Chapter 2
Snow, Ice and Verticality in the Karakoram

Abstract The distribution of perennial snow and ice in the Karakoram Himalaya is examined and its area–altitude relations. The presence and extent of snow and ice are shown to depend upon, and be positively correlated with, interfluve heights. The elevations and extent of the highest altitude terrain are of decisive significance. The size, length and lowest reach of glaciers increase as elevation increases up to the highest watersheds. In the Central Karakoram, the 'glaciation level', or minimum elevation needed to generate a glacier, is found at about 5,250 m on north-facing slopes and 5,500 m on south-facing slopes. At the western margins, the averages are 4,600 m and 5,200 m, respectively. They rise eastwards by about 1,200 m and 900 m to the highest glaciation levels found in the eastern margins of the Karakoram. A main set of the 42 largest valley glaciers is introduced, with basin areas exceeding 130 km^2 and ice streams over 16 km in length. These have exceptional elevation ranges, five spanning more than 5,000 m and 34 more than 3,000 m. Their long profiles exhibit two main features. Most of the vertical descent is accomplished in less than 10 % of ice stream lengths, mainly in icefalls in the upper parts of the basins. However, their longest sections, in the middle and lower reaches, are of relatively gentle gradient. Some 85 % of main ice stream areas lie between 4,000 and 6,000 m, the critical elevation zone in terms of ice cover. This must be balanced against the extreme high elevations of their watersheds and also the exceptionally low termini of many Karakoram glaciers compared to most in the Greater Himalayan Region.

Keywords Verticality • Elevation range • Area–altitude distributions • Glaciation limit • Rock glacier thresholds • Glacier long profiles

2.1 Glaciers and the Perennial Snow and Ice Cover

Most of the Karakoram ice cover and its largest glaciers are in the highest parts of the range, especially the main axis, aptly named the Mustagh (= 'ice mountain') Karakoram. Here the perennial snow and ice cover exceeds 70 % (Fig. 2.1). The Rakaposhi–Haramosh

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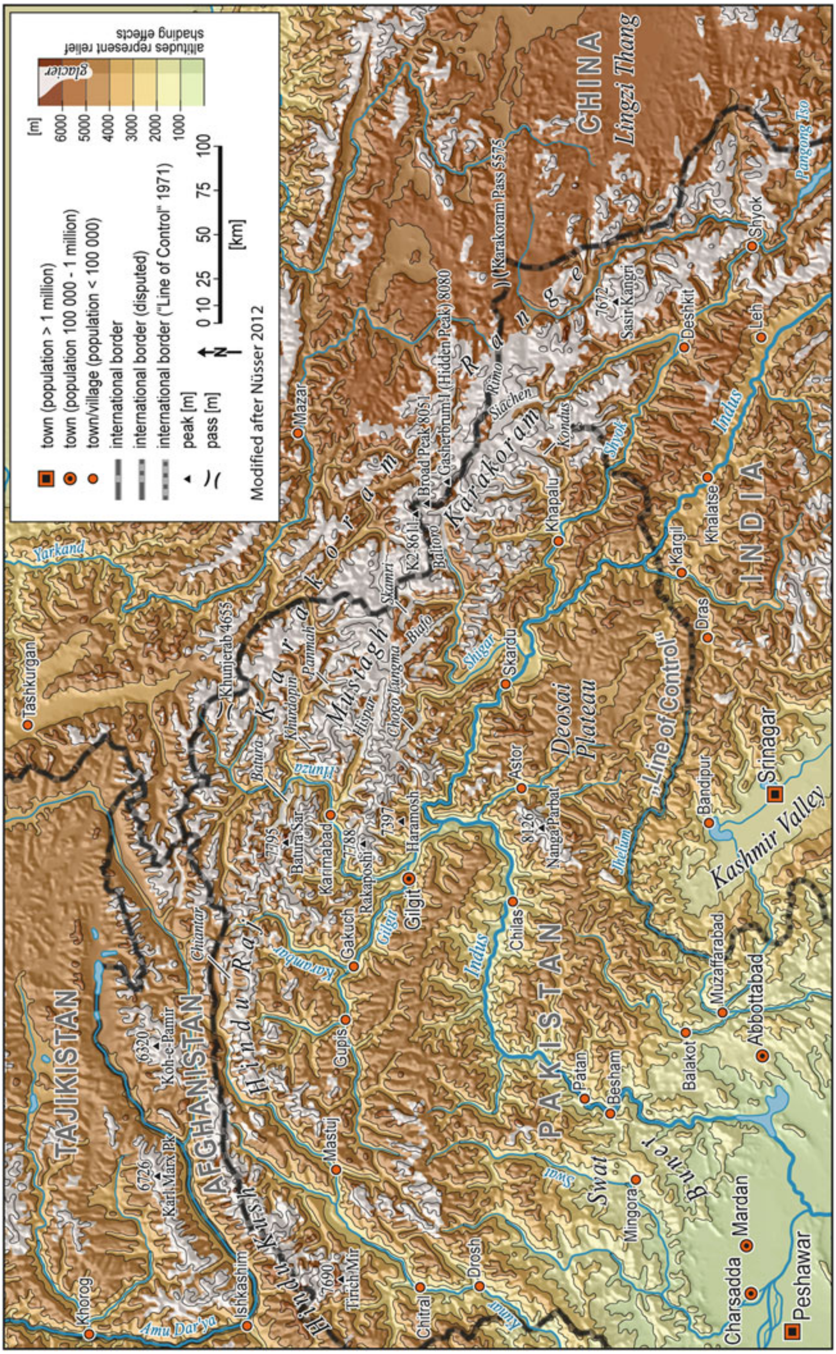

Fig. 2.1 Map of glacier cover and principal basins and sub-ranges of the Karakoram (modified after Nüsser 2012)

Massif is south of the main axis but shares its characteristics of great height, ruggedness and ice cover. The main glaciers commence on the highest watersheds, but the larger ice masses spread outward and down to relatively low elevations. They form a nearly continuous glacierised zone over a distance of some 400 km and from 20 to 70 km in width. This Mustagh zone comprises about 12,500 km^2 out of the total Karakoram perennial snow and ice cover of 20,500 km^2.[1]

All of the larger glaciers are in the highest headwaters of the Indus and Yarkand Rivers. The greatest concentration surrounds the highest K2 (8,610 m) Massif where the longest ice streams originate: Siachen (76 km), Biafo (66 km) and Baltoro (62 km).[2] These and several others comprise most of the biggest valley glaciers outside high latitudes.[3] On the Karakoram north flank, glaciers draining to the Shaksgam and Eastern Yarkand tributaries include the largest in China, the Skamri or *Yengisogat Binchuan*, 50 km in length and over 500 km^2 in area (Yafeng et al. 2010).

