Auden and Spender (?).
1939	Map	Mott (1950).
1953	Position relative to Bakhor Das Cliffs.	Desio et.al. (1961).
1954	(Surveyed but map not drawn up at present).	Desio et.al. (1961).
1955	Sketch Map	Matsushita and Huzita (1966).
1959	Position relative to cliffs of Bakhor Das.	Maraini (1961).

between 100 yards and 1/4 mile long have experienced sudden advances within the general pattern of retreat. Few of the old terminal moraine ridges consist of single concentric arcs of the dimensions of the overall ice-lobe, but rather of series of smaller arcs (see Plate A2 and Appendix 8). While the smallest irregularities can be explained by variable impedance by frontal debris, and differential melting, the larger ones must reflect differential movement of localised pressure waves in the glacier. Too little is known of the degree of independence of individual streams in a main glacier to say whether the effects of variable mass balance in tributaries could explain this. However, the net result in terms of their geomorphological expression in terminal deposits, is to extend and complicate the broader secular development of till morphology and fabric described elsewhere (see Appendix 8). An additional question of some interest, the effects of interaction between the glacier terminus and the Braldu River, will be discussed in the following chapter.

CHAPTER 14

FLUVIAL GEOMORPHOLOGY I

STREAM VALLEY FEATURES WITH SPECIAL REFERENCE TO THE BIAFO-BRALDU AREA

The rivers of the area commence fully grown from the snouts of glaciers and express their action in large erosional and depositional features of which no small area gives a full picture. However, practical difficulties, especially lack of moderately reliable maps put a wider survey beyond the scope of this investigation. The main features of the Upper Indus-Shigar Valleys seen in reconnaissance are described, and a detailed coverage of fluvial conditions near the Biafo complete the survey of that area.

14.1 General Characteristics of the Upper Indus-Shigar River Valleys

Between Skardu and the Plains around Attock the Indus cuts a deep gorge whose slopes rise 10,000 - 15,000 ft. from the river in 5 - 10 miles. The average gradient of the river is 16 ft. per mile. The stream lies in a constricted rocky or bouldery bed with rock walls and steep talus slopes descending to it (Plate 14.i.a.). In a few places the gorge opens out somewhat the floor being occupied by arid river terraces and alluvial fans (Plate 14.1.b). Tributaries cut deep ravines to join the river leaving large triangles of terrace at the junctions and several hundred feet above the stream. 4,000 - 8,000 ft. above the floor of the Gorge are many alpine shoulders and relatively open hanging valleys.

Above the Narrows of Komara the river changes to a maze of braided channels wandering over the floor of Skardu Basin; an area of sand, gravel and boulder bars several miles wide. The Shigar Valley has the same character, the braided flats lying below a main terrace 200 - 500 ft. above the river (Plate 14.2). These wide valley floors allow the development of enormous alluvial fans, especially where torrents descend from high glaciers. Outwash, debris-flows and mudflows are the common processes building the fans (Plate 14.3).

Where the Braldu joins the Shigar it covers a four-mile wide swath of braided channels, but for most of its length is more like the Indus Gorge; a deep slot flanked by high river terraces and rock-walls(Plate 14.4). It has an average fall of 60ft. per mile. The river terraces are most striking, some standing over 1000 ft. above the present river. The old valley fill composing the terraces consists of complex interfingering of valley train, moraine, pro-glacial and ice-dammed lake sediments, and mass-movement materials (Plate 14.5;see also Norin 1925).

14.2 Fluvial Landforms in the Vicinty of the Biafo Terminus

In the vicinity of the Biafo Terminus, the Braldu River passes through three distinct morphological phases. Above the Biafo, the river (here called Biaho) flows in multiple braids over a mile-wide belt of valley train(Plate 14.6). At the Biafo entry the main stream is confined to a narrow path under the cliffs of Bakhor Das with a secondary set of braids passing into the old Biafo moraines (Plate 12.11). Below the Biafo the river is confined between high terraces and in places forms large meanders in the valley fill before plunging into the main Braldu Gorge(Plate 14.7).

There are no discharge measurements available but we can obtain some approximate estimates based on the assumption that precipitation minus evaporation in these areas should give a run-off of not less than 36 inches per year (1920 acre-feet per mile^2), and that 80% of this will be concentrated in three summer months (see Chapter 5).

In these terms, discharge above the entry of the Dumurdo should average 5,000 cfs in the summer with peak flows over 10,000 cfs. Just below the entry of the Biafo waters, the average at this time should be about 13,000 cfs. with high flows exceeding 20,000 cfs.

14.2.i. The Biaho Braided Valley Train

This section of river is distinguished by complex braiding over a wide valley floor, and by the size-sorting of the valley train. At the surface nearly all the material of the bars, banks and channel floors was well-sorted ranging from coarse gravel to moderate sized

boulders (about 2 ft. diameter in the coarsest bars). Fine material was rare, as were the very large boulders common below the Biafo. The material was well-rounded. During high summer flows the braids shifted rapidly, boulder andcobble bars appearing and being eroded quickly. In winter there was very little channel change owing to the low competence of the streams, and to extensive covers of "icing" (aufeis) which stabilised channel and bar patterns (Plate 14.8).

14.2.ii. The Junction with the Biafo, and Biaho Streams

The Biaho braided area narrows rapidly as at approaches the Biafo and is pinched into a single channel between the first of the old moraines and a buttress of Bakhor Das (Plate 12.11). From all past descriptions, the Braldu normally follows a single deep channel against the cliffs of Bakhor Das until it passes beyond the morainic crescent of the Biafo. This is still the case with the principal channel; the only one which sustained a flow from early October to late May. However, sometime between 1955 and 1961, the Braldu had burst into the central old moraines to form a broad belt of braided valley train destroying all but the largest and coarsest moraines. During high summer flows the coarse bed load of the Biaho moves into the moraine area, flooding it with well-rounded and sorted boulders and cobbles as well as with water. Erosion and reworking of morainic material, at least by 1961 had become a minor affair compared to the steady extension of the Biaho braided valley train into the moraine area. At the same time there had been widening and some tendency to braid along the main channel.

By contrast, the main Biafo stream and the Braldu itself from where the Biafo waters join it, were quite different in channel character. There was only a little crude braiding, not seen at all during high flows, and the bed material was poorly sorted with many large boulders lodged in it. There was a braided section of well-rounded cobble and boulder size material close to the snout of the glacier. However, some 300 yds. out from the ice the gradient steepened and stream became confined between cohesive banks of old terminal moraine (Plate 14.9). This was accompanied

by a change in channel character involving the absence of shifting braids, and of most well-sorted channel material. Instead the channel was floored with massive, immobile boulders giving an extremely rough and irregular cross-section.

The western outlet the Biafo comprised a large channel area but carried very little water in 1961-62. Evidently this was a recent phenomena for in 1953 as at most earlier times, the western outlet appeared as large or larger than the other (Capt. A. Streather p. com.). This channel comprised a broad swath of braided valley train for over a mile out from the glacier, but also steepened up to join the Braldu becoming choked with large boulders (Plate 14.10).

14.2.iii. The Braldu below the Entry of the Biafo

Beyond the Biafo moraines the combined waters of the Biaho and Biafo lie in a narrow trough cut in old valley fill. Well-sorted bars of cobbles and boulders do occur intermittently along the river, but there is no development of classic valley train below the Biafo. Large boulders line much of the channel and the base of the flanking terrace slopes. High flows transport abundant bed load of coarse material. Evidently, the concentration of discharge into a single channel provides sufficient energy for the size fractions seen in the Biaho valley train and Biafo outwash (Appendix 8) to be moved rapidly through the main reaches of the river. Only where the Braldu again opens out in the wide embayment where it joins the Shigar are there extensive spreads of small boulders and cobbles and a braided stream.

Occasionally, the Braldu impinges on a rock buttress or wall creating a complex of pot-holes, but only in two places is the channel itself cut in rock; one being an epigentic gorge of the kind commonly found in these mountains (Heim and Gansser 1939; Dainelli 1922-1934 v. 3. p. 58 and 71; Plate 14.11). Otherwise, the river lies between cliffed terraces in valley fill, and is floored by large boulders which the present stream is rarely competent to move (Plate 14.13).

14.2.iv. Form and Texture of Large Channel Boulders, and of Pot-holes

While the river cannot normally move the large boulders in its channel it can abrade and shape them. Close inspection of the boulders

at low water shows this action to be very fierce. Fine-grained, massive rocks are smoothly polished but also have deep fluting carved in them unrelated to any structure in the rock. (Plate 14.14). Coarse-grained rocks are minutely pitted the pits picking out the weaker crystals but being elogated with the line of stream-flow (Plate 14.15). On a larger scale, the most striking feature is the number of immobile boulders which are stream-lined in the direction of stream flow after the fashion of roches moutonnées. At the same time, the steep downstream slope of these stream-lined boulders is normally as smoothly polished as the rest. (Plate 14.15).

In the case of the boulders, the water envelops the rock. Where the river has been let down onto a rock spur the water is enveloped by the rock. In these cases it cuts pot-holes. In the epigenitic gorge these have become successively larger as the river has incised itself deeper into the rock (Plate 14.12). At the top, the gorge is barely 20 ft. wide in places. The pot-holes forming the bed of the gorge 200 ft. below are 80-100 ft. in diameter. The whole gorge consists of a series of coalesced pot-holes. The rock surface is scoured and fluted in the same manner as the boulders.

The large, coarse bed-load and fairly abundant sand in suspension in the river at high flows offer partial explanations of the effective stream-lining and pot-holing. In addition, the high speed, turbulent and cavitating flows of summer (see Dainelli 1959 p. 106) make it very likely that cavitation erosion is an important factor (Barnes 1956). In high speed flows - experiments suggest greater than 25-30 ft. per second - pressure differences within a liquid, created by obstructions in its path, lead to the sudden vapourisation of moisture and the formation of cavities ("bubbles"). Downstream of the obstruction high speed collision of the cavities and restoration of nearly uniform pressure in the liquid produces sudden collapse. The imploding shock-wave thus produced releases enormous local energy (see Callis 1956; Zel'dovich and Raizer 1967 v. 2 pp. 794-812). It has long been known that cavitation is responsible to such things as rapid pitting of ships' propellers. In an early paper Hjulstrom (1935) suggested it might be

an erosional agency in landscapes and Barnes (op.cit) has recently shown that the forces involved should be adequate to damage rock surfaces quite rapidly. The requirements are, the occurrence of high velocity flows, and impingement on the rock surface to sufficiently concentrate the attack. These would seem to be satisfied in many sections of the Braldu where it is confined in a bouldery channel, or against rock. Furthermore, whereas cavitation is apparently very localised and selective under normal conditions, the turbulent high flows of these rivers and many channel obstructions probably distribute the attack more widely than is common in large rivers.

14.3. Fluvial Features of the Braldu Valley Floor.

14.3.i. The Braldu Terraces.

Some striking features in the fluvial zone record profound changes in the geomorphic environment. Well-defined terrace levels occur, some difficult to differentiate as either river or kame-terrace levels without close inspection, but the largest series obviously record fluvial trenching of old valley-fill (Plate 14.17). The highest, and usually the largest, of the main river terraces steadily increases in height above the river downstream from the Biafo, and until the sharp bend just below Chokpoing. At its highest point it is about a thousand feet above the stream. Below Foljo the main terrace gradually decreases in height above the river and is several hundred feet lower at the junction with the Shigar River. Along most of the valley a further distinct break occurs several hundred feet above the main river terrace. This is a rock-cut break of slope forming the lip of the Braldu Gorge in which the main valley deposits are found (see ed. Dainelli 1922-34 v. 7.). As many as six sharply defined terraces occur at places within the gorge but three is more common. Correlation of terrace levels and the trend of their surfaces would require an intensive programme of surveys since there are no topographic maps of even moderate reliability. Meanwhile, the terraces are complicated, and their local height variation considerable. Where they cross large alluvial fans or truncate compact taluvium they vary two or three hundred feet in height over short distances.

In addition to its variety, the material composing the terraces is generally distinguished by considerable cohesiveness. Terrace flanks often stand in cliffs exceeding 45^{o}. The cohesion is mainly a function of the silt-clay content of the old valley fill. Since the contemporary fluvial materials contain negligible fines, a change in conditions seems to be reflected. The explanation of the change seems certainly to be tied to that of the anomalous amounts of fines in some older slope deposits. It is not clear at this time whether the situation reflects a change in the calibre of weathering and entrainment materials, or periods of selective accumulation of fines controlled by local erosional situations. Much of the old valley fill was deposited during and after glacial recession, a considerable amount constituting mass-movement materials probably derived from lateral glacial deposits as at present. With time there must have been a reduction in the available till on valley walls and a lessening of the supply of fines. In addition, the age of the older terraces means there has been more opportunity for infiltration of fine material as a matrix. This question of how far climatic change acts directly to change the erosional products rather than indirectly by changing the erosional situation and selective removal and accumulation of materials is the chief unanswered problem in interpreting past deposits. For the Karakoram situation, it has already been suggested that changes in weathering products may have been less significant than changes in the pattern of removal (see 7.3. vi).

14.4. Relation of the Glacier Terminus to the Braldu, and the Question of Ice Dams.

14.4. Present Conditions.

The position of the Biafo snout has produced a complex history of interaction between glacier and main river. The Braldu affects the relative build-up and removal of debris at the ice-front both in position and through time. The flanks of the terminal lobe are relatively protected areas, while the river causes considerable erosion along the southern part of the lobe, (Plate 12.11), also controlling its position by triming the ice. On the other hand, the glacier tends to force the river towards the southern valley wall, both by ice-obstruction and deposition.

The critical factors in the Biafo-Braldu situation are:-

a) The topographical arrangement whereby the Biafo enters the Braldu facing slightly upstream, and opposite precipitous rock cliffs on the river's south side.

b) The great size of the glacier reflected in its large terminal lobe which, in the last 110 years, has been known to fill the Braldu to a height of 600-750 ft. above the valley floor (Schlagintweit, 1861-66 vol. 11 p. 462; Pfannl 1904 p. 255). The terminal lobe has spread to a width of two miles along the valley.

c) The large quantities of debris which the glacier sheds onto the valley floor, building a thick wedge of moraine across it.

d) The secular variations in the above factors, particularly the scale and rate of advancing phases. Recent variations have allowed the glacier to build morainic masses on its two flanks rising 100-300 ft. above the level of the river which has only a narrow through-channel. In the 1850's the glacier advanced sufficiently to over-arch the Braldu and lean on the walls of Bakhor Das (Austen 1964).

e) The seasonal relations of river discharge and terminal movement. From the high discharges of summer when the snout is rapidly wasting, the river is reduced to a minor stream in winter when the glacier advances many yards. This may be crucial to the formation of partial and complete blockages, both of which will be followed by vigorous river action when it forces a passage through (c.f. Visser 1938 v. II. p. 177).

f) A long-term factor is the downcutting of the Braldu. This has deepened the trunk stream leaving extensive, unremoved terminal deposits of the Biafo on arid terraces.

14.4.ii. <u>Damming of the Braldu River by the Biafo.</u>

Mason's opinion, echoed by that of Auden, was:-

"...It is inconceivable that this glacier could block the combined waters of the Panmah and Baltoro glaciers, which should always be able to maintain a channel" (1930 p.256).

However, Godwin Austen wrote of a local report of a large Biafo ice-dam and of, "...the greatest chronicled flood 200 yrs. before and in the Braldu...which...destroyed a Braldu village (etc)..." (1864 p.29). He believed these stories were related and that the Biafo would dam the river, catastrophic floods resulting. The same opinion was reiterated by de Filippi (1912 p.166).

While examining the pro-glacial flat west of the Biafo terminus, the writer came to the conclusion that the valley had been subject to devastating flood(s). Furthermore, the nature of the flat pointed unequivocally to damming action by the Biafo. The matter has been argued in a separate article (Hewitt,1964) relevant parts of which will be quoted here:-

"...Over a mile wide near the Biafo, the flat tapers gradually for about two miles...The nature of this relatively level surface is unusual even for the varied conditions associated with glaciation. It represents the outwash plain but...morainic material or superficial evidence of old glacier positions are absent, and neither are there the complex scroll patterns and old channels left by outwash streams... Such ephemeral water courses as exist are subsequent to the formation (of the flat).

"On the other hand there is abundant evidence of water action over the whole flat. It is covered with more or less water-worn debris. There are sheets and swathe-like expanses of water-laid boulders, each rock a yard or more in diameter. Sand and other material is absent in many parts or lies under and between boulders. The whole surface is dotted with sub-angular boulders of large and small dimensions. Within the general flatness of the plain there are certain minor irregularities of note. It is noticeably more hummocky at the downstream end where there are also masses of very large angular boulders showing but a little fluting by water action. Interesting too is the perceptible cross-valley slope so that the flat shelves gently from south-east to north-west. Hence it has a fan-like appearance when viewed from where the Braldu passes the old frontal position of the Biafo. Finally, may be mentioned the existence at certain points of concentric hollows into which the

water-sorted material has slumped. These holes may be as much as thirty feet deep and have no outlet.

A little way onward down the Braldu, where the valley opens out again, is another such flat of about the same size and with a similar surface. There seems to have been a greater tendency for the water to concentrate its action along certain lines, leaving long, scoop-shaped hollows. (see Plate 14.7). But again there are no definite stream channels but the same deposits of great boulders, worked and crudely sorted by water. Most conspicuous is a broad tongue of particularly large boulders spreading into the flat from the narrows that separates it from the Biafo (pro-glacial plain)" (Hewitt 1964 pp.21-22).

De Filippi noted the delta-like form of the flat (1912. p.162). Auden however spoke of "...an extensive flat terrace of water-rounded river gravels upon which the glacier has probably never flowed since the great secular retreat after the Ice Age." (1935 p.404). This does not solve the question of the nature of water action on the flat and the great size of much of the superficial 'gravel'. Along the side of the Braldu 200 ft. above the present river bed, and for several hundred yards below the outermost Biafo moraines there is a wide 'levee' of large rounded and sub-rounded boulders, 18 inches to 4 ft. in diameter. Generally, these are much larger than the material which the Biafo and Braldu streams transport at present. At the same time they are smaller than those in the great boulder swathes on the flat. They seem to indicate the occurrence of other less spectacular floods.

The only adequate explanation of the features observed is the mechanism of enormous floods coming from upstream of the Biafo entrance (see similar features associated with other ice-dam bursts in Bretz 1923; Pardee 1942; Richmond et.al. 1965 p.236). Since there is no other likely place for a dam of adequate proportions to form, the evidence vindicates Godwin Austen's belief that the Biafo has created large ice-dams. The details of ice-damming, a common occurrence in the region, and further interpretation of the phenomena appear in Chapter 16.

CHAPTER 15

FLUVIAL GEOMORPHOLOGY II: SOME CHARACTERISTICS OF REGIONAL EROSION REVEALED BY THE UPPER INDUS GAUGING RECORDS.

15.1. Introduction.

A major function of rivers in landscape is relatively efficient entrainment of erosional waste through and out of drainage basins. The net denudation of a fluvial basin is represented by solids transport at the mouth. It is of great value to know the scale, rate and regime of this solids transport. Fortunately, partial compensation for scanty knowledge within the Upper Indus Basin is provided by an unusually long record of river stage where the Indus leaves the mountains, and good stage/discharge, and discharge/solids transport rating curves. At present it is, of course, only possible to speculate on the exact relations between net removal and erosional conditions treated so far. Nevertheless, the context of the latter is seen more clearly, and the speculation raises some of the most significant geomorphological problems of the region.

15.2. Water Discharge and Regime.

Since April 1868 a once-daily stage reading of the Indus has been taken at Attock. In the last few years a good stage/discharge curve has been established (W.A.P.D.A. West Pakistan, 1960). Since the channel is considered relatively stable the curve can be applied to the whole stage record with fair confidence (Note 15.1).

The mean annual discharge at Attock (1868-1961) is 91.6 MAF, derived from an area of 102,000 mi^2. That is equivalent to a yield of 914 acre-feet/mi^2/year, or 17.3 ins. water over the whole basin; considerably more than the low precipitation and high evaporation indicated by the valley weather stations (Chapter 5). Most of the water derives from snow and ice in the high mountains, as is reflected in the glacial regime with 80% of the discharge occurring between mid-June and mid-September (Fig. 15.1). The even greater peakedness of the Upper Indus' regime compared to its southerly Himalayan tributaries reflects greater relief, higher altitude of main precipitation belts,

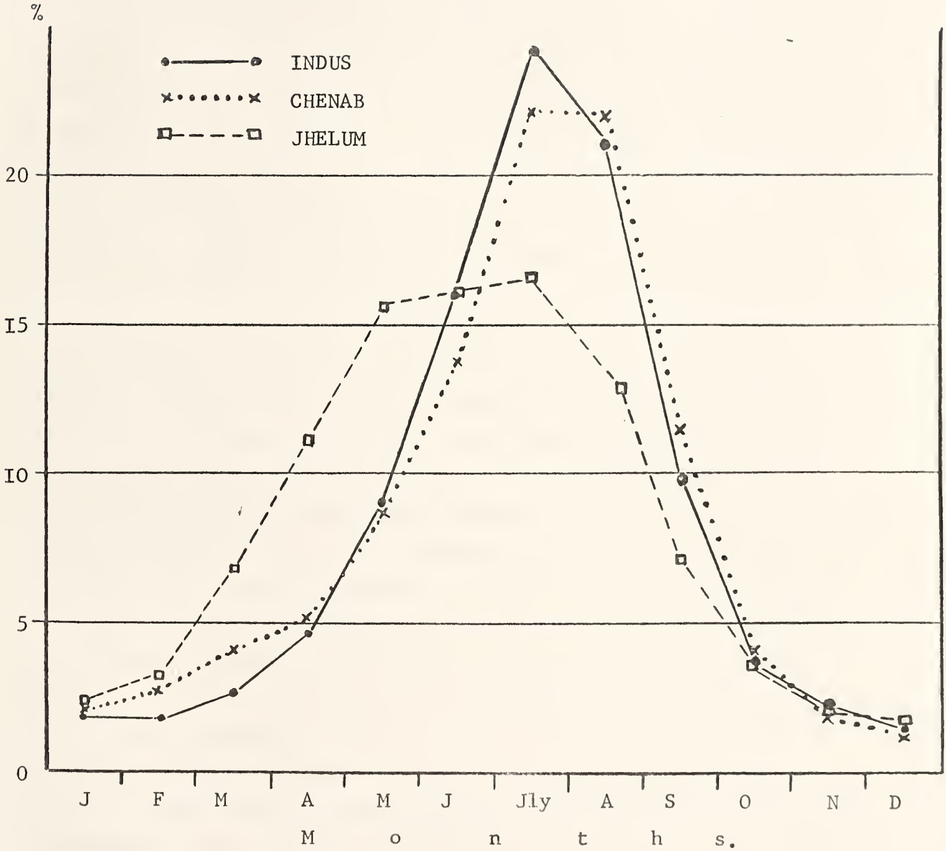

FIG. I5.I. Graph showing mean monthly discharge as percentage of annual yield for the Indus at Attock, and its Himalayan tributaries. The actual annual yield of the Indus is averaged for the period I922-I96I as 93.8 million acre-feet. That for the Chenab is 25.69MAF and for the Jhelum 23.05MAF. This is the period of record for the last two rivers at Marala and Mangla respectively.

and accompanying broader arid zone and higher percentage of frozen precipitation. The glacial regime of the Upper Indus is essentially an extreme orographic effect.

15.3. Sediment Yield of the Upper Indus.

Recent expansion of water resource development has led to an intensive programme of surface water measurements including that of solids transport. Stations occur at Gilgit, Partab Pul, and Darband within the region (W.A.P.D.A. West Pakistan, 1967). Only the Darband station has a reliably large number of readings. At high flows current meter and sediment samples are taken from a cableway. A P-46 point integrating sediment sampler is used making three measurements, - near the bottom, mid-depth and near the surface - at several sections across the stream. The data is available from 1960 to 1965, and gives the only reasonable coverage of the crucial peak flows on the Upper Indus. Also the ratio of flow between Darband and Attock has been used to calculate a 100-year series of ten-day/average discharge for the former. Sediment yield for the Upper Indus based on this series and the rating curve has been found to average 420 million short tons per year. On the basis of valley topography and bed-material size the engineers have used the formulae of Meyer-Peter, Schoklitsch and Kalinske to estimate bed-load. They consider a further 20 million tons should be allowed for this (Sir Alexander Gibb and Partners, p.com.). A yield of 440m tons from an area of 70,000mi^2 is equivalent to 6290 tons erosion per mi^2.

The sediment rating curve for Darband approximates fairly well a direct linear log-log relationship, as is common with such curves (see Appendix 10). However, in relation to discharge this produces a striking seasonal regime with an average 91% of the total sediment being carried in 2-2½ months, or 20% of the available time.

During the summer, the suspended sediment is predominantly sand (60%), with 33% silt and only 7% clay. This size distribution is interesting in the light of the size-distribution of materials in the Biafo area and general questions of the source of the sediment. Observations at the Biafo indicated that contemporary weathering produces

silt-clay, but that large amounts accumulate in some pro-glacial sediments or occur as a legacy in slope deposits. Another, equally significant detail in relation to this, is the obvious inference to be drawn from the sediment sampling that the river is usually transporting well below capacity. "Capacity" is a highly relative term, but what is meant here is that at given discharges the river normally has a much lower sediment concentration than the highest values recorded for these discharges. Furthermore, the Upper Indus usually has lower concentrations than a number of other rivers in the area for equivalent discharges. The logical explanation of undertransporting by any river is restricted availability of sediment. The lack of vegetation and considerable quantities of lag deposit - valley train, river terraces, alluvial fans, slope deposits and glacial deposits - hardly suggest that the overall erosional environment is producing too little sediment. One explanation, which ties in with observations in the mountains is that the aridity of the fluvial valleys, and recent incision into coarse valley fill or solid rock may be responsible. Incision and aridity cut off many slopes from direct transport to the rivers, while the streams flow in channels armoured with immobile boulders. If this is in fact the main constraint on sediment transport then a further logical inference would be that a high proportion of the present removal represents outwash from contemporary glaciers being flushed right through the river system. The size distribution of the materials tend to support this. Occasional large pulses of sediment at a given discharge may be attributed to bank collapses or large mudflows. Other high concentrations are associated with steep flood waves. Usually high concentrations of sediment may have greater fines fractions (Table 15.1). This is not always the case however, though it seems normal for high percentage of fines to occur in the periods following flood waves. The relative silt-clay content at low discharges is higher than at high ones but the actual volumes are too small to significantly affect the arguments above.

Table 15.1. Records of exceptional sediment concentration at Darband with size distribution where, clay <0.0055mm; silt 0.0055-0.0625mm; sand >0.625mm. (from W.A.P.D.A. p.com.).

Date	Discharge (cfs)	Suspended Sediment (ppm by weight)	Sand	Percent Silt	Clay
19/8/60	470,000	15,160	24	72	4
14/4/61	34,300	763	25	73	2
21/4/61	29,900	316	19	60	21
23/5/61	63,200	919	55	30	15
28/5/61	66,200	1,170	37	38	25
16/7/61	293,000	12,500	58	36	6
19/7/61	310,000	14,300	53	41	6
3/7/62	121,000	38,100	8	61	31
24/10/62	27,800	125	20	14	66
4/11/62	23,800	140	13	19	68

15.4. Dissolved Solids Transport of the Upper Indus.

Using measurements from 1963 to 1965 a Dissolved Solids rating curve for the Indus at Attock was kindly prepared for the writer by W.A.P.D.A.'s Surface Water Hydrology Project (Ch. M.Umar. p.com. 30/12/66). The total quantities of solution transport for these years, using the D.S. Rating/Flow Duration Curve method were, 17.3 million short tons for 1963, 17.2 for 1964 and 17.9 for 1965 - an average of 17.7. Observations at Attock, Darband and Partab Pul show no clear variation in D.S. concentration in the river with month of the year, and therefore little variation between high and low flows. This is unusual since low flows normally have greater concentrations. However, it means we can take the calculations above as fairly representative of most years since the flows in those three years were slightly below or equal to the average.

Taking the annual solution yield to be 18 million tons in round figures, its relative proportion to total erosional yield is not typical for most regions of the world. A systematic increase in the proportion of solution transport with increasing water yield has been found in a wide range of North American environments (Leopold et.al. 1964 p.77). The

relation of these figures to the Upper Indus is shown in Table 15.2. revealing the Indus to be atypical. However, erosional organisation is not simply a function of climate, and it has been found elsewhere that D.S. transport does decrease proportionately with increasing relief (Corbel 1959 p. 15). Only in the mountainous S. W. United State and Tunisia, however, does Corbel's value approach that of the Upper Indus. Undoubtedly, the latter is an extreme case of the orographic effect which not only increases sediment yield, and limits vegetation cover, but also concentrates run-off in a very short period of time. On the other hand, evaporation of soil moisture, and large salts accumulation in the sub-nival zone of the mountains makes it difficult to extrapolate directly from low solution yield to the idea of low solution weathering (c.f.7.1.ii; 7.3.v), though solution per unit area is probably restricted by climate and relief.

Table 15.2. Variation of the ratio of dissolved load to total load with average discharge per square mile of drainage.

Discharge (cfs/mi^2)	Number of Streams in Sample	Dissolved Load as per cent of Total	Source
0 - 0.1	22	9	Leopold et. al.
0.1 - 0.3	19	16	" " "
0.3 - 0.7	7	26	" " "
0.7	22	37	" " "
$1.24 = \frac{127{,}000 cfs}{102{,}000\ mi^2}$	1	3.5	Upper Indus at Attock

15.5 Rate of Regional Denudation.

On the basis of average net yield of sediment and dissolved solids from a drainage basin, it is possible to calculate the net rate of regional denudation (see Dole and Stabler 1909; Corbel 1959; Schumm 1963). Here, the calculations assume an average transported solids density of 2.64, so that erosion of one ton of material is equivalent to removal of 12.1 ft^3 of rock. For the Indus at Darband average sediment yield is 440 million. There is no D.S. rating curve for Darband but measurements there indicate the same concentrations of D.S. as Attock,

and we can assume .75 the Attock transport rate, this being the ratio of flow from the Darband branch (Sir Alexander Gibbon Partners p.com.). Solution transport is therefore about 13.5 million short tons, giving a total solids yield of 453.5 million tons from 70,000 mi^2. In round figures this is equivalent to 6500 tons per mi^2, or 78,500 ft^3 rock, which gives 78,500 x 4.34 x 10^{-7} feet of denudation per year; or very nearly 3.5 feet erosion per thousand years. The rate is higher than that calculated for the Kosi River in the Greater Himalaya (3.2ft per 1,000 years for 23,000mi^2: see Khosla 1953 p.111 and Schumm op. cit.), and suggests that Schumm's average maximum rate of denudation of 3ft per 1,000 years is not excessive. At the same time, the Upper Indus does not fit the usual pattern of decreasing yield with basin area. However, at Attock, where the writer calculated total solids transport at roughly 501 million tons/year from 102,000mi^2, the rate of denudation reduces to 2.54 feet per 1,000 years (see Appendix 10). The reduction reflects the lower relief of the main Kabul Valley, and lower sediment yield of the partly forested Lesser Hindu Kush basins.

Clearly, if these rates of erosion are representative of the recent geological past, they are much less than rates of uplift. An erosional rate of 3.5ft per 1,000 years must be compared with a probably 10ft of uplift per 1,000 years for the Pleistocene Period (see 3.1). It is also worth noting that within the region, since the rate of erosion is for projected area, average removal from the true landscape area with its very steep slopes (e.g. 8.3), would be less than 2/3rds that value. In effect the area over which erosional processes act is much larger than appears and it would be worth carrying out some investigations into how far this influences erosional yield as compared to the effect of greater relief energy.

Finally, it is interesting to note that while denudation is proceding at a greater rate than for any basin of comparable size for which data is available, nevertheless the river is transporting well below its apparent capacity (15.3). On the one hand this apparent inefficiency may be an inevitable consequence of the climatic modulation occurring with widespread deep dissection (i.e. perhaps only Front Ranges

or relatively isolated massifs could have large high altitude precipitation without a broad arid belt lower down). On the other hand, the effect of periodic climatic deterioration in a region like the Upper Indus, may produce large increases of erosional yield, and the figures obtained from contemporary rating curves could be well below those obtaining at other times. Any long-term increase in moisture might, of course, have the opposite effect by increasing vegetation cover along the lower valleys.

15.6 Extreme Discharges and Sediment Transport.

In the study of landscape processes it is always important to know the magnitude/frequency relations of erosional events. In a case such as the Upper Indus where average river flow and sediment yield are highly peaked in a short period of the year, brief, extreme events are more likely to have a major erosional role.

On approach to describing the magnitude and frequency of extreme events is to consider the annual maxima; in this case the annual peak discharge values. By plotting these on extreme value probability paper, the average return period for flows of various magnitudes can be estimated, and, while understanding of what lies behind these distributions is very poor, empirically they seem to fit most cases which have been tested (Gumbel 1958).