Several clusters of intermediate and small Karakoram glaciers occur south of the main axis, between it and the courses of the Shyok, Middle Indus and Gilgit Rivers. Others are to the northwest, mainly in the Shimshal and Chapursan Basins. The perennial snow and ice cover of these mountain areas varies from 20 % to 50 % (Dainelli and Marinelli 1928, Plate XII), and their glaciers add another 6,500 km^2 or so to the Karakoram total.

The larger Karakoram glaciers are exceptional for the subtropics and compared with most of High Asia (Table 2.1). They are of special interest in themselves, because they comprise such huge stores of fresh water and make significant contributions to the Indus or Yarkand Rivers. Water yields are as much as ten times greater than their share of the whole basin area.

Many of the larger glaciers have received little attention and the smaller ones none at all. Taken alone, however, even the latter add up to greater concentrations of ice than some of the most intensively studied systems elsewhere. And the small glaciers are usually more crucial to the livelihoods of people living in the mountain. In part, it is because the valleys of the lesser ranges provide more land suitable for settlement and partly because local communities are better able to exploit waters

[1] I estimate that not more than 4,500 km^2 of Karakoram perennial snow and ice is in the Yarkand drainage. Yafeng et al. (2010, F143) find the glacier cover on the north, China flank to be 6,262 km^2. It seems high, but opinions vary as to how far east the Karakoram extends, and their estimate seems to include the Aghil Range and others adjacent to the Karakoram in the Yarkand Basin.

[2] Chiantar Glacier, at the head of the Yarkhun–Chitral River, is often placed in the Hindu Raj (von Wissmann 1959) but is treated as a 'Karakoram' Glacier here. Its headwaters are in the western extremity of the range. Also in the upper Indus Basin, on the Chitral flank of the Tirich Mir range, are three glaciers of intermediate size: the Tirich, 21 km long; Atrak, 21 km; and Kotgaz, 16 km (ibid, p. 135; Shroder and Bishop 2010, F 211–212). Two Nanga Parbat glaciers, the Rupal (Toshain), at 15.5 km, and Rakhiot, 15 km, are just within the intermediate category. A few glaciers of intermediate size drain to the trans-Himalayan Indus from the Greater Himalayan range to the southwest of the Karakoram.

[3] Only the Fedchenko Glacier in the Pamir Range, which is 77 km long and 652 km^2 in area, exceeds all Karakoram Valley glaciers in length, but seven of the latter have larger basins (Kotlyakov et al. 2010).

Table 2.1 Some dimensions of the fifteen largest glaciers in the Karakoram, including three in Yarkand Basin (= Shaksgam River), sorted by basin area

Glacier	Basin area (km^2)	Length (km)	River basin
Siachen	1,400	75	Shyok–Indus
Baltoro	1,270	62	Braldu–Indus
Biafo	855	68	Braldu–Indus
Hispar	785	53	Hunza–Indus
Batura	710	59	Hunza–Indus
Chogo L.	690	47	Shigar–Indus
Panmah	680	44	Braldu–Indus
Rimo	612	45	Shyok–Indus
Skamri	510	40	Shaksgam–Y.
Kondus–K.	490	36	Shyok–Indus
Chiantar	436	51	Chitral–Indus
Braldu	430	36	Shaksgam–Y.
Khurdopin	415	41	Hunza–Indus
Sarpo Largo	390	32	Shaksgam–Y.
Virjerab	389	36	Hunza–Indus

from small glaciers (Chap. 13). The latter appear more sensitive to climate fluctuations adding to their significance for mountain societies. The lack of investigations limits what can be said, but an attempt to increase awareness is made below.

2.2 Verticality: The Primary 'Himalayan' Dimension

In a high mountain context, the elevations at which glaciers exist and elevation ranges they span are critical in their maintenance, morphology and behaviour (Plate 2.1). The Karakoram is singled out as having the greatest array of high peaks, elevated mass and deep dissection in the whole Himalayan region and said to include the 'steepest places on Earth' (Miller 1984).[4] There are four peaks over 8,000 m and 71 recognised summits between 7,000 and 8,000 m. As noted, the bulk of the ice cover originates in the highest and steepest parts of the mountain range.

In high mountains, the consequences of elevation relate to, but differ from, free air phenomena or elevated plateaux.[5] Environmental relations between elevation and topography are as important as their absolute dimensions and need to be addressed together. The term 'verticality' conveys this. In particular, it identifies issues 'Relating to or composed of elements *at different levels*' and 'of, constituting, or resulting in, *vertical combination*' (Dictionary.com 2010, *emphases added*). Verticality includes conditions defined by the 'vertical zonation' of Klimek and Starkel (1984), the

[4]While these comments are often made, it seems the greatest vertical span of a rock face is the nearby south-facing Rupal Wall of Nanga Parbat and the highest measured elevation range in the Annapurna Region of Nepal (Dr. M. Nüsser, personal communication).

[5]The words elevation, altitude and height are used interchangeably, except where 'elevation' refers to the act of lifting.

Plate 2.1 Bualtar Glacier descends northwards from Minapin Peak (7,266 m) in the Rakaposhi Range, a fall of some 4,965 m in 22 km to its snout. The extreme steepness and elevation ranges of larger Karakoram glacier basins are indicated, and a sense of the great vertical changes in conditions from the debris covered ice of lower tongue to precipitous, avalanched walls at the head (Hewitt June 1997)

'altitudinal belts' of Ives et al. (1997, p. 7) and the 'elevation effect' and 'altitudinal organization' of Hewitt (1993, 2005). While these terms tend to privilege horizontal zoning, verticality directs attention to spatial–physical relationships in which gravity is of foremost significance. It reinforces the sense of connections up- and downslope, quite as important as the distinctive elevation belts evident in high mountains.