For the Upper Indus it is necessary to return to the Attock data for extreme value work to obtain a large enough set of daily readings. Values of the maximum discharge for each year between 1868 and 1963 were ranked according to magnitude and plotting positions on "Gumbel" extreme value probability paper determined from the equation:

$$\text{Recurrence Interval} = \frac{N + 1}{M}$$

where N is the number of years of record, and M is the rank position of the particular value (see Dalrymple 1960). These were then plotted (Fig. 15.2). In addition to the flow magnitude scale, equivalent sediment yield according to the rating curve is given. Although less reliable than the flow data this gives an idea of the order of magnitude of maximum-day sediment yield for various recurrence intervals (c.f. Appendix 10). It is clearly that the annual maximum days carry only a

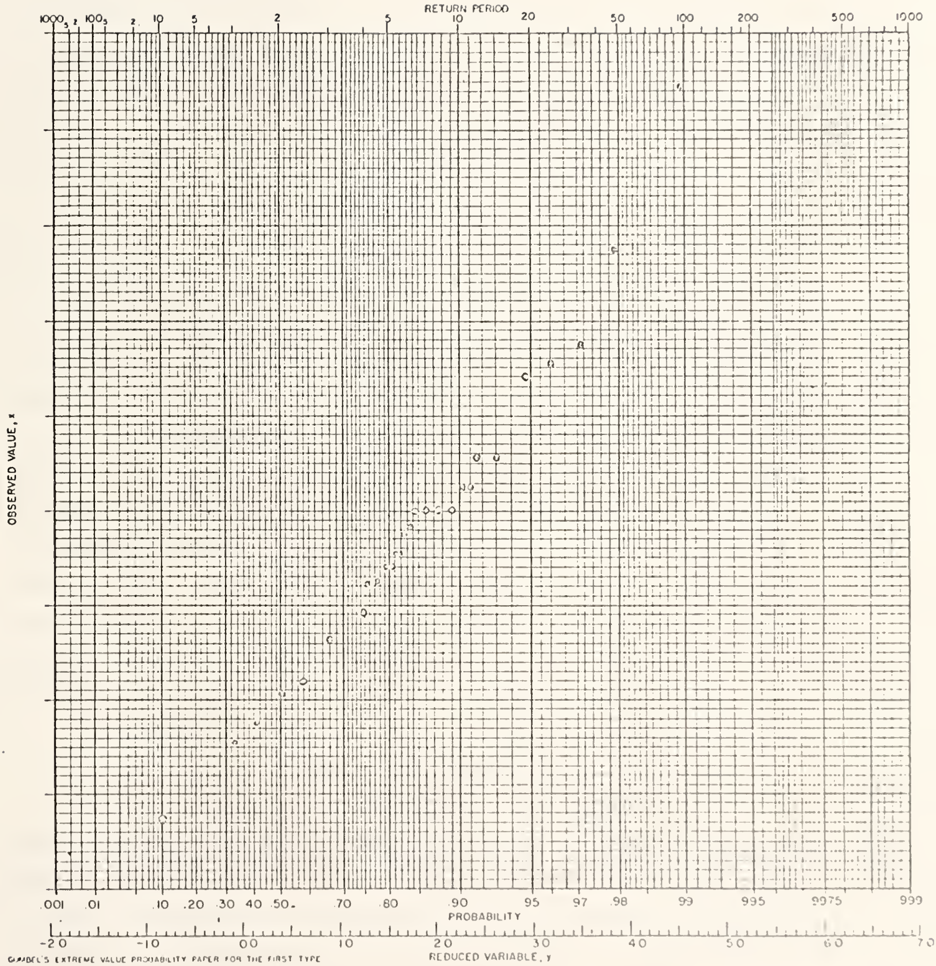

Fig. I5.2. Annual peak daily discharges for the Indus at Attock over the period I868-I963 plotted on "Gumbel" extreme value probability paper. Some of the lower values are not entered to avoid excessive congestion of the graph.

small fraction of the total sediment yield. The 100 year flood would only account for 7.7% of the average annual yield.

However, it is not very realistic to look at single days. Examining the Indus records it is found that there are, in fact, very many short flood peaks lasting a few days and involving increases in flow exceeding 100,000cfs in 24 hours. In view of the sediment/discharge relation these flood events are likely to achieve a significant proportion of transport of solids. To examine this, the conventional base flow defined for the Partial Duration Series was used - namely the annual maximum flow with an average recurrence of 1.15 years (Dalrymple op. cit. p.12). This was found to be 439,000 cfs. All daily readings of flow at and above this value were tabulated from the Attock record, and converted to equivalent day's sediment yield (Table 15.3). For the 96 years involved there were 1094 days with readings equal to or above the base, with 191 individual flood peaks. Thus we are concerned with an average flood wave of 5.74 days duration, adding up in total to about 3% of the complete time series. However, the total sediment yield of the high flow days was very nearly 11,120,000,000 tons. This is equivalent to a little over 25% of the total sediment yield which averages about 501 million short tons per year (Appendix 10). Hence, we can say that 25% of the net erosional yield is achieved in 3% of the available time. These results tie in with the statements of Leopold et.al. (1964 p. 73).

> "(That) the more variable the flow of the streams the larger the percentage of load... carried by a relatively few isolated events or in a relatively few days."

Again, however, the size of the Upper Indus drainage basin is much greater than those where these characteristics have been found in the past. In general the greater the size of drainage area the more conservative the flow tends to be; a reflection of the usual tendency for the effects of extremes of relief and climate to be evened out over large areas. The relative homogeneity of the extreme orographic effect over the whole Upper Indus restricts this tendency, although, when small constituent basin of the region are considered a greater role of more extreme events seems to occur as will be discussed in the next chapter.

TABLE 15.3. Table showing sediment yield of flows above the Partial Duration Series Base (439 thou. cfs.) with days of flow and number of individual flood peaks. Indus at Attock 1868-1963.

YEAR	No. days Flow ≥ 439 cfs.	No. Flood Peaks	Sediment Yield (Millions Short Tons)	YEAR	No. days Flow ≥ 439 cfs.	No. Flood Peaks	Sediment Yield (Millions Short Tons)	YEAR	No. days Flow ≥ 439 cfs.	No. Flood Peaks	Sediment Yield (Millions Short Tons)
1868	11	2	98	1911	10	3	94	1954	-	-	-
1869	2	1	16	1912	14	2	135	1955	6	1	49
1870	5	2	44	1913	8	2	72	1956	16	2	151
1871	7	2	67	1914	29	3	313	1957	4	2	35
1872	25	3	268	1915	-	-	-	1958	21	2	274
1873	9	2	87	1916	10	2	100	1959	20	5	181
1874	33	5	376	1917	8	1	80	1960	18	2	200
1875	10	3	88	1918	-	-	-	1961	1	1	7
1876	29	4	303	1919	19	4	165	1962	-	-	-
1877	1	1	8	1920	24	2	224	1963	1	1	8
1878	44	3	520	1921	18	2	186				
1879	4	1	33	1922	15	3	143	SUM	1094	191	11,117
1880	4	1	33	1923	9	3	77				
1881	2	1	15	1924	43	3	522				
1882	16	4	180	1925	8	2	69				
1883	14	1	124	1926	3	2	24				
1884	6	2	56	1927	7	3	58				
1885	9	2	83	1928	4	1	43				
1886	13	1	125	1929	13	3	192				
1887	10	3	88	1930	23	3	266				
1888	-	-	-	1931	1	1	14				
1889	20	1	250	1932	24	2	267				
1890	10	1	93	1933	13	6	124				
1891	6	2	46	1934	19	2	195				
1892	9	2	101	1935	28	3	240				
1893	11	3	110	1936	-	-	-				
1894	29	3	330	1937	2	1	17				
1895	1	1	8	1938	6	2	51				
1896	18	3	185	1939	12	2	112				
1897	30	4	321	1940	2	1	16				
1898	3	2	25	1941	2	1	16				
1899	4	1	32	1942	23	5	254				
1900	7	2	65	1943	22	2	191				
1901	11	2	124	1944	5	1	43				
1902	-	-	-	1945	22	3	237				
1903	-	-	-	1946	1	1	7				
1904	4	1	34	1947	-	-	-				
1905	5	1	45	1948	11	2	110				
1906	27	3	297	1949	12	2	100				
1907	2	1	16	1950	20	3	179				
1908	28	2	310	1951	-	-	-				
1909	3	2	25	1952	7	2	62				
1910	19	7	160	1953	9	1	107				

CHAPTER 16

THE INCIDENCE AND SIGNIFICANCE OF GLACIER SURGES AND NATURAL DAM-BURSTS IN THE REGIONAL GEOMORPHOLOGY

16.1. Introduction.

The Upper Indus region is notorious for its history of catastrophic natural events, of which exceptional glacier advances, and the natural damming of rivers with resulting dam-burst floods, are most often referred to. A cursory review of the literature indicated that these events were relatively numerous and widespread within the region. A careful compilation of the available information showed that they are not simply important for being spectacular and peculiar to the regional environment; they also are large enough and frequent enough to have significant erosional effects. On all of these counts, however, it seemed necessary that any examination of the regional geomorphology should review the importance of these events, the nature of the evidence on them, and their place in the hierarchy of geomorphic processes.

16.2. Surging Glaciers in the Karakoram.

A number of the Karakoram glaciers have suddenly advanced distances up to several miles in the space of a few weeks or months. This area and the Alaska-Yukon region probably account for 85 per cent of the known instances of surging glaciers. Exceptional glacier advances have marked geomorphic effects in the valleys where they occur and can be the origin of glacial damming of rivers. Equally important is the additional light they throw on the special geomorphological environment of the region.

Before turning to the phenomena two points of interpretation need discussion. Mason treated surging glaciers and glacial damming - "threatening glaciers" - as essentially one topic. He believed damming would not occur without exceptional "accidental" forward surges (Mason 1935). A re-reading of Mason's sources shows that, while some dams resulted from surging glaciers, many did not. This is certainly true for a number of the dams formed by his classic cases,

the Khumdan Glaciers (Note 16.1). There is no reason to believe a glacier cannot form a dam without exceptional advance (see 16.3. and Hewitt 1964). It cannot therefore be assumed that some fifty cases of glacial damming of main rivers (see 16.3), record the same number of surging glacier events.

A thornier problem is to decide when an advance comes into the special category of a "surge". In the steeply falling, medium sized glaciers of the Karakoram, rates of movement in the ablation zone can be large under normal conditions, available measurements indicating between 800 and 1400 ft. per year (Pillewizer 1957; Marussi 1964). While snout movement is much smaller than this there is a potential for rapid response to climatic fluctuations. Four main features are usually stressed as occurring with surging glaciers: sudden advance little related to activity of adjacent glaciers; rates of advance greatly in excess of normal ones for an area; sudden creation of new surface and terminal features; and virtual stagnation of the lower glacier after the surge. Normally we only have information on the first item for Karakoram examples. However, there are several cases in which apparently exceptional rates of advance were not followed by stagnation. Several of the Khumdan and Karambar glaciers advanced suddenly but then remained active at the terminus for ten years or more. Further, at least two of the Khumdan Glaciers which have experienced sudden, large advance, are also reported at other times as moving forward relatively slowly (e.g. Hedin 1902 quoting Ryall; Longstaff 1910 p. 650). In these terms we have to bear the following possibilities in mind:-

a) The classic surging glaciers described in Alaska (e.g. Post, 1960), may not represent the only or principal conditions under which surges occur.

b) Some of the advances in the Karakoram may be rapid compared to normal rates elsewhere but not for these very high relief regions, and therefore may not be special cases of glacier movement.

c) That, alternatively, there may be a hierarchy of surges

or surge types varying with the combination and intensity of controlling conditions.

16.2.i. The Record of Surging Glaciers in the Region.

The actual number of individual surges that are clearly identified is eleven according to an intensive search of the literature (Table 16.1). Yet, with all the problems of observation, the short period of time involved, and few observers, it seems clear that surging glaciers are an important component of glacial activity in the region. In addition to the record of particular events there is other evidence. The exceptional advances of the Minapin, Hassanabad and Yengutz Har Glaciers fitted in with a tradition of such activity in the Hunza Valley (Neve 1907). For the Sultan Chhussku to dam the Upper Shyok in 1935 and the Aktash in 1850 they must have advanced several miles very suddenly. There are other examples of glaciers changing their frontal position by one or two miles over a few years (e.g. the Khiang, tributary of the Hispar advanced 1½ miles some time between visits in 1925 and 1930).

In addition to the relative frequency of the phenomenon, its occurrence is widespread, examples occurring along all the major Karakoram tributaries of the Upper Indus. Significantly they are almost all in the heavily glaciated, deeply dissected parts of the region (Plate 16.1). Hence, while the individual instance appears as a "rare" event, overall these surges seem a fairly typical outcome of the Karakoram geomorphological environment.

16.2.ii. Controlling Factors in Glacier Surges.

A glacier surge requires the sudden large-scale displacement of ice. The mode of transfer seems to approximate fairly well to the kinematic wave model (see Nye 1960; Weertmann 1962). A more difficult and largely unsolved issue is what initial conditions and trigger mechanism will produce the intense, brief surge. It must require a sudden, large accumulation on the glacier, and/or triggering of a discharge of ice already in the glacier. Suggested origins of surges are:-

a) Exceptional snowfall of short duration.

TABLE 6.1. Exceptional Glacier Advances Recorded in the Karakoram.

Date	Glacier	Advance	Sources
?	Garumbar (Hispar)	sudden, very rapid, (1½ miles sometime between 1892 and 1925)	(ed. Mason, 1931)
1892-93	Minapin (Hunza)	1200 yards rapid advance	(Mason, 1935)
1892-93	Hassanabad (Hunza)	6 miles very suddenly	(Mason, 1935)
1901 or 1903	Yengutz Har (Hispar)	sudden and very rapid, "...26oo metres in spring..." "...2 miles...in 8 days..."	(ed. Mason, 1931) (Hayden, 1907)
1903	Hassanabad (Hunza)	6 miles in 2½ months (i.e. at least 13om/day)	(Neve, 1907 Hayden, 1907 Workman, 1914 Kick, 1958)
1906	Hassanabad	"...2 miles in present summer (to) end of July..."	(Neve, 1907)*
1929-30 (Winter)	Hopar (Hispar)	600 yards and further 150 yards during summer.	(ed. Mason, 1931)
1930 (March)	Karambar	"...100 paces (in) three weeks..."	(ed. Mason, 1931)
1930	Sultan Chhussku (Khumdan)	"...enormous push forward...200-300 million cu. metres of ice..."	(Visser, 1938)
1935-36 (Winter)	Aktash (Khumdan)	1½ miles in 7 months.	(Lyall Grant et..al. 1940)
1953	Kutiah (Haramosh)	12km(?) in two months (March to early May)	(Desio, 1954. Desio. et. al. 1961)

*There has been confusion about the Hassanabad advances. Mason thought Neve reported the 1893-93 advance but Neve speaks of a trip "..this year.." in an article of February 1907 and must refer to 1906. (Mason, 1935 p.31. Neve.1907). The only evidence of the 1892-93 Hassanabad advance is therefore the survey map (Mason op.cit. p. 29).

b) Sudden accumulation on (part of) the glacier through heavy avalanching of snow and ice from mountain walls or tributary ice-falls. In this case topographic conditions and climate must produce large accumulations of snow and ice on valley walls and crest-lines. Seismic tremors or severe weather are sometimes invoked as trigger mechanisms for the avalanching.

c) Forward movement stimulated directly by earthquake tremors.

d) Sudden surge relieving a cumulative imbalance between accumulation, movement and ablation. Basin form may be a major factor in retarding evacuation of ice from the accumulation area or sensitivity to wastage in the ablation zone. Also, the actual occurrence of a surge may produce the kind of mass-balance situation which can lead to another surge at a later stage since the depleted upper glacier and swollen lower glacier become out of phase. Evidently, this type of mechanism involves some critical threshold to which accumulation may proceed before an equilibrium is restored by the sudden downstream transfer (see Russell 1899; Hebling 1935; Streiff-Becker 1957; Post 1960). There are several instances where thickening of the upper glacier is recorded while the snout is retreating (e.g. Reed 1964).

At the time of writing none of these explanations is wholly satisfactory and new theoretical developments in glacier physics seem likely to change the picture radically as more information is obtained. However, for Alaskan examples which have received most attention, the fourth explanation seems the least objectionable. The volume of ice displaced in the surges is too great to be explained by short-term precipitation, or, in most cases, avalanching. Direct seismic triggering is difficult to demonstrate, and no one has clearly established a causal relation between an earth tremor and a surge, while surges in periods without local earthquake activity are known (Post 1966). Meanwhile, superficially unusual relations between upper and lower glacier are observed in the surging glaciers of Alaska (Post 1960), which would

equate with the "mass imbalance" thesis.

In only one case of a Karakoram surging glacier is there observation from the upper as well as lower glacier; the Sultan Chhussku surge in 1930. Photographs shortly after the surge show the main firn surface to have dropped as much as 300 ft., leaving a rim of sheared-off tributaries, old avalanche cones and firn. The lower glacier had suddenly advanced rising high above lateral moraines and translating some "...200-300 million metres^3 of ice..." into the Upper Shyok Valley (Visser 1938 v.2, Figs. 17,18,21 and 86 and pp.176-178). The descriptions seem very similar to those of conditions following Alaskan surges (Post 1960), or the disastrous Nevado Plomo surge in the Andes (Hebling 1935). Both Post on the Alaskan ones, and Hebling on the Andean, decided the only satisfactory explanation was budgetary imbalance. This may also be true for the Sultan Chhussku. However, there are features of other Karakoram surges which create difficulties for this as a general explanation.

The Kutiah surge of 1953 was typical in advancing the snout "...12km..." at an average speed of "...113m a day...", after which the front began to retreat slightly (Desio 1954c; Desio et.al. 1961). However, it seems to have begun as three separate surges of the tributary glaciers Kurankar, Nan and Kutsambar. If this is so the budgetary imbalance theory seems an unlikely explanation unless some over-riding trigger mechanism were present. Desio suggested massive avalanching from the walls of Haramosh (24.27oft) possibly started by an earthquake (op.cit.). The same problem of how possible synchrony of surges on different glaciers can be explained by budgetary imbalance alone applies to the Hassanabad and Minapin surges of 1892-93 and the Hassanabad and Yengutz Har of 1903. Of course, the budgetary imbalance "threshold" may be approached gradually allowing different glaciers to reflect their own idiosyncracies, or an over-riding factor might carry two or more glaciers up to or above their respective thresholds. In the Karakoram the vigor and large fluctuations in the geomorphological environment provide a variety of ways in which the latter could be achieved. Seismic activity is an obvious possibility, its effects

being exaggerated by the enormous relief and concentration of precipitation at high altitudes. The rare influx of the monsoon is another possibility. In fact, it is extremely difficult to make any crucial observation concerning the various mechanisms for glacier surges, since the Karakoram environment provides abundantly for all of them! In general terms they simply reflect and contribute to the vigorousness of the environment.

16.2.iii. Geomorphic Effects.

A description of the conditions during Yengutz Har advance was given by a villager to Capt. Berkeley (see ed. Mason 1931 p. 114). It seems quite authentic and will be quoted here:-

"The glacier was above where the present snout is (nearly 2 miles and 2,000 ft. above the Hispar River). One day...we noticed that the water in the irrigation channels was very muddy and coming down in greater quantity than usual. We went up the nullah...and saw the glacier advancing. It came down like a snake, quite steadily; we could see it moving...At the same time water and mud gushed out from the ice while it was still advancing and flooded our polo ground and some fields. When an obstruction got in the way the ice went around it at first then overwhelmed it. The ice was not clear but contained earth and stones... The ice continued to move for eight days and eight nights and came to a stop about forty yards from the Hispar River. As soon as the ice stopped, the mud and water, which had been coming out higher up, stopped too. The ice remained down for fifteen years...Twelve years ago (1918) the ice began to go back. Each day, a length of about fifteen yards would break-off the main ice and was washed away by the water..."

The devastating erosional effects of these surges is apparent. The increased melt-water action is equally or more important than ice-movement since it attacks the normally thick clastic deposits of the arid pro-glacial valley. In the Hunza Valley examples, the glaciers descent as low as 7,000 ft. where conditions are thoroughly arid. These abnormally advanced tongues become smothered with moraine and produce devastating glacier mud-flows (see 12.7; Hayden 1907; Workman 1914; Gamble 1961). However, while locally important in flushing out lag deposits and extending glacial action, the large-scale geomorphic effects of these glacier surges are primarily indirect when they give rise to glacial dams and dam-bursts.

16.3. Natural Damming and Catastrophic Floods on the Upper Indus.

The Biafo Glacier dammed the Braldu in the past, and devastating floods occurred when the dam(s) failed. The discovery was not due simply to accident of choice. There are few Karakoram tributaries of the Upper Indus that lack a record of natural dam-bursts, including both glacial and landslide dams. So extensive is the record that the geomorphologist cannot ignore their role in regional erosion. In relation to other areas, it has been suggested that rare, devastating floods can exercise a dominant control over the form and development of mountain valleys; normal conditions tending rather to "repair" slopes and channel patterns (Hack and Goodlett 1960 p.42; Leopold et.al. 1964 p.83-85). Such ideas are obviously pertient to features in Braldu Valley and to the Upper Indus generally.

16.3.i. The Record of Natural Dams and Related Events.

Reports of these phenomena were compiled to try and establish their real significance (Tables 16.2; 16.3 and 16.4). At least 32 major dam-burst floods have occurred since 1826; and associated evidence reveals damming as a frequent and widespread feature. Despite the inaccessibility and observational difficulties of the region, there is little doubt that natural damming and dam-burst floods are a typical component of the geomorphic environment. The phenomenon is concentrated where the greatest relief combines with heaviest precipitation at high altitude,- the flanks of the Greater Karakoram, Haramosh and Nanga Parbat Ranges - or where the rivers have effected the greatest recent downcutting in the Indus and Hunza Gorges.

TABLE 16.2. Chronological List of Natural Dams and resulting floods recorded for the Upper Indus. (Coding: D for Dam, F for Flood, G for Glacial, L for Landslide.)

Date and Code	Events in the Mountains	Events in the Attock Area	Sources
1533 GD	An isolated record of damming of Upper Shyok by Khumdan Glaciers.		Hedin(1917)
1780(?)[x] GDF	Last pre-19th Cent. dam-burst flood from Khumdan Gls.		Strachey (1854)
1818-1840 GD	Advance of Khumdan Gls. damming the Upper Shyok. (1836-38, "nearly closed" - Hedin, but Mason shows Chong Khumdan dam).		Hedin(1917) Mason(1935) Mason(1929)
1826 GDF	Major flood-wave, possibly Khumdan dam-burst.	Serious flooding.	Cunningham (1854) Becher(1859) Mason (1929)
1833a GDF	Flood wave ascribed by some to Khumdan, but uncertain.	"Not even known in Plains country".	Mason(1935) Becher(1859)
1833b(?) GDF	Glacier dam-burst of Yashkuk Yaz Gl. on Chapursan Trib. of Hunza R. Devastating floods.	Rise of 30 ft. above normal at Attock.	Morris(1928)
1835 GDF	Khumdan Dam Burst ascribed by early authors to Sultan Chhussku Gl. (Mason's objection no longer acceptable or his wish to ascribe it to Chong Khumdan Gl. - see Visser 1938, v.II, p.177)	No noticeable rise.	Strachey (1854) Becher(1859)
1839 GDF	Further Khumdan dam-burst. Floods "...of much less extent" than 1835.		Strachey (1854)

[x] Note: (?) Refers to uncertainty of date not actual occurrence.

Date and Code	Events in the Mountains	Events in the Attock Area	Sources
1841 ADF	Massive landslide dam on main Indus. Slide from Lechar Spur of Nanga Parbat. Lasted approx. 7 months and drained in 24 hours in June.	Major catastrophe. Greatest known flood at Attock. Rise of over 80 ft. 2 million cfs conservative estimate of peak discharge.	Henderson (1859) Becher (1859) Drew(1875) Hewitt (1964)
1842 GDF	Khumdan dam-burst. (Ascribed by Mason to Chong Khumdan) Small flood.		Longstaff (1910) Mason(1935)
1844 GDF	Glacier dam-burst from Ishkoman Valley. Serious floods in Gilgit area.	Minor flood wave.	Drew(1875) Mason(1929)
1848 GDF	Khumdan block by both Aktash and Kichik. (In 1935 publ. Mason no longer shows block by Kichik)		Hedin(1917) Mason(1929)
1850a GD	Aktash Gl. blocking Upper Shyok.		Thompson (1852)
1850b(?) GF	Glacial dam-burst from Tarshing Gl. Astor Valley, S.E. flank Nanga Parbat. Local devastation.		Drew(1875) Collie (1902)
1851(?) GD	Dam formed by Niaro Gl. Kero Lungma Valley, N. of Shigar. Drained gradually.		Godwin Austen (1864)
1852-58 GD	Khumdan Gls. blocked Upper Shyok. Probably Kichik Gl.		Hedin (1917) Mason (1935)
1855a F	Inundation of Gol village 4 mi. below Shyok-Indus Junct. Altered local course of river. Source not known.		Godwin Austen (1860) Mason (1929)
1855b F	Major flood wave, originally attrib. Khumdan but this doubted by Mason.	Large rise at Attock.	Mason (1935)

Date and Code	Events in the Mountains	Events in the Attock Area	Sources
1858 LDF	Massive landslide dam above Baltit on Hunza R. Lasted 7 months then burst in August. Devastating erosional and economic effects described.	Major catastrophe. 2nd largest Flood known at Attock. Rise about 55 ft. in 7½ hours.	Becher(1859) Henderson (1859) Montgomerie (1860) Todd(1930) Cockerill (1922)
1862-64 GD	Khumdan dam, ascribed to Kichik Gl. by Mason.		Johnson (q. in Mason 1929) Hedin(1917)
1865 GDF	Ice-dam burst in Ishkoman Valley, bringing serious flooding in Gilgit Agency.	Negligible flood.	Drew(1875) Todd(1930)
1869-72 GD	Khumdan blockage of Upper Shyok Valley by Kichik Gl.		Hedin(1917) Shaw(18)
1873 GD	Possibly damming of Hunza R. by Batura Gl. (verbal report to Mason but he and Todd doubt it.)		Mason(1929) Todd(1930)
1879(?) F	Major flood wave but source not known. Mason suggests Khumdan dam burst.	Mason says rise of 28.7 ft. at Attock, Aug. 11-20. Not on Official Stage Record. (O.S.R.) for Attock.	Mason(1935)
1882 F	Major flood wave. Origin not known but Mason suggests Khumdan burst.	Mason says rise 33.8 ft. on 29th July, "higher than 1929 flood by 5 ft." (This gives 752.000 cfs on modern rating curve.) Rise of 27.5 ft. appears on O.S.R. to 739,000 cfs.	Mason(1935)
1884 GDF	Ice-dam burst in Shimshall Valley. Considerable devastation at Ganesh and Altit in Hunza Val.	(Rise of 10 ft. 9-10th Aug. on O.S.R.)	Todd(1930)
1889 GD	Block of Upper Shyok by Khumdan Gls.		Younghusband (1896) Mason(1929)

Date and Code	Events in the Mountains	Events in the Attock Area	Source
1891-92 GD	Damming of Ishkoman R. by Karambar Gl.		ed.Mason (1931)
1893a F	Dam-burst flood from Shimshall Valley. Probably from glacial dam.		Godwin Austen in Visser (1926)
1893b GDF	Dam burst from Ishkoman Valley. Flood reached Gilgit on 6th July. 23 ft. above summer flood level.	Small rise appears on O.S.R. (5 ft.)	Todd(1930)
1899 GD	Khumdan block (doubted by Hedin)		Longstaff (1910)
1901 F	? Khumdan dam burst	Rise of 20 ft. May 6th on O.S.R.	
1902-11 GD	Block by Kichik Khumdan Gl.		Hedin(1917)
1903 GDF	Dam burst from Kichik Khumdan. Serious damage.	No marked flood waves this year on O.S.R.	Oliver (1903) Longstaff (1910)
1904-5 GD	Karambar Gl. dammed Ishkoman R.		Longstaff (1920)
1905a GDF	Dam-burst from Kichik Khumdan. Small flood.		Huntingdon (1907) Longstaff (1910)
1905b GDF	Dam-burst from Karambar Gl., 17-18th June. 20 ft. above summer flood level at Gilgit. Considerable damage.	Minor flood wave.	Todd(1930)
1905c GDF	Glacial dam-burst from Shimshall Valley. Khurdopin-Virjerab dam (?). Occurred Aug. 2. Flood wave 30 ft. above summer flood in Hunza valley (Tushot and Bunji). Many landslips caused. High level lasted 8-10 hrs. at Tushot.	Not apparent on O.S.R.	Neve(1907) Todd(1930)

Date and Code	Events in the Mountains	Events in the Attock Area	Sources
1906 GDF	Glacial dam-burst in Shimshall Valley from Khurdopin-Virjerab. Aug. 11-12th. Much larger than 1905. Askurdas, Tushot & Chamogah bridges washed away. Rise 36 ft. at Chilas on Indus. 50 ft. above high summer flood in Hunza Gorge (Chalt).	Rise of 10 ft. on O.S.R. 12-13th Aug.	Todd(1930)
1907 GDF	Khurdopin-Virjerab dam-burst. Overtopped barrier, slower rate of release. Took 11 days to empty lake. Maximum rise at Bunji only 7 ft. September.	Not apparent on O.S.R.	Bridges " (1930) Todd(1930)
1908 GD	Khurdopin-Virjerab dam reformed.		Bridges (1930)
1916 GD	Karambar Gl. dammed Ishkoman R.		Longstaff (1920)
1924-33 GD	Chong Khumdan barrier on Upper Shyok		Mason (1935)
1925 GD	Large lake behind Khurdopin-Virjerab barrier.		
1926a GD	Reduced lake behind Khurdopin-Virjerab barrier		Visser (1926)
1926b GDF	Chong Khumdan dam burst. October. Devastating floods.	Minor flood damage at Attock. 16 ft. rise on O.S.R.	Mason (1935)
1927a GDF	Glacial dam-burst from Besk-i-Yeng Gl. Upper Hunza Valley. Serious floods of local extent. Massive sediment movement.		Morris (1928)
1927b GDF	Khurdopin dam-burst of minor proportions.(?)		Todd (1930)
1928 GDF	Glacial dam-burst in Kilik Valley, Upper Hunza. Local damage only.		Morris (1928)

Date and Code	Events in the Mountains	Events in the Attock Area	Source
1929 GDF	Chong Khumdan dam burst. Aug. 15. Large flood performed massive erosion.	Largest discharge definitely identified with ice-dam flood. 689.000 cfs on O.S.R.	Mason (1930) Todd(1930) Gunn(1930)
1929-30 GD	Karambar Gls. formed ice-dam.		ed. Mason (1930)
1931 LD	Landslide dam near Chilas, on main Indus. Drained slowly from Apr. 9th	Not apparent on O.S.R.	Mason (1931)
1932 GDF	Chong Khumdan dam-burst somewhat smaller than 1929. Considerable erosion	Rise of 17 ft., July 12-13 from 407.000 to 614.000 cfs (O.S.R.)	Mason (1933)
1933 GDF	Chong Khumdan dam burst of smaller proportions, Aug. 27th.	Rise of 12 ft. on O.S.R. Aug. 29-30.	Mason (1934)
1939 GD	Chong Khumdan across Upper Shyok; Kichik Khumdan advancing into the river		Lyall-Grant (1940)
1958(?) GDF	Glacial dam-burst flood on Upper Indus (?) (Mentioned by Meier but have found no other confirmation. May refer to 1858 flood?)		Meier (1965)

Note: The O.S.R. consists largely of once-daily stage reading and cannot be relied upon to give flood peaks.

TABLE 16.3. List of Natural Dams inferred from geological or other evidence.

Location	Comments	Sources
Upper Indus Basin. (pre-historic)	Suites of enormous ice-dammed lakes during the Third Glaciation. Indus Plains "erratics" may be related to dam-bursts floods from such lakes. (See. Sect. 2. 2.iv.)	Dainelli (1933) Theobold (1880) Lydekker (1883)
Upper Indus Basin. (early historic)	Early travellers including 5th Cent. Chinese record notorious inundations of "White Water". A 12 year recurrence is sometimes quoted.	Stein (1921) Hedin (1917)
Hunza, Ishkoman, Khumdan, Braldu, Basha, Shimshall Valleys	From each of these a tradition of glacier dams and dam-burst floods reported to earliest observers of known, modern floods.	Vigne (1842) Strachey (1854) Hedin (1917) Neve (1907) Godwin Austen (1864) Cockerill (1922)
Ladak	Dams and ancient lakes due to landslips (and protrusion of alluvial fans?)	Drew (1875)
Damsan near Junct. Saltoro and Kondus R.	Remains of ancient "earth" dam from landslip, breached by river.	Workman (1917)
Biafo Glacier	Dammed Braldu River with devastating floods as a result. (18th Cent.?)	Godwin Austen (1864) Hewitt (1964)
Malangutti Gl. Shimshall.	"years ago.." blocked Shimshall River. Now cuts through moraines and old lake bed above. (1892)	Cockerill (1922)
Bawoni Gl. Goma Valley (Saltoro)	Dry lake bed above where glacier lay across river in 1909	Longstaff (1910)
Batura Gl. Hunza	Tradition that had dammed river though Mason questions possibility.	Mason (1929) Todd (1930)
Basha Valley	Village of Tisir devastated by glacial outbreak: Evidence in erosion and disposition.	Godwin Austen (1869)

x
Note:

Upper Shaksgam River	- On north side of Karakoram not Indus Drainage - several old and extant ice-dammed lakes reported	Duke of Spoleto (1930) Mason (1928)

TABLE 16.4. Record of Glaciers interfering with rivers and creating barriers without formation of lakes. (excluding Khumdan Record. q.v.)

Date	Location	Comments	Sources
1861	Biafo Gl. Braldu	Bridged river and leaned on cliffs of Bakhor Das along front of nearly 2 miles.	Godwin Austen (1864)
1873	Tarshing Gl. Astor. (Nanga Parbat)	Maintained much decayed barrier across valley since 1850 (?) dam-burst. River cut tunnel beneath snout.	Drew (1875)
1887	" "	Same situation but increased thickness of snout.	Neve (1907)
1892	Yazghil Gl. Shimshall	Nearly sealed valley (called Virjerab by mistake)	Cockerill (1922)
1895	Pasu Gl. Hunza.	Snout at river's edge	Curzon (1894)
1896	? Stak River.	Photo showing snout of glacier bridging river. (Author calls it "snow-bridge")	Deasy (1900)
1906	Tarshing Gl. Astor	Still formed barrier but thickened considerably and stood 300 ft. above river which cut a path underneath.	Neve (1907)
1908	Malangutti and Yazghil Gls. Shimshall	Both glaciers across the river which tunnelled underneath them.	Bridges in ed. Mason (1930)
1909	Bawoni Gl. Goma. (Saltoro Valley)	Barrier across valley beneath which river maintained channel.	Longstaff (1910)
1919	Chilling Gl. Upper Ishkoman.	"...river burrowing beneath its base..."	Longstaff (1920)
1925	Hopar Gl. Hispar.	Barrier across Hispar valley beneath which river cut channel. Danger of damming.	Visser (1926) Mason (1931)
1926	Yazghil Gl. Shimshall.	Shown on Visser map as blocking Khurdopin valley, but river passed underneath.	Visser (1926)
1930	Hopar Gl. Hispar	Following phase of retreat had again advanced across valley. River maintained channel beneath.	Mason (1931)

can create.

16.3.ii. Glacial Dams: Types and Upper Indus Examples.