Phenomena associated with verticality also increase in importance and intensity as elevation and, especially, elevation range and slope angles increase. In the Karakoram, these drive key aspects of glacial and other cold-related or cryosphere hydrological and geomorphic processes. Geographically, the scope and diversity of conditions relating to verticality tend to increase towards lower latitudes. Studies of cryogenic features and vegetation zones suggest the subtropics are where the widest diversity and strongest gradients occur (Troll 1954; Ives et al. 1997). It is partly because of greater variety in the lower elevations, as well as the requirement of very high elevations if the mountains reach into cold climates. In the Himalaya–Karakoram–Hindu Kush (HKH), conditions and ecosystems at lower as well as higher elevations vary markedly according to prevailing weather systems, degrees of rain shadowing, topography, steepness and orientation.

In the Karakoram, great height, elevation range and the sheer extent of high altitude terrain are decisive for the distribution of snow and ice. Such conditions are, therefore, pivotal throughout this book. Verticality will be looked at first as it relates to relevant dimensions of glacierised areas and, especially, glacier basins.

2.3 A Main Set of Glaciers

With respect to size, Karakoram glaciers will be treated in four groups. The first three groups are valley glaciers. Those called 'large' have main ice streams longer than 40 km, which also involve basin areas exceeding 400 km^2. There are twelve of these in total. 'Intermediate' glaciers are between 15 and 40 km in length, and 35 have been identified. Together, these large and intermediate ice masses comprise about two-thirds of the Karakoram glacier cover. The remaining valley glaciers are 'small', between 2 and 15 km long. There are probably as many as 2,000 of these, although they comprise the lesser share of total ice cover. By far the most numerous is a fourth group of 'minor' ice masses, less than 2 km in length or diameter, probably more than 7,000 in all (Williams and Ferrigno 2010). Most of these are not strictly valley glaciers, but occur in a wide variety of forms addressed in Chap. 3. They are scattered below lesser peaks and watersheds with limited areas in the perennial snow zone, or high up within the perennial frozen zone of larger glacier basins, but disconnected from main valley glaciers.

To help define some basic dimensions of glacierisation, a reference set of 42 glaciers has been chosen (Table 2.2). They are all of intermediate or large size and have basins that are 130 km^2 in area or larger, up to the maximum of Siachen Glacier at 1,400 km^2. These basins comprise about 75 % of the perennial snow and ice cover of the Karakoram. Being much thicker than the majority of smaller glaciers, they store a larger fraction of regional ice mass. They will serve, firstly, to establish area, verticality and environmental relations of the glaciers and their basins. The 'glacial zone' is treated as all areas above glacier termini. It includes, in addition to parts covered by glacier ice, seasonally thawed off-ice areas surrounding the lower glacier tongues and perennially frigid areas above, mostly too steep to support build-up of snow and glacier ice.

2.3.1 Available Relief and Elevation Range of Glacier Basins

As a whole, the Karakoram glacial zone spans more than 6,300 m vertically, that is, from the summit of K2 (8,610 m) to the lowest glacier termini which, in the Hunza Valley, reach down to, and occasionally below, 2,300 m. No individual basin spans the whole elevation range, but some are exceptional with over 5,000 m (Fig. 2.2; Table 2.3). At least 34 fall more than 3,000 m.[6]

There are dozens of small Karakoram glaciers with basins spanning 2,500–3,500 m and some that rival the larger glaciers. In the Hunza Valley, Pisan Glacier falls 5,388 m in just 11 km. Compare this with the largest valley glacier in western Eurasia, the Aletsch in the Swiss Alps, with a maximum descent of 2,540 m in 23 km. The major glaciers of the Alaska–Yukon ranges are much larger than those of the

[6]This refers to the elevation difference between termini and highest points on the basin watersheds. Few of the main connected glaciers are continuous over the full span (Chap. 3).

Table 2.2 Locations and dimensions of the main set of 42 Karakoram glaciers, of which seven drain to the Yarkand from Shaksgam River[a]

Glacier	Lat.: °N; Long: °E	Basin area (km^2)	Length (km)	River basin
Siachen	35 28; 77 01	1,400	75	Shyok–Indus
Baltoro	35 44; 76 31	1,270	62	Braldu–Indus
Biafo	35 56; 75 36	855	68	Braldu–Indus
Hispar	35 04; 75 18	785	53	Hunza–Indus
Batura	36 33; 74 37	710	59	Hunza–Indus
Chogo Lungma	35 56; 75 06	690	47	Shigar–Indus
Panmah	35 56; 75 56	680	44	Braldu–Indus
Rimo	35 26; 77 24	612	45	Shyok–Indus
Skamri	36 04; 76 08	510	40	Shaks–Yark'd
Kondus–K.	35 28; 76 39	490	36	Shyok–Indus
Chiantar	36 45; 73 43	436	51	Chitral–Indus
Braldu	36 08; 75 51	430	36	Shaksgam–Y.
Khurdopin	36 13; 75 27	415	41	Hunza–Indus
Sarpo Laggo	35 54; 76 17	390	32	Shaks–Yark'd
Virjerab	36 13; 75 38	389	36	Hunza–Indus
Terong NS	35 31; 77 24	355	26	Shyok–Indus
Yashuk Y.	36 42; 74 18	330	20.5	Chapursan–Indus
Hasanabad	36 25; 74 33	320	23	Hunza–Indus
Bilafond	35 16; 76 52	290	19	Saltoro–Indus
N. Shukpa	34 49; 77 52	280	25	Shyok–Indus
Charakusa	35 30; 76 28	265	18	Hushe–Indus
Kukuar	36 31; 74 12	225	22	Hunza–Indus
Toltar–Bal.	36 29; 74 24	205	17	Hunza–Indus
Yazghil	36 23; 75 23	220	29	Shimshal–Indus
Sosbun	35 50; 75 35	215	16	Braldu–Indus
Karambar	36 36; 74 09	205	23	Gilgit–Indus
Barpu	36 08; 74 51	198	29	Hunza–Indus
N. Gasherbr	35 50; 76 41	190	26	Shaksgam–Y.
Sherpigang	35 21; 76 55	190	20	Saltoro–Indus
Ghondo'ro	35 35; 76 22	180	21	Shyok–Indus
Momhil	36 29; 75 03	175	25	Shimshal–Indus
Singhi	35 40; 77 00	170	24	Shaksgam–Y.
Malangutti	36 29; 75 13	170	22	Shimshal–Indus
Urdok	35 45; 76 45	162	26	Shaksgam–Y.
Gyong	35 08; 76 59	160	16	Saltoro–Indus
Chong Khum	35 12; 77 33	155	21	Shyok–Indus
Sokha Lungma	35 56; 75 26	150	15.5	Basha–Indus
Bualtar	36 08; 74 44	140	22	Hunza–Indus
S. Shukpa	34 43; 77 47	135	21	Shyok–Indus
Gharesa	36 15; 74 58	135	22	Hunza–Indus
Kutiah	35 48; 74 58	130	18.5	Stak–Indus
Kyagar	35 39; 77 10	130	19.5	Shaksgam–Y.
Total		**15,542**	**1,312**	
Mean		**370.0**	**31.2**	

[a]The northern part of the Rimo drains across the watershed to the eastern Yarkand River

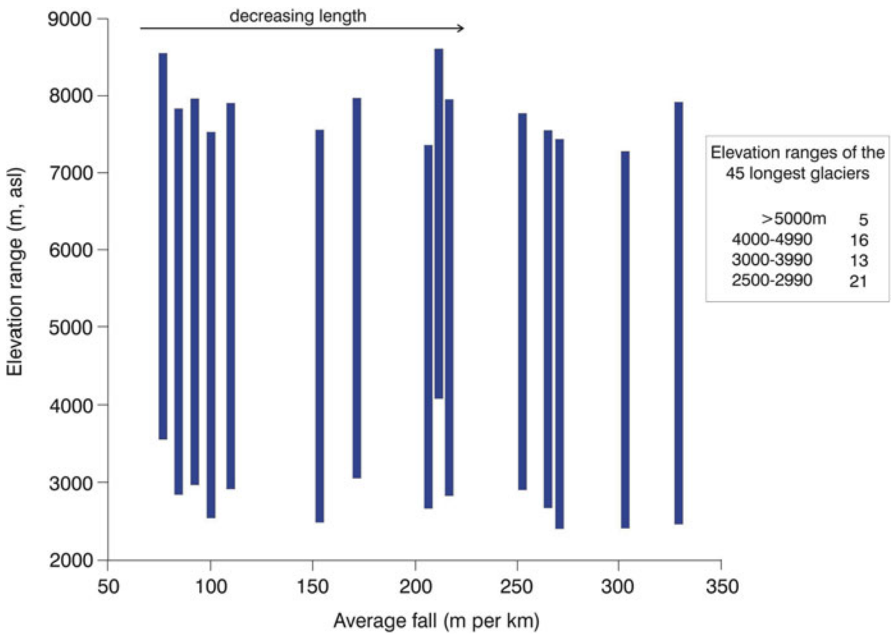

Fig. 2.2 Elevation ranges of the largest Karakoram Glaciers

Table 2.3 Elevations, elevation range and gradients of the main set of Karakoram glaciers

Glacier	Lowest elevation (m asl)	Highest elevation (m asl)	Gradient (m per km)
Siachen	3,600	7,742	55
Baltoro	3,600	8,610	81
Biafo	3,070	7,285	62
Hispar	2,950	7,885	93
Batura	2,570	7,795	86
Chogo Lungma	2,760	7,458	100
Panmah	3,500	7,285	86
Rimo	4,850	7,455	74
Skamri	3,910	7,265	84
Kondus–K.	3,320	7,665	136
Chiantar	3,600	6,245	52
Braldu	3,540	6,477	73
Khurdopin	3,200	7,760	111
Sarpo Laggo	3,900	7,360	124
Virjerab	3,540	6,477	74
Terong NS	3,975	7,385	131
Yashuk Y.	3,380	6,928	173
Hasanabad	2,530	7,762	267
Bilafond	3,780	7,428	192
N. Shukpa	4,670	7,672	120

(continued)

Table 2.3 (continued)

Glacier	Lowest elevation (m asl)	Highest elevation (m asl)	Gradient (m per km)
Charakusa	3,480	7,282	211
Kukuar	2,880	7,168	185
Toltar–Bal.	2,950	7,785	252
Yazghil	3,230	7,852	159
Sosbun	3,545	6,462	182
Karambar	2,870	7,168	172
Barpu	2,835	7,453	159
N. Gasherbr	4,230	8,047	167
Sherpigang	3,510	7,742	212
Ghondo'ro	3,435	7,163	178
Momhil	2,895	7,885	200
Singhi	4,520	7,245	114
Malangutti	2,910	7,885	226
Urdok	4,260	8,068	147
Gyong	4,140	6,620	155
Chong Khum	4,700	7,530	135
Sokha Lungma	3,255	6,413	204
Bualtar	2,300	7,266	169
S. Shukpa	4,500	7,513	143
Gharesa	3,500	7,728	197
Kutiah	2,800	7,397	271
Kyagar	4,740	7,245	134
Total	**147,730**	**310,856**	**6,146**
Mean	**3,517.4**	**7,401.3**	**146.3**

Karakoram, and some that descend to or near sea level have comparable elevation ranges, but their interfluves are not so high.[7] The highest Karakoram elevations are matched in some other parts of the Himalaya, but few glaciers descend as low or have comparable elevation ranges. Two of the larger Everest region glaciers, the 12 km long Khumbu in Nepal and the 17 km long Kangshung on the Tibetan side, commence on Mount Everest (8,848 m), higher than any Karakoram glacier. But they terminate at 4,800 and 4,560 m, respectively, a vertical span of just over 4,000 m. The Pisan is shorter than either, of course, and its neighbour, the 16 km Minapin Glacier, spans 4,920 m vertically. Since lower elevations are immediately available for Everest glaciers, the main constraint must be the balance between nourishment and melting of the ice, not available relief.

In the Karakoram, on the other hand, elevation range of the larger glaciers is constrained more by available relief, or basin morphology, than nourishment. Most have long, low-angle tongues (Plate 2.2). The valleys in front of them are mostly of relatively low gradient too. Advances or retreats of some kilometres may have small effect on elevation range, meaning terminus elevations are fairly insensitive to changes in glacier mass (Plate 2.3). Similar reasons explain why termini towards

[7] The highest point is Mount McKinley (6,193 m).