Bodies of water ponded by ice range from small ice-contact pools to lakes over 100 miles long. The form and size of the glacial reservoirs depend particularly upon the topographic relations of glacier and lake area. For mountainous terrain with valley glaciers, it is possible to recognise several main types on the basis of the location of the lake itself.

a) Supra- and Englacial Lakes. These are water-filled holes walled in by ice on all sides. Normally they are small as on the Biafo at present (12.2). The Icelandic Grimstvötn Lake is a notable exception (see Thorarinsson, 1939 and 1953).

b) Lateral Embayment Lake. A lake between the valley wall and glacier, usually of moderate size. (e.g. Larsen 1959).

c) Kame Terrace Lake. Here the water lies between a lateral moraine and the valley wall. While the ice does not form the immediate barrier, changes of glacier level tend to create and drain such lakes.

d) Tributary Valley Lake. Here the lake forms at the mouth of a tributary valley of the glacier. The Märjelen See of the Aletsch Glacier is the classic case. While usually of moderate size, these lakes can be large if the tributary valley is itself large, and ice-free for some distance.

e) Main Valley Type I. The "glacier rémanié" type where a hanging glacier or ice carapace breaks away to form a barrier in the valley below. No examples are quoted from the Karakoram but several have been reported in the Alps (see Rabot 1905 p.534; Desio 1954c p.385).

f) Main Valley Type II. Here, a relatively narrow, steeply falling tributary glacier intrudes across a main fluvial valley. The glacier may form a more effective barrier size by spreading into a large 'bulb' or even turning down the main valley.

g) Main Valley Type III. Here, a large glacier descending with moderate gradient seals a major river valley to which it is tributary. The relations of size of ice-tongue and possible discharge in the main valley make this type potentially the largest which valley glaciers can create. (While it might seem difficult to distinguish between

Types II and III, all the examples looked at in the Karakoram fall clearly into one or the other).

The classification could be extended to include the enormous lakes dammed by encroaching ice-sheets of the Pleistocene (e.g. in North Shropshire and Yorkshire, or the Columbia Plateau and Great Lakes areas of North America).

Innumerable examples of types a), b) and c) occur in the region but only types d), f) and g) will be dealt with, these having more than local erosional effects. While, in aggregate, minor outbursts from small lakes may achieve equal erosion or more, it is unlikely they can have the unique and well-defined effects of the major outbursts in main valleys.

Large and dangerous <u>Tributary Valley Lakes</u> occur where the Khurdopin Glacier blocks the mouth of the Virjerab Valley, in Upper Shimshall. Before its outburst in 1907 the lake was 2¼ miles long, a mile wide, and varied in depth from 290 ft. at the dam to 165 ft. two miles above (see ed. Mason 1930 p. 136). The volume of water was over 0.3 million acre-feet (MAF).

Most of the recorded ice-dams of major proportions have been of <u>Main Valley Type II.</u> Glaciers forming such dams include:-

i) The Khumdan Glaciers, Upper Shyok River
  - Chong Khumdan
  - Kichik Khumdan
  - Aktash
  - Sultan Chhussku

ii) The Karambar Glaciers, Upper Ishkoman Valley
  - Karambar
  - Bukh
  - Wirgot
  - Chillinj

iii) The Shimshall Glaciers
  - Malangutti
  - Yazghil

iv) Tarshing Glacier, Astor Valley (Nanga Parbat)

v) Kutiah Glacier, Stak Valley (Haramosh Range)

vi) Bawoni Glacier, Goma Valley (Saltoro)

vii) Besk-i-Yeng Glacier, Upper Hunga Valley,

viii) Yashkuk Yaz Glacier, Upper Hunza Valley

We have relatively good information on the dimensions of the Chong Khumdan dam in 1929:-

The Barrier

Area of the ice in the valley bottom	2-2½ sq. mi.
Span of dam at the lake edge	4000 ft.
Maximum width of dam	1½ mi.
Height at lake edge	500 ft.
Maximum height	700 ft.

The Lake

Gradient of bed	30 ft./mi.
Depth of water at barrier	400 ft.
Average depth	170 ft.
Length of lake	10 mi.
Greatest width	2 mi.
Mean width	1 mi.
Volume	1.1 MAF

(Values in or calculated from: Ludlow 1929; Gunn 1930; Visser 1935-1938 v.2)

Examples of the Main Valley Type III have certainly occurred at the Biafo-Braldu Junction and probably the Batura-Hunza Junction. The enormous lakes of the Third Pleistocene glacier advance were of this type (3.4). From the known height of the Biafo Barrier in the mid-19th Century, and field evidence the probable dimensions of the Biafo lake would be:-

Effective height of barrier	500-600 ft.
General height of barrier	750 ft.
Area of barrier in Braldu Valley	3 sq. mi.
Gradient of valley upstream of dam	25-30 ft./mi.
Average width of lake	1½-2 mi.
Capacity of lake	4 MAF

(Deduced from field data and: Schlagintweit, 1861-66; Godwin Austen 1864; de Filippi, 1912)

16.3.iii. Glacial Dams: Principal Controlling Factors.

The occurrence of large ice-dams depends upon quite specific interactions of topography, climate and hydrology. Thick tongues of ice must descend well into fluvial zone, where canyon-like valleys can

be effectively dammed. Devastating dam-bursts occur where a large dam forms quickly, is very effective during period of high river discharge, than deteriorates rapidly.

Given a generally suitable regional environment a large number of factors govern the precise form, size and development of individual dams. A formal statement of these may be given before elaborating upon the Upper Indus examples.

A. Form and Scale Aspects.

The type and the Size of Dam are governed mainly by:

i) Geometry of the valley junction.

ii) Width of the dammed valley.

iii) Thickness of the effective ice-barrier.

The dimensions of the lake will depend upon the above and:

iv) The gradient of the main valley.

v) Discharge of the dammed stream.

vi) Timing of the dam, especially relative to local temperature and stream discharge curves.

vii) Duration of the dam.

viii) Efficiency of the barrier. i.e. state of the ice and sub-glacial materials in terms of strength, percolation, 'piping' etc.,

ix) Losses to evaporation and groundwater.

B. Genetic and Process Aspects.

Ice advances resulting in damming may be due to:

i) Climatic variables:-

a) General secular decrease in temperature and/or increase in precipitation. There may be cyclicity here. (c.f. Mason 1935, who believed that only 'accidental' advance would cause damming).

b) Isolated, aperiodic change in the same factors.

ii) Seismic Activity.

iii) Some 'harmonic' relation of basin form to the build-up and wastage of ice (see 16.2).

The response of the glacier may lag behind the variation

in environment in accordance with the magnitude of the change, and the size, shape and previous state of the ice mass.

The sealing of the stream valley depends upon:

iv) Negatively, the failure of the river to maintain a channel.

v) Seasonality of processes involved, a critical factor being terminal advance during the cold season when river flow is small or nil (c.f. Appendix 8).

vi) Structure and rate of movement of the glacier in the dam area.

viii) A general relation of altitude a.s.l. may exist as this controls the severity and length of the cold season.

The maintenance of the dam and growth of the lake depend upon the continued effectiveness of the processes and formal relationships outlined above.

The failure of the dam is related to the above factors and:-

ix) Generally, some yield value dependent upon the composition, geometry and perimeter conditions of the barrier.

x) Depth and level of water adjacent to the barrier controlling:-

a) Possibility of overtopping.

b) Possibility of floating ice off valley floor.

c) Creation of sub-glacial cavity through horizontal compression and flow response of the ice. Theoretically this must occur with 650 ft. of water, and in practice may commence when depth exceeds 300 ft. (Glen 1953; also Sieger 1895).

xi) A siphon effect, mentioned as occurring in Greenland but no details given (Larsen 1959).

The factors outlined above constitute a provisional system for the survey of dams and damming processes. Most of the factors have relevance to some, or all of the ice-dams on the Upper Indus though we rarely have

enough information to assess their role adequately.

Topography, drainage organisation and the size and distribution of glaciers in the region create a large number of potentially favourable dam-sites. Many large tributary glaciers descend to within a mile or less of rivers of high order and comparably high discharge. At least fifty glaciers have topographic relations such that moderate advances would throw them across stream valleys draining many hundreds, or thousands of square miles.

As well as favourable topographic relations, glacier behaviour is favourable to the intiation of a dam. Glaciers with large, high-altitude accumulation areas, and narrow, steeply-falling outlet tongues are common. Such an arrangement favours the vigorous response of the tongue to changes in mass-balance, typical of glaciers forming Main Valley Type II dams. The Khumdan dams of the Upper Shyok are created by glaciers with an average fall per mile of, 330 ft. for the Chong Khumdan, 400 ft. for the Aktash, and 500 ft. for the Kichik Khumdan (Mason 1929 p.23). The availability of mechanisms thought likely to cause rapid glacier advances has been demonstrated elsewhere (16.2).

The strong vertical variation in precipitation and temperature along with high local relief allows large glaciers to develop immediately above fluvial valleys. Large seasonal variation in climate means the snouts of Karakoram glaciers recede rapidly with intense summer ablation and advance a proportionate distance in winter (Appendix 8). The advancing winter terminus is also repaired and heightened, and at a time when river discharge is negligible. The winter advance of a glacier on the banks of a river may equal the width of the channel.

The precise development and sealing of a dam is complicated. Certainly, the number of ineffective barriers exceeds the successful ones. Glaciers have been found undercut by the river when themselves larger and the discharge smaller than cases where dams have formed. The explanation may be quite simple. Glaciers often cannot move even small boulders before the ice-front (Spencer 1887). In the

case of the Braldu, boulders in the river bed stand several feet above the stream surface in winter (see Plate 14.3). The advancing Biafo would probably over-arch these initially while the river maintained its channel in between. Slight differences in the typically heavy englacial and ablation moraine of the glacier termini could be crucial in whether a sealed, or porous barrier formed.

The outstanding number of successful Khumdan dams relates to location. Here, on the edge of the Tibetan Plateau, the major fluvial tributaries of the Indus flow at altitudes higher than the firn-line of the Biafo. The Khumdan glaciers terminate at 15,ooo ft. and winter is correspondingly longer and more severe than in most other potential ice-dam areas. Of course, the inflow to these dams comes from the enormous Rimo Glacier and nearly 1,000 sq. miles in the Chip-Chap Basin. Inflow estimates for the 1928-29 dam were between 2100 and 4800 c.f.s. in August - 4000-9500 acre-feet per day (Ludlow, 1929; Visser, 1935-1939, v.2. p.31).

Few ice-dams on the Upper Indus have lasted more than two summers, most of them for only part of one summer. Information on precisely how and why the dams fail is poor, but it seems that the two limiting conditions of overtopping and hydrostatic tunnelling are important. Whereas the cases of overtopping for the Tarshing (circa 1850) and Khurdopin (e.g. 1907) were for ice barriers about 300 ft. high; the much thicker Khumdan barriers of 1929 and 1931 failed through tunnelling (Gunn 1930; Gregory 1931; Mason 1933), with the water more than 400 ft. deep. This would fit Glen's hypothesis (Glen 1953).

Where overtopping occurs, the outbursts are apparently less devastating than with tunnelling. Although causing much damage locally the Tarshing and Khurdopin outbursts were moderated by the weir-effect of the barrier. The former took three days and the latter eleven days to empty. The 1926, 1929 and (probably) the 1931 Khumdan outbursts evacuated a million acre-feet of water within two days, the main part in the space of a few hours (Gunn 1929; Mason 1929). Along with size and location of the ice-dammed lake,

the rate of release of flood is of major importance in its erosional activity downstream.

16.3.iv. Landslide Dams.

Many of the major features that assist ice-dam development also favour landslide damming: river valleys flanked by steep mountain walls, seasonal variation in river discharge, and the general variability and intensity of the geomorphic and climatic environment. Certain processes and the constitution of the barrier differentiate the two types of dam. Since mass-movement conditions and processes have been discussed in detail (Chapter 10), only factors directly affecting damming are considered here: namely, the size of necessary landslide, the composition of the material, and conditions under which the dam may fail.

Available relief, and a variety of vigorous trigger mechanisms produce frequent and often large landslides in the region. Nevertheless, it requires a massive landslide to be equivalent in volume to the glacier dams; one which travels a mile across the valley and fills it to a depth of many hundreds of feet. These are rare in any area. The landslide is also a once-for-all occurrence compared to the glaciers which may continue to interfere with the river for many years. Hence, while minor blockages of small gullies are common enough, major landslide dams seems much rarer than glacial ones. Nevertheless, of the three recorded landslide dams in the past 130 years, two gave rise to the largest known floods on the Indus. All three dams were in the most deeply incised part of the Indus drainage; incision of recent origin giving the maximum local relief beside the rivers.

Composition is important in the success and behaviour of a landslide dam. The barrier may be formed of soil and superficial deposits creating a natural 'earth dam', or of large fragments of solid rock, or a combination of the two. A fairly high content of fines is essential for an effective barrier. In this respect, the stream terrace material, glacial till and slope deposits common to most of the Upper Indus Basin, will assist the damming process. The

three known dams are usually described as consisting of 'earth' and boulders.

The two Indus Gorge landslide dams failed after overtopping and rapid erosion by the outflow (Becher 1859; Drew 1875; Mason 1929 & 1931). There is no description of how the Hunza Gorge dam of 1858 failed. As with artificial earth dams, the likelihood of seepage and 'piping' causing failure seem to be greater with landslide dams than glacier ones (see Sherard et.al. 1962). Whatever the cause, once a breach is created, the incohesive dam material is quickly eroded, and the resultant flood release rapid. Given a high and impermeable barrier, other than overtopping there is no inevitable limiting condition which must destroy the dam. (c.f. Ice-dams where Glen's limiting condition would not allow survival until the water achieved 1,000 ft. depth).

The 1841 dam began with an earthquake-triggered landslide in the previous December, creating a barrier 1,000 ft. high which survived until overtopped (Becher 1859; Drew 1875 p.417). The lake was between 27 and 45 miles long ("18 coss", a coss varying from 1½ to 2½ miles!). A long broad trough above allowed the lake to grow without deepening rapidly. A conservative estimate of the capacity of the lake at the time the dam failed would be 20MAF (Note 16.2). The lake drained in 24 hours.

The 1858 landslide barrier dammed the Hunza 9 miles above Baltit and Imile below Atabad. The immediate cause of the Ghammessar landslide was the bursting of a small lake high on the mountain side. his "...completely blocking the river to a height of many hundreds of feet...(and lasting)...nine months..." (Todd 1930 p. 39). The lake stretched 25 miles to the Batura Glacier and into Shimshall Valley, with an inflow from about 1,750 mile^2.

A recent parallel of the large Indus landslide dams was that in Zerafshan Valley in the Pamirs (Popov and Chebotarev 1964).

16.3.v. Dam-Burst Flood Action.

Along the river system, failure of a natural dam expresses itself in an increased discharge of short duration. Whether it has

marked geomorphic effects depends mainly on the rate of release of water from the dam. If failure is catastrophic, flood-wave damage may outweigh the effects of normal discharges over many years, and act in ways outside the scope of ordinary floods. Catastrophic failure is relatively common on the Upper Indus, and its special geomorphic effects of more than incidental significance.

A natural dam may create a concentration of water in the river far in excess of normal weather-controlled run-off. The larger dams may have released between one and three years' run-off for the particular tributary in the space of a few hours or days. At Attock, these floods do not appear as a separate series (see 15.6). But here they are generally modified by hundreds of miles of travel and have become part of an enormous river system's run-off. In individual high valleys the dam-burst flood discharges may exceed average annual maxima at Attock, however, though stemming from 2% or so of the latter's drainage area. Thus the 1929 Khumdan outburst passed Sasir Brangsa in under two days. Allowing for 0.1MAF losses this represents an average flow of 250,000cfs (1 MAF in 2 days). The peak discharge must have been not less than 75o,ooocfs. from a drainage area of 1,500 mi^2..

For Attock we have a stage-discharge curve, on which the 1841 flood peak would stand at +92 ft. at least. Extrapolating the curve for an increase of 1,250cfs per 0.1 ft. the equivalent maximum discharge would be 1,116,000 cfs. Since the wave had already flooded hundreds of square miles of valley floor above Attock, and the rating curve is based on measures ceasing 30 ft. below the flood peak its actual discharge was probably greater at Attock and much greater in the Indus Gorge. In view of the size of the 1841 dammed lake a maximum discharge of not less than 2 million cfs is indicated for the Indus Gorge below Hatse Pir.

A major factor in the erosional capability of such floods is the nature, size and downstream modification of the flood wave. In particular, the distinction between dynamic and kinematic wave types becomes important. The former are associated with steep wave fronts - "head of water" - and the formation of bores and roll-waves which

have enormous erosional energy. The latter, best described as a concentration of water which moves through the wave (see Lighthill and Whitham 1955), while increasing erosional energy are hardly distinct from other high flows, and, in particular are not capable of developing the super-saturated, density-current character possible in a dynamic wave (see Bell 1942; Leopold and Miller 1956 Figs 4 A-E).

The sudden release of a flood will create dynamic and kinematic waves. The former rarely last long, losses to channel storage, increasing channel and valley cross-section, and incorporation of existing discharge in the river into the wave quickly damping them down. The slower kinematic waves then catach up and translate the flood downstream. However, vertical growth of a wave which will re-create the dynamic component (see Stoker 1945; Dressler 1946) can occur at any point if the wave enters shallow water,- which cannot translate it kinematically, - or enters a narrow gorge.

Information for the 1929 Khumdan outburst can, with reservations, be seen to illustrate the points made above in terms of the Upper Indus situation (Fig. 16.1). For over 130 miles the flood obviously formed a vast dynamic wave or bore; the large initial head of water being enhanced by the narrow gorge and negligible pre-flood flow in the channel. The wave rose 85 ft. in 4 hours at Saser Brangsa and 65 ft. in 2 hours at Khalsar. Another marked feature is the recuperative power of the wave after leaving the open flats of Skardu for the Gorge around Nanga Parbat (e.g. Partab Pul and Bunji). In fact only at Bilot does the flood clearly settle down to a largely kinematic wave profile. But the valley and channel conditions over some 800 miles of mountain course give the dynamic element a far greater role than is common in long rivers (c.f. Lighthill and Whitham op.cit). Though less complete, similar data for the 1932 Khumdan outburst show substantially the same pattern (ed. Mason 1933 p. 128). The 1841 landslide outburst had an enormous head of water at Attock and had persisted in dynamic form for at least 400 miles. The size, rapid evacuation of the lake, and negligible discharge in the river prior

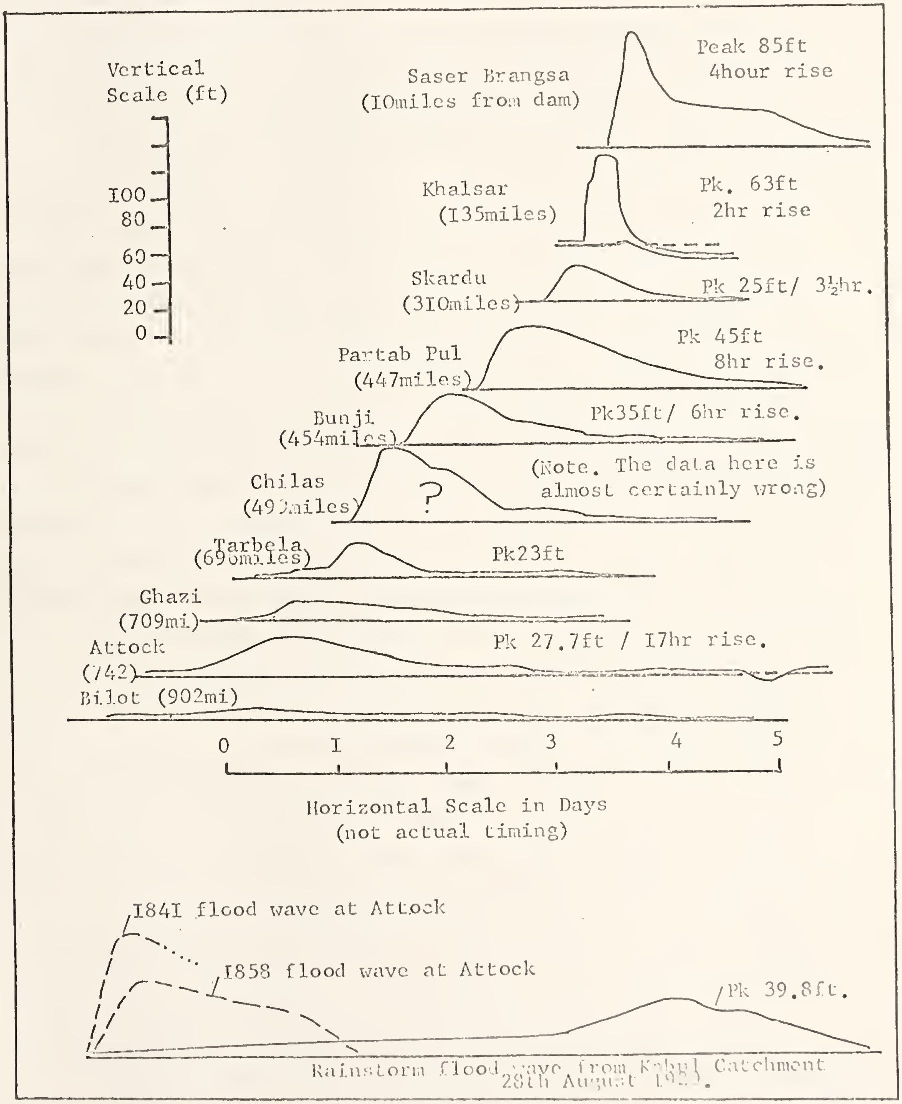

Fig. 16.1. Progress and general form of the Kumdan 1929 flood wave between the Upper Shyok and Indus Plains (after Mason). Some of the data on other flood waves at Attock is added for comparison.

to release were the principal factors here (see also Montgomerie 1860; Obbard 1860;and Pratt 1860; on the 1858 flood wave).

We may now relate these hydrologic and hydraulic points to some geomorphic effects of the floods. . The general context and potential of their action is tabulated for reference (Table 16.5).

Normally, height of flood has less erosional significance than in, say, socio-economic problems. A flood becomes greatly attenuated over the flood plain, and even its deposition tends to be less significant than "fill" in the channel. However, mountain gorges may allow a flood to rise tens and even hundreds of feet without great lateral spread and energy loss through over-bank spill. The singular importance of this on the Upper Indus relates to the aridity of most valley floors and recent fluvial incision which has left slopes terminating on arid stream terraces which only the most vigorous mass-movements can cross (see 10.9.). In many places as with the Biafo, terminal moraines build-up on terraces unremoved by normal processes. Only two mechanisms suggest themselves as maintaining a long-term balance here. First, lateral migration of the rivers. This occurs but in many areas seems minor, due to the massive boulders armouring bed and banks. Second we could have extreme floods high enough and powerful enough to erode the terrace surfaces. Along the Braldu a whole series of water-scoured terrace surfaces only seem explicable through catastrophic flood action (Hewitt 1964; 14.4.iii). This action included flattening and removal of frontal moraines of the Biafo, and clearly originated when that glacier dammed the Braldu River. A dam-burst flood in the Hunza Valley not only sluiced away accumulated deposits but triggered large numbers of new landslips (Neve 1907). Since normal river levels do not reach most of these slopes it follows that the rarer dam-burst floods must exercise a major controlling influence over the base-of-slope condition.

Reciprocally, fluvial transport is given an extra dimension by the slope and terrace erosion of the flood waves. The indication that the river is transporting well below capacity at Darband and Attock (15.3), relates to channel conditions and run-off from sub-nival

TABLE 16.5. Erosional Factors involved in extreme flood events; A tabulation of the range of erosional action available.

A) CONSTRAINTS.

Channel and Flood Plain shape parameters:-
- a) Surface Roughness.
- b) Longitudinal profile variations.
- c) Cross-sectional area and its variations.

Erodibility:
- a) Surface character and erosional resistance.
- b) Sediment availability in the flood zone.

Hydrography:
- a) Size and contribution of downstream tributaries.
- b) Flow of water in the river below the flood wave. i.e. timing in relation to annual regime, and importance of flow from dammed tributary in total of run-off.

These affect dissipation or recovery of the wave and therefore its nature at different points along the river system; erosional effects of energy available; speed of movement of the wave.

B) EROSION.

1. Scaling Upwards of Normal Processes.

- a) Hydraulic: increasing shear stress on wetted perimeter, increased turbulence.
- b) Sediment Transport: increased capacity, (sediment concentration) increased competence,
- c) Corrasion and comminution: increasing mass (sediment size) or impact velocity of transported fragments,
- d) Spatially: increasing wetted perimeter within flood plain area.

2. Novel Processes.

- a) Hydraulic: 'shooting' and 'cavitating' flows, travelling dynamic waves, and intermittent dynamic wave components.
- b) Sediment. Transport: 'New' competence thresholds. Formation of super-saturated flows, and density currents.
- c) Destructive action: Attack on Valley sides above normal flood plain. Creation of different channel form; lateral and vertical excavation. Cavitation erosion. Excavation of new stream courses.

C) DEPOSITION.

Change in 'lag' deposit forms in channel and flood plain. Deposits of different composition, especially with fragments of much higher calibre than usual.

areas. The high floods can tap accumulated finer material on terraces and slopes. The "dark chocolate colour" described in these floods contrasts with the usual grey to pale brown colour of the Indus, and is just the colour observed in most ephemeral and super-charged streams along the Braldu and Shigar Valleys. Furthermore, although there will be a complex interaction of erosion and deposition by the flood wave much material will be carried down for deposition in areas where later flows can gradually winnow them away.

In terms of competence there are two important effects these exceptional floods can have. The first relates to downcutting and the re-excavation of valley fill. The enormous boulders which armour so much of bank and bed along these rivers cannot be moved by most flows and are known to be stable from year to year. Movement of these is fairly essential for renewed downcutting or attack on terrace walls. Enormous boulders of this type are moved in vast numbers by the dam-burst floods. A second consideration is the movement of large calibre material falling on terraces and into the river during rock-falls and slides. These processes tend to show fall-sorting whereby the largest material comes to rest at the slope base where it is least likely to be moved further. The flood waves can offset the results of this situation by moving the large material.

During floods there is a complex relation between channel lowering or widening and deposition. The 1929 Khumdan flood wave deepened the Shyok by over 10 ft. at Khalsar, and the Indus at Attock by 8-10 ft. The 1858 flood widened the Hunza by hundreds of feet but, though much larger than the 1929 wave, reportedly raised the channel at Attock by depositing large "shingle banks" (Henderson 1858 p.211). Two examples of the cutting of new channels along part of a valley occurred with the 1850 Tarshing outburst and the Gol flood of 1855 (Drew 1875 p. 401).

Special erosional effects are less easy to identify from available information. The development of density flows in these floods is fairly certain, and the entire 1841 flood wave at Attock

was so saturated with mud and debris as to qualify for that description. Flow velocities are easily sufficient to promote cavitation attack and may help to explain the profusion of pot-holes and related forms on valley walls somewhat above normal flood levels.

Information is not sufficient to warrant further elaboration here, but the significance of the effects of these major flood events should be clear from what has been said. The effects are enhanced by certain special constraints operating in normal fluvial erosion. Both in terms of modern "magnitude and frequency" debates in geomorphology and conditions in the Semi-arid Himalaya this problem seems well worth deeper research.

CHAPTER 17

CONCLUSION

In this final chapter, the broad characteristics of the region's contemporary geomorphology are summarised and brought together under larger interpretive frameworks. Some important research problems which emerge from the present survey are outlined.

17.1. Summary of Erosional Processes and their Interrelations.

Weathering of rock to a state where removal becomes effective proceeds at a fairly rapid rate. In certain cases, as with sub-nival salt weathering, break-down is itself very rapid. In general, it is the high relief energy which promotes rapid release, since a much lower level of weathering is required to allow entrainment down steep gradients (Chapter 7). In turn, progress of waste down slopes is efficient, proceeding mainly by rapid, short-lived mass-movements. Rock-slides and rock-falls are prominent at all altitudes, but especially in a broad belt around the snow-line which also coincides with the zone of high precipitation. Mass-movements in the presence of moisture are dominated by avalanches above and immediately below the snow-lines; and by debris- and mudflows in the sub-humid and semi-arid zones. The movements show a strong response to seasonal variations in heat and moisture conditions. The extreme gradients of most slopes are over-ridingly important here in giving precedence to rapid movements, and the upslope increase in moisture availability further exaggerates this effect, as do the large seasonal fluctuations in local climates (Chapter 10). In the high glacial regions base-of-slope removal by glacial drainage appears highly effective in the entrainment of abundant avalanche debris, and this seems to be reflected in the steeper slopes descending to glaciers (Chapter 8). In parts of the recently incised river gorges removal of mass-wasting materials is also efficient. However, in large sections of the glacier ablation zones and of river valleys there is a well-defined discontinuity in the chain of erosion from slopes to axial drainage

(Chapters 10, 12 and 14). The discontinuity involves the accumulation of mass-movement materials on terraces, and reflects the combined influence of present altitudinal zoning of climate, legacy of past denudation, and the mountain erosional situation. The first acts through the severe aridity of lower sub-nival slopes which tends to choke off many movements through moisture depletion, and to preserve deposits through dryness. The cohesion imparted by accumulating fines and precipitated solutes is also important. Past denudation has left thick, fairly cohesive lag deposits as terraces lining glaciers and rivers, and a legacy of fines-rich slope deposits. Recent deep incision of rivers has served both to isolate the terraces, and form stream channels in bouldery or rocky beds resistant to erosion. The mountain situation adds to these effects by promoting rapid movement to the base of steep slopes, and especially the greater mobility of larger particles, so that axial drainage must have great capacity and competence to deal with the materials. Net erosional transport by the rivers is large but they nevertheless appear to be undertransporting most of the time, a fact which is partly, perhaps mainly, due to the discontinuity mentioned above (Chapter 15). However, if contemporary year-to-year conditions seem to produce a build-up of base-of-slope deposits there is no clear indication of long-term "clogging" of valleys or increase in slope deposits. The contrary is the case, most basal deposits seeming very recent, and there being abundant evidence of the re-excavation of old slope deposits. In this environment, the magnitude and frequency components of erosion include an important element of extreme or catastrophic erosional events, both in mass-movements and axial drainage. In particular, large glacier fluctuations and major flood waves, the latter mainly due to natural damming have the spatial arrangement, capacity and competence to deal with lag-deposits accumulating over the relatively long periods between their incidence (Chapter 16). These catastrophic events, though rare, are sufficiently well-established in occurrence and vigorous in action to be regarded as major controlling items in valley erosion.

17.2. Controlling Factors in the Environment.

17.2.i. Relief and Climate.

The broad controlling conditions over geomorphic activity in the Upper Indus Basin are summarised in relief energy, and the altitudinal distributions of heat and moisture (Figs. 5.4. and 5.5.). Relief energy comprises the combination of widespread deep dissection and high altitude summits, and the associated steep slopes (Chapters 1 and 8). The altitudinal zoning of precipitation, and regulation of its changes of phase by seasonal movement of temperature belts relate closely to the incidence and intensity of landscape processes (Chapters 5, 6, 7, 10, 12 and 15). But the predominant characteristic is integrated rather than independent effects of climate and relief as they are expressed in geomorphic activity. There is a strong case for thinking of the broad controlling conditions as a complex of both variables, since it is generally not possible to unravel their separate contributions. Very little work has been done by geomorphologists to specify the interaction of relief and climate. The broad relations between available relief and erosional yield have been examined (see Ichikawa 1958; Corbel 1959; Schumm 1963), and much has been done on the variation of process with climate. However, Corbel's work (op.cit.) shows clearly that differences in available relief within regions of similar climatic averages are much larger than between climatically different regions. On a world basis Schumm has shown a systematic increase of sediment yield with increasing relief (op.cit.). However, we know little about the relative roles of relief and climate in mountainous regions, and the data in the quoted works are not sufficiently detailed to isolate the variables. It is clear that the effect of relief in the Karakoram appears in both the pattern of climatic inputs and in their impact on the landscape. The impact of available run-off is a case in point. On the one hand, the "effective precipitation" of just over 17" per year from the Upper Indus Basin is close to that associated with peak sediment yield in the U.S.A. (Langbein and Schumm 1958). However, the fact that the region approaches a global maximum for solids

transport is only partly, and not mainly related to precipitation averages. Most of the run-off actually derives from areas within the region with much higher precipitation, and the high sediment transport is primarily a function of the short, concentrated period of run-off; both dependent upon the orographic effect. This same intensification and subordination of actual climatic norms to the relief factor appears at all phases of erosion.

Different morphological regions may be compared and contrasted both in terms of the sets of landscape features and processes present, and by the scale and tempo of erosional events in them. In its global context the Upper Indus region could be described as having an "extreme environment" in terms of the scale of landscape and the large fluctuations in conditions with space and time. The extreme climate-relief condition is expressed in short, intense bursts of activity rather than continual high level of erosion. In this instance the scaling upwards of available energy leads not only to the greater role of more "extreme" events (see Leopold et.al. Chapter 3), but also to a spectrum of "normal" events dominated by short periods of high energy erosion. The swiftest movements characterise mass-wasting so that individual transfers downslope are generally short-lived (Chapter 10). Large fluctuations in melting and reworking of debris characterise glacier ablation zones (Chapters 12 and 13). Run-off is mostly compressed into a short period of the year with associated sharp peaks of solids transport (Chapter 15). In each of these phases of erosion the region also has a well-established record of rarer large-scale events (Chapters 10 and 16), so that the magnitude and frequency components of events tend towards unusually high values.

An obvious method of summarising the regional environment would be to define its place in global "morphogenetic regions". However, most classifications of this type use annual mean temperature and precipitation as the primary variables. Clearly that is unsatisfactory in the Upper Indus region. The role of the climatic factors depends much more on their spatial and temporal variations than their mean values, and such a scheme fails to take account of the intimate relation

of climate and relief argued above. Furthermore, the valley station weather records are largely atypical of the region; which goes far to explain the eccentric plotting positions of the Indus on Fournier's graphs (1960). His only values for the Upper Indus climate are for Leh (c.f. Chapter 5). In sum, therefore, it does not seem profitable to use the "morphogenetic" approach at this time. The environment is dominated by the combined action of climate and relief whose most characteristic expression in geomorphic processes is to produce short-lived, high energy events at most phases of erosion.

17.2.ii. Rock Control.

It might be thought that the more vigorous the "process" environment is, the more subordinate the role of "structure". In the Upper Indus Basin, at least, the opposite is the case. Within the context of a vigorous process situation the expression of rock and regolith composition emerges strongly in the landscape. Particularly important in this region of extensive rock walls is the detailed expression of structural diversity in the geometry of cliffs and crestlines. At very high altitudes heavy snowcover may mask this, but lower down slopes and salients express very closely the primary planes of weakness or varying composition of the rocks. Undoubtedly, these features are equally an expression of the vigour of the processes which removed weakened rock quickly, preventing advanced weathering and accumulation of regolith from smoothing out structural variety. But we should also recognise the importance of the active role of rock, in the sense that any body of rock constitutes a physico-chemical system tending to adjust spontaneously to change in environment. While that is always true, where slopes are extremely steep and tectonically stressed rock is being rapidly excavated, stress,strain and failure, whether conserved or developing in the rock, become major components of weathering and the pre-requisites of entrainment (Chapters 7 and 10).