Plate 2.2 The broad, relatively low-angle main ice stream of Panmah Glacier, Nobonde Sobande branch, is shown between 4,300 and 5,300 m. It is about 2 km wide and 20–30 km above the terminus and typical of the main ice mass areas of the larger Karakoram Valley glaciers. The highest peak shown is Bobisghir (6,415 m) in the centre background. The highest point in Panmah Basin is Baintha Brakk (7,285 m) and total elevation range 3,785 m

Plate 2.3 Terminus area of Panmah Glacier showing relatively low-angle tongue and river flats or outwash plain. A retreat of some 2 km between the 1920s and 2005 changed the glacier's elevation span by barely 100 m (Chap. 12)

the eastern limits of the Karakoram, and on its northern Yarkand flank, are *not* among the lowest, regardless of glacier size. The North Gasherbrum and Urdok Glaciers, for example, descending from K2 have elevation ranges of roughly 3,800 m. They terminate at just over 4,200 m. However, even if they grew by many kilometres, they would not reach as low as, say, 4,000 m or not without considerable deepening of the Shaksgam River valley. Compare them with Karambar Glacier in the western Karakoram and of similar length. Its highest point is just 7,168 m, but a terminus at 2,870 m on the upper Gilgit (Ishkoman) River gives a fall of almost 4,300 m.

The longest glacier, the Siachen, has a terminus at 3,880 m, almost 1,500 m higher than the lowest in Hunza, essentially because it is 400 km upstream of the lowest sections of the Indus River in the Karakoram. Higher in the Shyok Basin, a huge glacier like the Rimo terminates at 5,000 m.

In this regard, it is useful to compare Karakoram glaciers with those on nearby Nanga Parbat (8,125 m). Maximum elevations and available relief are even greater than in the nearby Hunza Basin, and Nanga Parbat's west flank is as steep or steeper (Hewitt 2006). The Indus is incised to a greater depth. Yet, no glacier reaches as low down as in Hunza. The Rakhiot Glacier descends almost 4,500 m, beginning at the summit, to terminate at 3,070 m. However, below where the glacier ends, the valley continues to fall steeply another 2,000 m to the Indus for a total drop of over 7,000 m in 21 km. The glacier's vertical span is constrained by ice supply and not by available relief.

This can also be put in perspective by considering the largest glaciation(s) of the Quaternary. During maximum glaciations, Nanga Parbat ice moved well down into the Indus valley, the depositional evidence suggesting a total vertical span of at least 7,300 m (Shroder et al. 1989; Searle 1991, his Chap. 11; Kuhle 2006; Hewitt 2009). It was and remains a greater range than any other valley glacier in the world – with one possible exception! A continuous 'Indus Glacier' from K2 through the Nanga Parbat–Haramosh Massif would have had a greater vertical span, or around 8,000 m. However, there is uncertainty about whether or when this existed (Shroder 1993).

2.4 Interfluves and Glaciation Limits

Topography is, ultimately, a legacy of the interaction of tectonics and erosion processes working against rock resistance. Substantial changes in relief usually take many thousands of years, if not millions. At any given time, available relief or the height of interfluves and valley floors are relatively inflexible constraints and may be regarded as essentially fixed. They intervene in the atmospheric processes that supply and remove snow and ice. In high mountains, along with orientation of watersheds, interfluve heights exercise a critical influence over the incidence and scale of glacial phenomena.

Interfluve elevations can also be used to identify thresholds critical for cryosphere developments that are, otherwise, hard to observe in rugged terrain. Five threshold features for Karakoram glaciers are identified here:

(i) *The glaciation level or threshold*: the lowest interfluve heights which support glaciers at, descending from, or at some distance *below them*. The latter needs emphasis because of the role of avalanche nourishment. The 'glaciation level' is a widely employed limit (Ostrem 1966; Benn and Evans 1998, pp. 41–43).
(ii) *The glacier-free zone*: the highest interfluve(s) *without* glaciers. In the Karakoram context, this means having no glacier ice at and descending from the interfluve *or* displaced downslope by avalanche nourishment.
(iii) The *highest suitable peak* supporting, or *not* supporting, a glacier, a term introduced by Ostrem (1966).
(iv) *The lowest reach of glacier termini*.
(v) *The greatest elevation span of glacier ice*: the glacier(s) with the largest vertical or relief range in given valleys or sub-ranges.

To arrive at some values, interfluve elevations were measured along four north–south transects. They are based on crest line or arête heights sampled in multiple short scans across interfluves using satellite imagery and, where available, good contour maps. The complexity of Karakoram interfluve topography, including ridge orientation and microclimates, means it is best to sample interfluves fairly frequently in given areas. The figures determined here involve 10–15 local ridge heights and cross-ridge conditions, along one or more interfluves within a 5 km radius at intervals of 50 km along each N–S transect. In fact, just the highest local peak proved sufficient to define the glacier level to within 200 m, a tiny percentage of available relief. Variability arises less from how one measures interfluve heights than from how terrain influences the complex relations between wind direction and deposition, scouring and redistribution by wind action and exposure to sunshine (Barry 1992, p. 82). As with the problems of 'snowlines', there is considerable local variability, but the interfluve heights themselves are fixed.

The observations identify the absence or variable local presence of perennial ice masses. The limits given are mainly defined from lesser offshoots or ranges surrounding the high Karakoram. In much of the high Mustagh Karakoram, a glaciation limit cannot be determined as such because local interfluves are well above that limit and support glaciers.

2.4.1 Illustrative Transect, East Central Karakoram

A transect in the East Central Karakoram serves to show the threshold levels identified and some of the issues they raise (Table 2.4). Ridge heights were sampled and relevant glacial phenomena recorded in a belt roughly 100 km long and up to 40 km wide, from Shaksgam River through the K2 Massif southwards to the Indus River.