The relationship between mountain forms and rock type in particular areas of the Upper Indus has been described in the past (de Filippi 1932 pp.234-5, 248, and 288; Desio 1930 p.408; 1936 p.160 et. seq.). In the

Biafo Basin, many aspects of mountain slope-form vary with rock type, as between metamorphics and granites; and with the structures in these, as between steeply and gently dipping metamorphics (see Chapters 7, 8 and 9). The positive role of structure in the form of valley walls and mountain masses even under glacial conditions should not be ignored. The landforms of mountain glaciation are often treated as developing towards typical forms with little regard for structure (e.g. Davis 1906; Flint 1957 p. 103). Yet, in their way, the granodiorite towers and troughs of the Biafo are as different from the classic forms as, say, the glacial mountain terrain over much of Central Wales or the Southern Uplands. In each case, the rock types and structures are such that they have not responded to glacial conditions so as to produce the classic forms. The metamorphic terrain of the Lower Biafo appears rather more like the 'typical' glaciated valley, but even there, much variation is seen that must be attributed to varying response of structure.

Again, in transport processes and in the form and behaviour of lag-deposits, the composition of clastic material plays a major role (see Chapters 9, 10, 12, 13, 14 and 15). Slope deposits of coarse, non-cohesive debris show sorting and slope profiles highly sensitive to shape and size of the materials, often relating closely to original rock type. Wet flows, ranging from viscous mudflows to outwash streams reflect the nature and abundance of material available. The subsequent deposits, in appearance and erosional resistance depend upon compositional factors. In the talus zone, in river terraces, kame terraces and terminal moraines the importance of accumulated fines in the preservation of deposits cannot be over-estimated. One of the clearest legacies of past erosional conditions appears in the effects of high fines contents of old deposits. Of course, this is emphasised by the vigour of the contemporary process environment too, which prevents the advanced weathering necessary for an extensive fines-rich regolith to develop. Finally, this intimate interaction between materials and process media is seen in the erosional conditions in most main river channels where they have carved into old deposits,

winnowing out less coarse material but leaving large immobile boulders armouring banks and bed (Chapters 14 and 15).

In any environment, it is the interaction of process media with rock material which represents the focal point of erosional activity, and it is to this we must look to see exactly how a particular combination of climatic inputs, relief energy, and erosional legacy can lead to a given landscape. It seems fair to say that this physical basis for the explanation of landscape development requires a great deal of work in the Karakoram and most well-known areas.

17.2. iii. Situational Factors; Altitude and Aspect.

Within the broad environmental conditions there are well-defined, repetitive spatial variations in form and process which reflect erosional situation. Of these variations the clearest are those which occur upslope, and with aspect; both related most immediately to climatic differences.

Altitudinal variation in conditions produces broad upslope changes in the types and/or combinations of erosional forms and processes. For the Biafo area these changes are summarised diagrammatically (Fig. 17.1). The arrangement indicates the set of forms found in a given altitudinal zone, and broad variations in the incidence of a given form with altitude. Band widths only refer to the individual features, not to their importance among all features. Since high relief energy applies throughout, most variations are clearly related to upslope changes in the quantity and regime of moisture supply and downslope increase in the volume of erosional waste. Temperature mainly expresses itself by controlling changes of phase of the water compound. The clearest differentiations are defined by the climatic snowlines on slopes, and, for axial drainage, by the firn-lines and the termini of glaciers.

While it is useful to define altitudinal variations, the importance of the continuity of geomorphic processes downslope needs emphasis. High relief and steep slopes greatly reduce the independence of different altitudinal climatic belts. In particular, lower, drier

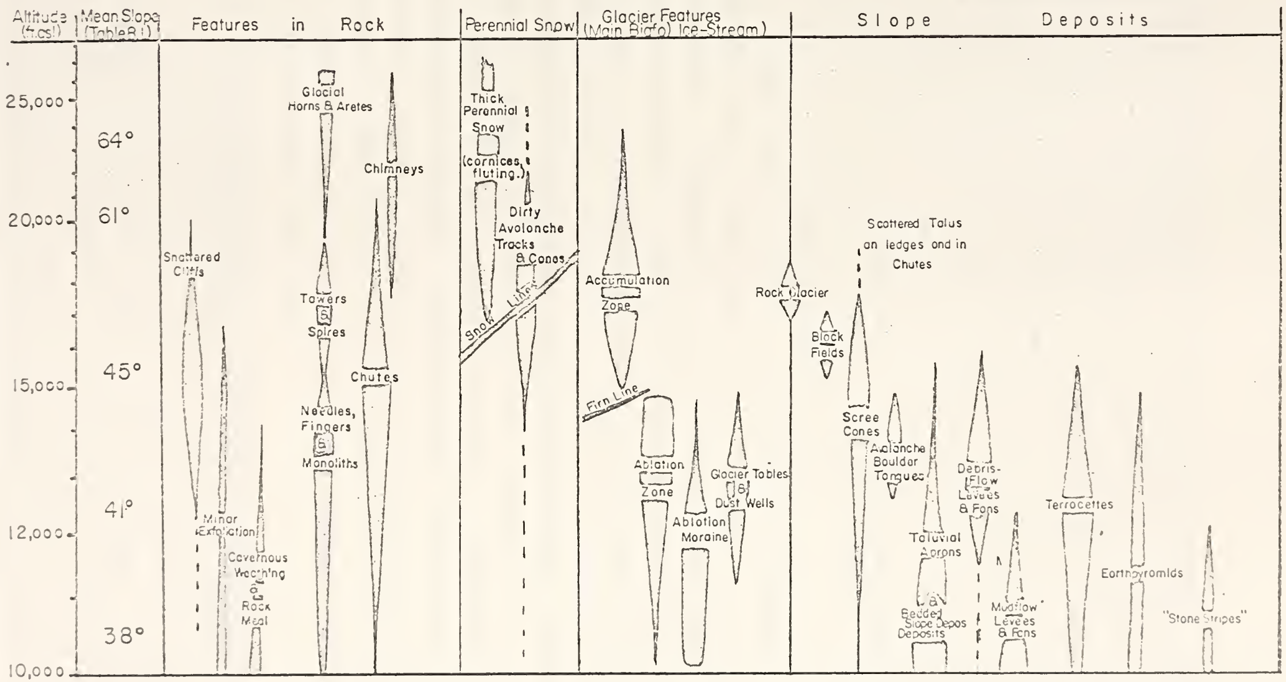

Fig. I7.I. Diagram showing the altitudinal incidence and variation of certain landscape features in the Central Karakoram. The bands are not used to illustrate the relative importance of each feature, and their widths refer only to broad variations in occurrence with altitude.

slopes are characterised by erosional and depositional features dependent on rapid downslope routing of moisture and debris from higher humid areas. Thus the features are not entirely typical of the climatic zone in which they occur. This is one of the most powerful ways in which greater relief modifies the effects of climate on processes. Of course, the continuity in the flow of mass and energy downslope is maintained with changes in the types of transport processes with altitude. The common sequence in long chutes, from upper avalanches to lower mudflows, or from glacial through fluvio-glacial to riverine processes are examples. The only well-defined breaks in these chains of events are the terraces mentioned above.

Aspect operates mainly as a modifier of climate. The main differentials are between north and south slopes (insolation factor), and at higher altitudes, between windward and lee slopes (snow accumulation factor). Above the snowline both affect snow deposition and rates of melting and evaporation, the incidence and type of avalanche activity, and areas of exposed rock (Chapters 8 and 10). The position of the snowline itself is also strongly dependent on aspect and exposure (Chapter 5). Below the snowline, type and rate of weathering, run-off, amounts of moisture in flows, and vegetation are dependent on aspect. There is evidence from the sampling of slope angles that northerly slopes are generally steeper and there seem to be greater volumes of slope deposit at the base of southerly slopes. This suggests an assymmetry of interfluves dependent upon topography-controlled climatic variations.

17.3. The Present Status of High Mountain Geomorphology and Some Outstanding Problems of the Upper Indus Region.

In general, high mountain geomorphology shares with that of the ocean depths and hot wet tropics a very poor stage of development. This is primarily a reflection of the difficulties of working in such regions. In high mountains, the logistics of field-work, the scale of the landscape and the problem of dealing with predominantly "high energy" processes are discouraging factors. These difficulties are reflected more in a lack

of continuity and integration of research than in a lack of actual study. There is a vast body of unco-ordinated but very useful information on the Himalaya for example. But it seems unlikely these problems can be solved directly. Indirectly, much could be done by study of certain poorly developed aspects of geomorphology in less exacting regions. One goes to remote, inaccessible regions for one of two main reasons; either to extend knowledge of the regional variation in geomorphological features of the earth, or to study some unique, or specially well-developed features. In either case the research format will depend to a large extent upon existing principles and techniques developed under more controlled research conditions. Certain important aspects of geomorphology which emerged as most significant in the Upper Indus Region, however, could not be adequately developed in that context owing to a general lack of basic knowledge about them. Clearly there is a need for greater understanding of the role of relief and distribution of slope angles in the organisation and intensity of erosional processes; and of the interaction of given climatic inputs to slopes of different inclination. Apart from some rather limited work in relation to soil erosion and crops, little is available on these questions that can be expressed in general terms. In all environments there is a need for the examination of the links between different erosional phases in the landscape; between weathering and mass-movement or slopes and axial drainage, or between transport and deposition by a single process. This problem becomes particularly acute in high relief areas where, in addition to these different process phases, there are marked downslope and downvalley changes in activity. Again, the fact that these problems have been considered in less difficult areas does not assist the study of extreme environments because few clear techniques and principles have yet emerged.

Perhaps more crucial is the poverty of basic knowledge concerning certain processes which become of major importance in high mountains. It is understandable that slow movements such as frost-heave, solifluction of soil creep have an enormous literature while high energy mass-movements such as avalanches, mudflows, debris-flows or rock-slides are still

little understood and have a relatively small literature. There are, however, many aspects of these high energy processes which could be studied in less difficult environments and even in the laboratory. For example, the roles of mechanical and clay mineral composition, gradient and moisture content in mudflows could be studied in a field laboratory. Perhaps the main area whose poor development inhibits progress in mountain geomorphology is that of rock control in geomorphic forms and processes, especially the role of solid rock in cliffs, crestlines, and salient development. By studying such basic processes and controls nearer home it should be possible to co-ordinate information on mountain regions and manage with less detailed data there, by defining sets of crucial observations.

In the Upper Indus Basin there is still a great deal to be done simply on the inventory of processes and forms present. But the present study suggests certain fields in which more specialised research is warranted. There are two types of problems; those which a researcher may reasonably expect to obtain adequate data in a field season, and those which are of particular regional importance. Only rarely can these two be said to overlap.

At all seasons of the year conditions are good for the study of high energy mass-movements on sub-nival slopes. It is also unnecessary to mount a large expedition for this. Even one researcher with an assistant could stay in Rest Houses within easy reach of a wide range of local environments and varied slope deposits whose study should contribute greatly to understanding of mass-wasting under high relief conditions. The Upper Indus river terrace systems would seem an excellent field for investigating the interaction of tectonics, and climatic change. They are well-defined, widely ramifying features whose mapping for form and sedimentary characteristics should prove highly informative. This would be an ambitious project but would hardly need the trappings which most expeditions to the area involve. It is now even possible to follow much of the Indus and Hunza Valleys by vehicle. There is a clear need for re-investigation of the denudation chronology of the region in the light of recent

reassessments of drainage development in mountains, and clima-geomorphic models of mountain landscapes (Chapter 3). In the absence of good mapping, investigation of terraces and associated slope deposits would seem the most practicable approach to the historical background of the problem. There is also a good air photograph coverage of the main Indus Trough, made in 1966.

Although they have received more attention than any other single aspect, there is still much to be done in the specifically geomorphological characteristics of the high glacier basins which form a unique feature of the region. It is unfortunate that such a programme was not implimented in the International Geophysical Year since only heavily financed, major expeditions can hope to tackle problems in these areas.

Finally, perhaps the most significant field in which study of the area would contribute to geomorphology would be in the magnitude and frequency components of erosional activity and their spatial location. The region emerges as having the highest known rate of regional denudation over such a large area. Meanwhile, the Attock gauging record in association with an increasing volume of new data on tributary streams provide a good basis for tackling this problem in a quantitative fashion. At the same time, the relative frequency of large-scale erosional events allows one to look at the actual controlling processes in extreme erosional activity. The problem of spatial variations in erosional rates within the region is much more difficult, but strong differentiation of climate, process and slopes might allow a relatively coarse network of observations to indicate the relative roles of erosion by glaciers, sub-nival slopes and rivers. A knowledge of the erosional components at the upper end of the erosional scale should make a major contribution to the theoretical development of geomorphology having ramifications beyond the context of high mountains. Few remote and difficult regions seem as well supplied with an initial body of relevant data for such a study as the Upper Indus Region. It

is hoped that the present study provides the necessary background of information and discussion to allow formulation of more restricted enquiries of the above type.

NOTES

Chapter 1.

1.1. The Karakoram Conference called the mountains immediately west of the Biafo Glacier the "Meru Group," after a name given to a prominent peak there by the Workmans. The Shipton Survey gives local names and it is consistent with the aims of the Conference to name the group after the principal peak, Sosbun Brakk (21,o4o ft).

1.2. On the accuracy of the 1939 Map, P. G. Mott the chief surveyor of the Shipton Party writes:-

"... I find it not easy to remember details of all the observations made. The Indian surveyor Fazal Ellahi, who carried out the plane-tabling of the upper parts of the Biafo and (Lukpe Lawo)..... was probably the most experienced Himalayan Surveyor in the Survey of India at the time.... I checked many of his spot heights with vertical angles taken on our small theodolite and the result showed that his work was extremely accurate, usually within plus or minus 20 ft. of my own values which in this sort of country is very little. The triangulation points of the Hispar Glacier and those of the major peaks intersected by the Survey of India triangulation should be correct within 5-10 feet. The second category of points are those provided by the photo-theodolite in the Snow Lake and Biafo area and should be reliable to 20 ft. Spot heights on the basis of the plane tabling work should be accurate between 20 and 50 ft. and the contouring within 100 feet.... (these are) relative accuracies only within the area and related to the Survey of India points to which our survey was referred......(The reliability)...of the Panmah Glacier area and especially the Sosbun area west of the Biafo are of much lower order........ I hope and believe that the map as a whole is of considerably higher standard than the results produced by most expeditions....." (personal communication. 20th April. 1967)

The present writer used that map as a basis for morphological mapping in the field and found that the draughtsman's originals held by the R.G.S. certainly met these standards of accuracy. The 1:253,440 Map produced from them cannot be used with the same degree of local reliability owing to simplification in the redrawing.

Chapter 2.

2.1. Descriptions and analyses of classical writings on the region in Western and Oriental literature can be found in many works, in particular Francke, 1907; Bretschneider, 1910; Aurel Stein, 1912, 1930, and 1933. For a very detailed description and evaluation of

knowledge and exploration of the region from ancient times until the early Twentieth Century, see Hedin 1917-1922, especially Volume 7. Descriptions of the modern period of exploration also appear in Kick 1957, and Dainelli, 1959.

Chapter 3.

3.1. A rise of 6,000-8,000 ft. in the Pir Panjal is noted elsewhere in the text. In addition there has been two to four miles of uplift in the Pamirs since the Oligocene, (Gerasimov 1964, quoting Chediya and Trofimov 1962) and a rise of perhaps 10,000 ft. in Tien Shan during the Pleistocene (Charlesworth 1957, p. 604 quoting Mertzbacher 1916; see also Ming-ye et. al. 1965).

3.2. Desio disagrees with Gattinger's interpretation of the strata referred to, but the problem remains open and therefore relevant to our current arguments. Also it is worth noting that in much of the region the climatic snowline describes a surface roughly parallel to Lester King's Late Tertiary planation surface. It is interesting to speculate on the relative merits of a clima-geomorphic interpretation as against the old erosion surface.

3.3. De Terra was opposed to the Penckian approach and related German ideas about landform development.

3.4. The writer has not seen this thesis argued but it appears relevant to the semi-arid Himalaya. Nearly all the existing tracts of high level, low-angle plateau linked to the trans-Himalayan drainage exist well beyond the deeply incised main gorges of the great rivers. In the Upper Indus Region these upland basins are mainly in the east and not only do they interfinger with basins of interior drainage; the Indus basin itself encloses one small basin of interior drainage (Kailas Indus) and nearly surrounds another (Tso Moriri Basin). A significant portion of the present Indus basin may until quite recently have been part of the vast patchwork of interior basins that cover the Tibetan Plateau. Glaciation and melt-water run-off, combined with rejuvenation along the main Indus drainage suggests a means whereby many small interior basins could have been captured. Such basins, whose

erosional development had been controlled by the ephemeral streams, and high, interior base levels would have been brought into the sphere of Indian Ocean drainage. There is reason to suppose that the original basins could have been carved at approximately similar levels and that their surviving remnants would give the impression of related planation surfaces. But, instead of being precursors of the present era, most of the time they have been contemporaneous features related to different base levels. There seems to be nothing in de Terra's observations that would refute this.

3.5. The proponents of the ancestral river thesis are dismayed by the idea of two major rivers flowing in opposite directions on either side of the orogenic belt (Spate 1954 p.33). They failed to note that many pairs of rivers do just this, (e.g. Elbe and Danube, Po and Arno, Volga and Irtysh, Yarkand and Ili, Gongola-Benue and Benue, Forth and Clyde). It is a poor theory which can be so swayed by purely formal patterns of this kind.