Along this transect, the lowest interfluves supporting a glacier, or glaciation levels, cluster around 5,250 m on north-facing slopes and 5,500 m on south-facing

Table 2.4 Glacier thresholds based on a transect north from 2,465 m on the Indus River through the Shimshak Mountains and K2 Massif to Shaksgam River at 4,200 m (Lat: 35°16′-55′; Long: 76°15′). Where they involve particular glacier basins, they are specified

Cryosphere threshold	Elevations (m)	
Glaciers		
(i) Glaciation level	Average	Extremes
North faces	5,250	5,050
South faces	5,500	5,350
(ii) Glacier-free zone (at and below)		
North faces	5,050	
South faces	5,350	
(iii) Highest 'suitable' peak	8,610 (K2)	
(iv) Lowest glacier termini	3,050 (Biafo Glacier)	
	3,400 (Baltoro Glacier)	
	4,200 (N. Gasherbrum Glacier, Shaksgam, Karakoram north slope)	
(v) Glacier elevation spans		
North faces	4,460 (K2 Glacier–Shaksgam)	
West faces	5,210 (Baltoro Glacier)	
South faces	4,345 (Kondus–Kaberi Glacier)	
East faces	3,820 (N. Gasherbrum Glacier–Shaksgam)	
Greatest span	(8,610–3,400) = 5,210	

slopes. Extreme values show that a few glaciers occur with interfluves as low as 5,050 m but, in some south-facing slopes, are not found if interfluves are below 5,500 m. A glacier-free zone is defined at and below 5,350 m on southerly slopes and 5,050 m on northerly ones.

Where interfluves are at the glaciation level and a few hundred metres above it, only minor glaciers develop, rarely more than 1 km in diameter. The relation between ice mass elevations themselves and glaciation level is not straightforward. Minor glaciers can start at and hug the interfluve. Small aprons or flag-like tongues of snow and ice may delineate the watershed, usually on the lee flank. Equally common, however, is to find *no* glaciers at the actual interfluve. The ice masses are displaced well downslope, usually being avalanche fed, sometimes wind fed. In this transect, again according to orientation, glacier ice may commence 500–1,000 m *lower* than the glaciation limits, and some minor glaciers terminate below 4,400 m.

For many interfluves close to the glaciation level, glacier ice is interspersed with rock glaciers and in complex relations to them. Separating the two is complicated by local topography, wind and avalanche nourishment, debris covers on the ice and abundant talus. Given the complexities and neglect of the considerable numbers of rock glaciers, these questions will be addressed in a separate chapter (Chap. 11).

Ostrem's (1966) notion of a 'highest suitable mountain without a glacier' (Sugden and John 1976, p. 92; Benn and Evans 1998, p. 42) needs qualification. In the Karakoram, there are vast areas of rock wall and countless summits above the glaciation limit that do not have glaciers on them. There are plenty of summits 'without space for a glacier'. However, there is no evidence for an upper limit to glacier

Plate 2.4 A view of K2 (8,610 m) from Concordia (4,600 m), showing the vast extent of rock walls and small cover of glacier ice on this flank, which faces the prevailing winds (Hewitt 2005, see text)

formation. For example, in classic views of K2 from the south, glacier ice is virtually absent from the last 2,500 to 3,000 m below the summit (Plate 2.4). The north and northeast flanks tell a different story. Ice aprons and small hanging glaciers are within 300–600 m of the summit, therefore above 8,000 m. They reflect prevailing wind direction and wind-deposited snow on the lee slopes. Meanwhile, the base of the peak is completely enveloped in glaciers that derive most nourishment from avalanches down its rock faces. Much the same applies to nearly all peaks above 7,000 m. Windward flanks are commonly bare of ice but leeward flanks draped by perennial snow and minor ice masses. Large snow cornices and aprons at these elevations show that wind action is more critical for snow concentration than precipitation.

Nevertheless, the K2 situation shows that enough snow for glacier nourishment is available up to the highest elevations. This contrasts with Ostrem's (1966) idea, deduced mainly from conditions in Europe and North America. It may apply elsewhere in the Himalaya, reports suggesting some of the highest peaks lie in frigid deserts (Harper and Humphrey 2003). No glaciers are found on or below them because snowfall is absent or insufficient to sustain ice masses. In the Karakoram, absence of glaciers at any place above the glaciation limit is due to steep walls and high winds, not lack of snow.

As a rule, basins with higher elevations not only have greater ice covers but their glaciers penetrate to lower elevations. Glaciers surrounding massifs culminating above 7,500 m are much more extensive than around those culminating between,

Table 2.5 Glaciation limits and other relations of elevation and terrain in metres for different south–north transects across the Karakoram

Cryosphere threshold	Darkot–Karambar Pass		Hunza–Bagrot–Sost.		K2–Shimshak Mts		Rimo–Chang Chenmo	
	Lat: 36°30′–54′		Lat: 36°00′–44′		Lat: 35°16′–55′		Lat: 34°30′–35°30′	
	Long: 73° 31′		Long: 74° 32′		Long: 76°15′		Long: 77° 30′	
(i) Glaciation level	Average	Extreme	Average	Extreme	Average	Extreme	Average	Extreme
North faces	4,600	4,500	4,900	4,550	5,250	5,050	5,800	4,750
South faces	5,200	5,150	5,350	5,300	5,500	5,350	6,100	5,930
(ii) Glacier-free zone								
North faces	4,720		4,800		5,000		5,960	
South faces	5,300		5,200		5,350		6,020	
(iii) Highest 'suitable' point	6,860		7,794		8,610		7,742	
(iv) Lowest glacier terminus	2,750		2,310		3,050		4,600	
Greatest span	6,860–2,900		7,794–2,700		8,610–3,400		7,455–4,850	

say, 6,500 and 7,000 m. The K2 Massif not only supports the most extensive glaciers in the region but Baltoro descends to 3,600 m and Kondus–Kaberi to 3,300 m, more than 2,500 m below the glaciation level.

2.4.2 Glaciation Thresholds Across the Karakoram

Comparing the results of three other transects, it is shown that glacier limits and thresholds vary across the range from north to south and east to west (Table 2.5). At the western margins, the glaciation level averages 4,600 m for north-facing slopes and 5,200 m for south-facing slopes. Between these and the eastern margins of the Karakoram, it rises by some 1,200 m and 900 m, respectively, or more than 1,000 m on average.

In each of the transects, perennial snow and glaciers tend to form at slightly lower elevations on east-facing slopes than west-facing slopes, and except at the highest levels, as noted, northeast slopes have the lowest descent or reach of glaciers as well as lower glaciation limits. It may reflect a combination of shading from sunlight and blow-over of snow from the dominant westerly airflow. However, in some parts of the Karakoram, these limits are lower on westerly slopes, while, elsewhere in the High Asian mountains, glaciers may commence at lower elevations on southerly slopes (Williams and Ferrigno 2010). It is a reminder that sources and quantities of snowfall and, especially, its seasonal occurrence can override the role of sun angle.

In the Karakoram, where the highest elevations occur, north versus south relations of glacierisation are reversed compared to lower watersheds and the lesser ranges. Up to about 6,700 m, the glacier cover and reach of the glacier termini are generally greater on northerly slopes. For watersheds above 6,700 m, however, glaciers on *southerly slopes* tend to be longer and to reach the lowest elevations. These relations of orientation, elevation span and descent of glaciers seem to reflect conditions critical for glacier maintenance. As noted earlier, the lowest penetration of glacier termini also depends on the depth of valley incision in different tributaries of the Indus and Yarkand.

Except for the far west of the Karakoram, all the 42 largest glaciers come from watersheds that rise above 7,000 m (Table 2.3). For these, there are no substantial differences in length or ice area in comparing pairs of glaciers that flow in almost opposite directions, for example, Biafo and Hispar, or Baltoro and Siachen, or Batura and Chiantar. Yet, these pairs of glaciers will be shown to be significantly different in morphology, nourishment and behaviour. For instance, one of each pair is predominantly avalanche nourished, the other by direct snow accumulation, also leading to differences in debris-mantled ice and flow stability (Chap. 3).

2.5 Glacier Long Profiles

The great elevation range of Karakoram glaciers goes along with steep gradients (Table 2.3). These tend to decline with glacier length, but in a very noisy way, a further reflection of constraints of available relief, ruggedness and orientation or how the snow and ice cover itself is distributed by altitude. The long profiles of three of the major ice streams with the large elevation ranges will serve to introduce the point (Fig. 2.3).

Two characteristics of these long profiles are of interest. Firstly, most of the vertical descent, some 2/3 to 3/4, is accomplished in less than 1/10 of ice stream lengths, in some of the steepest tributaries, less than 1/50th. This occurs almost entirely in the uppermost basin areas and directs attention to the prevalence of steep rock walls and ice falls there. Secondly, however, by far the longest sections lie in mid-reaches with relatively gentle gradients. Some 85 % of these main ice stream surfaces plot between 4,000 and 6,000 m and about half between 4,500 and 5,500 m. It means the greatest extent occurs in a relatively narrow part of total elevation range, although the highest *and* lowest elevations lie well above or below these midsections. In intermediate and small ice masses, steep sections usually comprise a greater part of long profiles although, typically, many of their lower tongues also have relatively gentle slope, while more than half of their descent involves steep gradients and series of extensive ice falls (Plate 2.5).

It will be necessary to address questions that arise from the large elevation range and steepness of a seemingly small fraction of the profiles, conditions

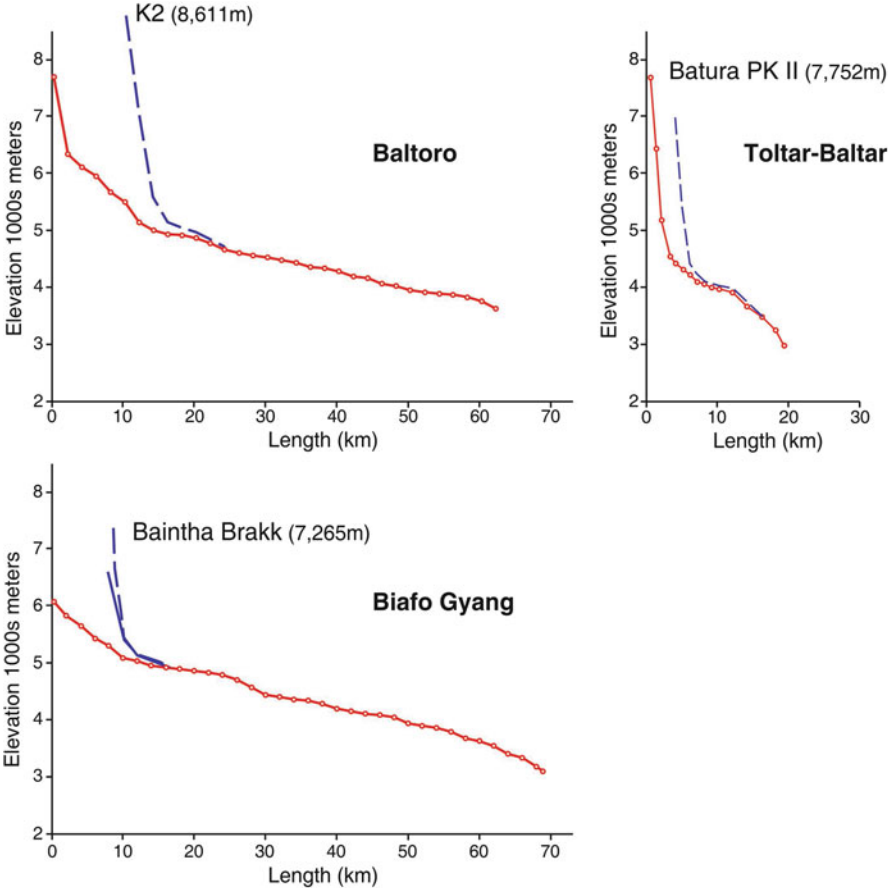

Fig. 2.3 Long profiles of three large glaciers and their major tributaries

above 5,000 m about which so little is known. The significance of ice tongues below, say, 4,000 m, which most investigations have actually focused on, seems diminished although distinctive because of the unusually low penetration of ice for the HKH region.

2.6 Steepland Properties

> Many of the mountains far above the snow-line have such sharp slants and perpendicular faces that snow will not lodge on them, and these remain bare of snow at all times…. (Workman and Workman 1905, p. 261)

Plate 2.5 Kaberi Glacier, a tributary of Kondus Glacier, EC Karakoram, showing its extensive, debris-mantled lower ice stream of relatively gentle slope and precipitous upper source areas around Chogolisa (7,665 m). It is viewed from 3,800 m and 10 km above the terminus (Hewitt July 1998)

Glacier long profiles only hint at the extent and exceptional steepness of the higher terrain in these basins. Icefalls are common and will be shown to account for the greater part of their vertical descent. Rock walls make up most off-ice areas above and below the perennial snow zone. An example will highlight something of the steepness involved.