3.6. This refers strictly to long-term "antecedence" as from Tertiary Peneplain rivers, rather than to transverse streams across the Himalaya such as the well-known Arun example. Even with those streams however, there seems no reliable evidence for preferring antecedence to rapid headward migration and capture by Front Range rivers (c.f. Sparks 1960 p.124) Von Engeln said "...the fact that the interior valleys of the older Himalayan mountains hold vast gravel accumulations...is supporting evidence for antecedent origin of gorges across the new southern ranges" (1942 p. 299). In the case of the Upper Indus Region there are other explanations of the intermontane sediments available (see 3.4.). Finally, some recent work demonstrates the need for a search reassessment of the adequacy of the physical notions which make it necessary to explain drainage transverse to an orogenic belt as being largely superimposed or antecedent (see Oberlander 1965 on the Zagros Mountains drainage).

3.7. It is not certain that the ice-dammed lakes of the Third Glaciation created ice-dam bursts, but it seems likely (c.f. Gansser 1964 p. 54). Indus Plains "erratics" stretch practically to Karachi (Theobold 1880) and are heavily concentrated around Attock (Cotter 1929; Coulson 1929). They seem too large to be related even to the greatest of recent natural dam-bursts; that in 1842 (see Ch. 16). Coulson's reasons for feeling the Potwar "erratics" were rafted from an ice-front resting in a lake there, fail to take account of the power and the form of ice-dam bursts. He gives no data to show that the surrounding sediments are wholly lacustrine.

Chapter 4.

4.1. The writer deposited a dozen large hand specimens from the Biafo area in the British Museum (Natural History), Cromwell Road, London. These have not yet been analysed apart from one item mentioned in Table 4.2. They are, however, more suitable for analytical work than the small stones of the Conway collection which appears to be the only other source of Karakoram specimens in Britain.

Chapter 5.

5.1. The writer is indebted to Professor Hermann Flohn, the leading authority on climate in these areas, for reading and commenting on preliminary drafts of this and the next chapter.

5.2. Von Wissmann believes the localised morainic outcrops and bare cliffs of the Sim Gang north flank represent the general southerly slope snowline of the Upper Biafo. It does not, however, apply to the Lukpe Lawo area, the Sim La branch of the Sim Gang where no consistent limit of snow is found. Even in the Uzun Blakk Valley the southerly snowline is below 16,ooo ft. (c.f. von Wissmann 1959 p. 1242).

Chapter 7.

7.1. All grain-size terminology in this study refers specifically to the Wentworth scale of grade unless otherwise stated (Wentworth

1922).

7.2. The method devised for trying to locate and measure stress in water-filled cracks during freeze-thaw cycles was as follows. A number of very small Brinnel Hardness Test cyclinders were made, 3/16ths inch deep and 1/4 inch in diameter. These were to be used in reverse sense to their normal engineering application. Small discs of various metals of known hardness were used so that the diameter of the imprint made by the steel ball impressed into these could be converted to equivalent stress exerted. The idea seemed good but in the field, even with the softest metals used no impression was made. However, very few water-filled cracks of suitable dimensions and location were found, and the longest period for which a Portable Brinnel Test was left in any crack was 10 days. In all cases the water either was mostly lost during the period, or a porous ice structure developed such as is described in the main text.

Chapter 9.

9.1. The following examples quoted from the available literature indicate the widespread occurrence of earth pyramids in the region.

Reference	Location	Comments
Workman, 1908, p.391.	Astor, Nanga Parbat, E. flank.	Poorly developed examples in photograph.
Longstaff, 1910, p.639.	Tributary of Shyok, near peak K25.	Suggests material glacial, probably lateral moraine.
Workman, 1910b, p.84.	Lower Hispar Glacier.	Pillars carved in flanks of kame terrace.
Rickmers, 1913, p.311 & 315	Pamirs	
Hedin, 1917, vol. II, p.153 & p.294.	Uppermost Tsangpo, east of Indus source.	"...slopes...covered with clay,sand and detritus, in which the rain has modelled out curious steep cones and pyramids..."

Wood, 1922	Eastern Karakoram.	Photographs
Dainelli in de Filippi 1932, p.293. \	Upper Shyok.	"...(in) extensive remains of clay stuck here and there on valley walls.
Raechl, in Finsterwalder et. al. 1935, p.47.	Between Indus and west flank Nanga Parbat.	Extensive on steep slopes of terraces.
E. S. Williams. p.com.	Nagar and Hunza.	Frequently seen.
F. Azhar. p.com.	Babusar Pass to Gilgit.	Several suites seen.
Present Author.	Shigar Valley, Skardu Basin, along Indus Gorge.	Scattered examples seen in these areas.

9.2. Of the pyramids found along the Uppermost Tsangpo (Brahmaputra) Hedin says, "...On the top of some of these pyramids there is a flat block showing that they have been formed almost in the same way as glacier tables, the block protecting the underlying soft material from destruction." He also ascribes their formation to rain modelling (1917, vol. II. p.153). While our discussions show that his visual evidence alone is insufficient to be conclusive on the point, it will be remembered that the area concerned has most of its precipitation in the form of convectional, summer thunderstorms. It is also reported that the earth pyramids of the lower Indus Gorge are predominatly boulder-capped. (F. Azhar. p.com.). Here again much of the precipitation is in the form of rain, with a number of reports of occasional torrential rain storms.

Chapter 11.

11.1. Reference may be made to the following texts for descriptions of the other major Karakoram Glaciers:-

The Siachen. Longstaff (1910a and b), Workman (1914a and b. and 1917), Dainelli (1932), Mason (1930).

The Baltoro. Austen (1864), Conway (1894), Guillarmod (1904), de Filippi (1912), Mason (1930), Dyhrenfurth et. al. (1935 and 1939), Desio et. al. (1936 and 1961), Desio (1940 and 1955), Caputo (1958), Marussi (1956 and 1964), Maraini (1961), Gansser (1964 Photos 3 and 5).

<u>The Hispar.</u> Conway (1894), Workman (1910a and b), Visser (1926), Mason (1930), ed. Mason (1931), Shipton (1940), Mott (1950), Desio (1955), Desio et. al. (1961).

<u>The Rimo.</u> Deasy (1898), Dainelli (1922), Mason (1930), Trainkler (1931), de Filippi (1932), Visser (1938).

<u>The Panmah.</u> Schlagintweit (1861-66. vol. II), Austen (1864), Desio (1930 and 1940), Shipton (1940), Mott (1950).

<u>The Batura.</u> Curzon (1896), Visser (1926, 1933/34 and 1938), Mason (1929 and 1930), Todd (1930), Pillewizer (1957), Edwards (1959).

<u>Chogo Lungma.</u> For a modern investigation and extensive bibliography see Kick (1964).

11.2. According to von Wissmann, who also used the Shipton Map in his calculations the glacial area within the Biafo Basin is 242 square miles, or 73%. It can only be assumed that his measurements were more generalised than the writer's and ignored the extensive areas of exposed peak and rock wall between tributaries above the snow-line.

11.3. On July 20th 1892, Conway found slushy firn and the beginnings of hard ice somewhere below the entry of the Sim Gang tributary (1894 v. II. p.386). A photograph of the Workmans in late July 1899 shows the first outcroppings of glacier ice running obliquely across the glacier opposite the Ghur tributary at 14,5oo ft. (Workman 1901 opp. p.118). E. S. Williams recorded the firn-line as between the 14,25o and 14,5oo ft. contours as shown on the Shipton Map (p. com.).

Also, Conway (op.cit. p.364) reported the Hispar firn-line at between 14,5oo and 14,75o ft. on July 17th. (N.B. He gave the name "Kanibasar Glacier" to the one named "Julmau"on Shipton's Map). The Workmans recorded the Hispar firn-line at between 14,75o and 15,ooo ft. in early August, 1908 (1910a. p.160). In both cases this is the higher part of the firn-line on the glacier's north side.

11.4. No measurements of rates of ablation on the Biafo are available. Workman made some stake measurements of melting in "Hard-packed" firn near the Hispar firn-line at 15,ooo ft. He

recorded 2.56 inches per day during some cloudy weather (July 31st - August 5th); and 3.25 inches/day during sunny weather (August 5th - 10th) (see Workman 1910a p.160). How far these measures are comparable with those made with modern techniques is hard to say. On Chogo Lungma in the middle ablation zone, rates of ablation varied between 1.2 and 2.4 inches/day in October 1954 (Kick 1964).

Chapter 12.

12.1. The writer is sceptical of the ¼ mile retreat reported by Conway for August alone. The text of his description shows that he was not very sure of this himself, and that he crossed the glacier on the two occasions by different routes and without time for careful inspection (1894 v. II. p. 417 & 550). It is difficult to keep one's bearings in this kind of country even after a long stay, and in any case, understanding of glacial features was still not very advanced at that time. Mason and Auden, however, both with considerable Himalayan experience, accepted the substance of Conway's observation (Mason 1930 p. 255; and Auden 1934 p. 406).

Chapter 13.

13. 1. A well-defined instance of the isolation of a large terminal tongue of ice occurred on the Lower Trivor (Gharesa) Glacier above Nagar. This was during the recession of the 1920's and 1930's (c.f. Visser 1928 and Shipton's 1939 Map).

13.2a. The Sella photograph of the Biafo terminus in 1909 shows it 30-40 ft. below the level of "The Nose" where it entered the Braldu Valley (de Filippi 1912 opp. p.163). The Workmans described some parts of the glacier as overhanging the kame terrace and building lateral moraines. The published photographs illustrate this (Workman 1910a pp. 190-192 and 1910b p.123).

13.2b. In 1932 Auden made an estimate of the thinning of the Biafo on the basis of the trim-line. He says:-

"A very approximate idea of the loss in volume may be obtained by assuming a uniform loss of thickness of 50 ft. for ten miles of the glacier one mile in width... (a loss of)

13,940,000,000 cu. ft. or nearly 1/10th of a cubic mile..." (1936 p.405).

He also stated that the trim-line was not noticeable above ten miles from the snout. However, he was at the mercy of very inadequate mapping. In his published photograph at "Camp 12,8oo ft." called by us Mango, there is quite a distinct kame terrace which, from comparison with 1961 condition must have been 50-100 ft. (15-30 m) high. Mango is 16 miles (25.75 km) from the snout! He also omits the effect of thinning considerably greater than 50 ft. (15 m) over the lower 5 miles (8 kms). Hence, though the Biafo was certainly thicker at that time than in 1961, his estimate cannot be accepted as a basis for thinning in the subsequent period.

13.3. By comparing Workman photographs of 1908 on the Middle Hispar with those of E. S. Williams (p. com.) in 1956 we find thinning of the order of 150 ft. on that glacier also.

13.4. A problem has always surrounded the 1899-1909 period in relation to the Workman observations. Both Auden and Mason presumed the Workmans found the glacier in the same position in 1908 as in 1899, though Pfannl, Guillarmod and Penny found it up to the banks of the Braldu in 1902 and 1905 (Mason 1930). In fact, the question of the Biafo being able to advance and retreat at this rate should not have arisen. Workman had already stated in 1917:-

"... I am not aware that we have anywhere made any statement regarding the position of the Biafo tongue or lower extremity in 1908..." (1917 p. 87).

He implies, as the text on the 1908 expedition shows, that they did not inspect the Biafo snout on that occasion (see 1910a). Hence, the problem of such rapid, large fluctuations of one of the largest Karakoram glaciers need no longer trouble us.

There is, however some doubt about whether the Biafo was as far back in 1899 as the Workman Map suggests. The Biafo is shown following a straight line across the entrance to the Biafo Valley, without intruding into the Braldu Valley. Yet, the ice buries

"The Nose", making the ice-front rise sharply in a 500 ft. cliff. This is not impossible, but is certainly very unusual for this glacier. Meanwhile, the writer is fairly sure he can pick out the terminal lobe of the Biafo on one Workman photograph, in advance of its 1961 position (Workman 1901 p. 105). It is practically impossible to accurately judge the position of the Biafo in the Braldu Valley without viewing it from all sides (see Featherstone 1923 p.353). From their narrative the Workmans do not seem to have done this, and their map is certainly a very sketchy affair. This is important since all the other evidence we have indicates that the Biafo did not retreat or thin as much during the late 18th Century retreat as the one in this century. If that is so, it adds to the evidence that these large glaciers are, apart from seasonal variations, relatively conservative in their terminal fluctuations (c.f. Mason 1930).

Chapter 15.

15.1. WAPDA (West Pakistan) supplied the following information concerning Attock records:-

" Location — Latitude 33°54', Longitude 72°15', on both banks at downstream end of wall of Attock Fort about one mile downstream from mouth of Kabul River and 1¼ mile upstream from Attock Bridge.

Drainage area — 102,000 square miles.

Gauge — Staff gauge on left bank painted on wall of Attock Fort (0 to 32 feet), on masonry pillar on right bank (32 to 54 feet) and on downstream right corner of Kas Nallah bridge about one furlong upstream (54 to 70 feet). Left bank gauge read by telescope from right bank.

Measurements — Discharge measurements made by current current meter at 0.2 and 0.8 of depth from motor boat about 5 miles downstream by Surface Water Circle starting July 1960. Measured by floats from bridge May to October 1948 by Irrigation Research Institute Lahore.

Determination of discharge A rating curve dated 19.12.62 was drawn using all measurements available. Discharges from 1.1.63 to 31.8.63 were computed by applying mean daily gauge heights to this table. Measurements made after August 1963 indicated scatter to the right of the above curve, which was therefore modified. Consequently new rating dated 29.7.64 was developed and used for computation of discharge from 1.9.63 onwards.

Remarks Records fair. Gauge height record furnished by Discharge Division of Irrigation Department."

Chapter 16.

16.1. Mason believed the Kumdan glaciers showed definite cycles of advance and retreat, and that the cycles were significantly different for each glacier. Hence, he considered the advances must be "accidental", and related to characteristics of each glacier and basin rather than to climate. In fact, it is doubtful whether the evidence supports his beliefs. His cycles are based wholly on whether observers record the glaciers as being in the Shyok River or on its west side. But under the conditions in these regions such observations are quite inadequate to decide with any accuracy the phasing of glacier oscillations. Quite minor differences in movements, melting, and erosion by the river, - even the time of year when the observers passed by - could account for many of the variations recorded. However, more important is the fact that Mason's cycles as shown in the 1935 paper (pp.26 et.seq.) do not correspond with the evidence in the literature as it is employed by him - nor, indeed with the written statements in his own account in the 1929 paper (pp.23 et.seq.). Specifically, his diagrams do not correspond with reports as follows:-

a) 1832, the evidence inferred from the 1835 dam-burst which is actually attributed to the Sultan Chhussku not the Chong Khumdan.

b) 1869, when the Kichik was advancing into the river but the Chong Khumdan is recorded as projecting far across it.

c) 1873, when the Kichik projected into the river as well as having masses of ice stranded on the far side, and the Chong Khumdan almost reached the east side of the river.

d) 1909, when the Kichik and Chong Kumdan were both projecting into the river with little difference.

In several other reports the observers do not say which glaciers were in the river and on little or no evidence but his own cycles Mason has assumed which glacier they were referring to. The increasing faith which Mason placed in these cycles, - he also inferred similar ones for the Karambar and Minapin Glaciers (op. cit. 1935).- detracts from some otherwise very useful discussions which foreshadow modern interpretations to a surprising degree. But, for the Kumdan glaciers it is no more likely that Mason's thesis is sounder than the "Rainfall Cycles" of Longstaff (1910), who saw the variations between each glacier as minor responses to slight differences in size and shape of ice mass (c.f. Hedin 1917 vol. 2, p. 198).

Sources of information on the behaviour of the Kumdan glaciers include:-

Becher (1839 p.222), Izzet Ullah (1842-43), Thomson (1852 p.420 & 450); Cunningham (1854 p.99), Strachey (1853; 1854 pp.55-57), Syud (1856), Shaw (1871 pp.433-4), Bellew (1875), Trotter (1875), Scully (1876), Gordon (1876 pp.8, 17, 18), Veniukov (1876), Younghusband (1829 & 1896), Dunmore (1893 pp.190-205), de Rhins and Grenard (1897-98 v.1 p.138), Hedin (1899-1902 v.4 p.410; 1910 p.184), Novitsky (1903), Huntingdon (1907 p.81), Fraser (1907 p.142), Longstaff (1910 pp.649-650), Rabot (1911), Stein (1912 v.2. p.486), Dainelli (1922-34 ser.2. v.3), Wood (1922 p.7), Roosevelt (1926 pp.59-60), Ludlow (1929), Sinclair (1929), Mason (1929a,1930,1932b,1934, 1935,1940), Church and Phelps (quoted Mason 1929a), Johnson (quoted Mason 1929a), Gunn (1930), de Filippi

(1932 pp.320-22), Visser (1938 v.2), Lyall-Grant and Mason (1940).

Several original sources have been used as evidence that a Kumdan barrier had formed because the authors took an alternative route to the Karakoram Pass. However, in some cases the alternative route could have been taken for other reasons, and the Kumdan route could be blocked although the glaciers only just reached into the river.

16.2 An estimate of the actual volume of water dammed by the 1841 landslide, can be made though the two lines of approach available give widely different results. From the description of dam and lake the volume can be calculated using topographical maps. Planimetric measurements indicate a lake area of 96 sq. miles and a volume of water of the order of 15 cubic miles. This is roughly 50 MAF! The second approach is to calculate the average inflow at this point on the Indus using the Darband discharge curve for the period December to mid-June. The result is about 21 MAF. In particular years, however, it could be as large as 40 MAF or as small as 15 MAF. The topographical data is the least reliable of the two and we will accept a conservative estimate for present purposes of 20 MAF. As the lake level and dam site are still preserved perhaps someone will determine the actual figure in due course.