2.6.1 Off-Glacier Slopes

The relatively good-quality 1937 Shipton (1938, 1940) survey and topographical map of Biafo Glacier Basin makes it possible to determine and sample slope angles at higher elevations.[8] Random samples of slope angles surrounding ice masses

[8]The original survey sheet held in the Royal Geographical Society's map library was used, being much more detailed than the published version (details, Hewitt 1968, I, Table 8.1, and II, Appendix 3).

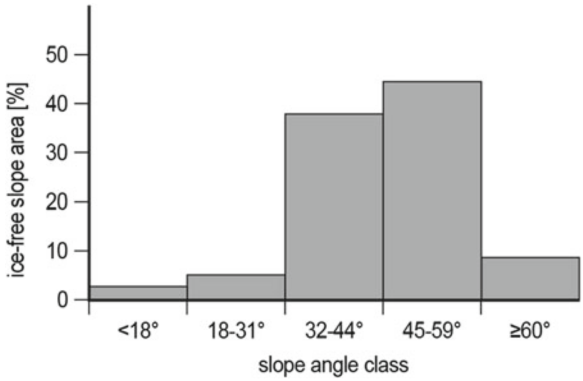

Fig. 2.4 Distribution of slope angles in off-glacier terrain of Biafo Glacier

indicate a prevailing steepness but also considerable variety. Important features that emerged were as follows:

(i) Angles in excess of 32° predominate almost everywhere away from the glacier surfaces.
(ii) Mean slope angle increases with elevation.
(iii) Above 6,000 m angles greater than 45° apply almost everywhere and those over 55°predominate.
(iv) The largest class of off-glacier slopes is between 55° and 60°.
(v) While the steepest values are more frequent at higher elevations, some occur throughout, meaning an increased spread of angles towards lower elevations, not an absence of steep cliffs there.
(vi) Northerly slopes have somewhat steeper average angles compared to southerly. Angles less than 45° are more frequent on the latter, those greater than 60°more frequent on northerly slopes.
(vii) Of the two predominant rock types, average slope on the granitics is some 13° steeper than for metamorphics. This cannot be attributed only to lithological differences. Granitics mainly outcrop above 5,000 m elevation where angles are much steeper in both rock types. Metamorphics are more prevalent below about 4,800 m where the only slopes in unconsolidated material occur.
(viii) Slopes with lowest angles are most frequent between about 3,500 and 4,800 m, representing talus build-ups which only occur below the snowline and relatively limited areas of lateral moraine and kame terrace deposits along glacier margins.

Almost 50 % of the off-glacier terrain lies between 45° and 60° and 80 % between 32° and 60° (Fig. 2.4). Most of it is so steep it cannot support glacier ice because snow cannot build up there. Such steepness also means that *actual* off-ice surface areas are two or more times greater than their map area, which is likely to be critical for interactions with atmospheric conditions, and in the downslope cascade of snow, ice, meltwater and debris.

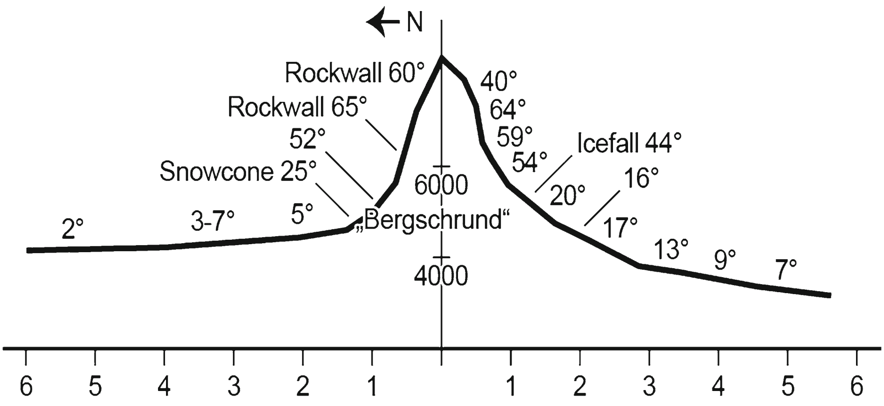

Fig. 2.5 Slope profiles around Baintha Brakk, Biafo Basin

Two profiles from the highest part of the Biafo watershed around Baintha Brakk (7,285 m) indicate what to expect in the steepest areas of the perennial snow zone (Fig. 2.5). Rock walls prevail and although veneers of snow and ice are present everywhere above 6,000 m, there is almost no glacier cover except near the base of the cliffs. Slopes are generally steeper than 55°, and areas steeper than 65° are not unusual. Avalanche flutings can develop at angles around 40–45°. Areas less than about 55° but steeper than 25° involve complicated transitions between rock wall, ice flutings, wind-shaped cornices, avalanche cones and aprons merging into glacier ice. These various elements can be difficult to differentiate or identify as more than surface forms. Nevertheless, they recur over vast areas of the upper glacier basin areas in the Karakoram (Chap. 3).

While glacier ice can stand vertically in terminal cliffs and crevasse walls, the data here suggest ice streams rarely occur with slopes steeper than about 20°. It is possible that some glacier ice occurs beneath cones and aprons of avalanched and windblown snow with surface slopes between 20° and 35°. The only obvious glacier sections occur as icefalls characterised by intense crevassing and with surface slopes between about 7° and 20°. It is of note that, like so many of these mountains, Baintha Brakk appears massive from certain viewpoints, but others show it actually consists of remarkably narrow, flake-like interfluves between steep bounding walls (Plates 2.6, 2.7, and 2.8).

2.7 Glaciers and Regional Hypsometry

The area–altitude distribution of perennial snow and ice needs to be situated within the overall hypsometry of the Karakoram. More than 80 % of the perennial snow and glacier ice cover occurs between 4,000 and 6,000 m (Fig. 2.6). Only about 10 %

Plate 2.6 The south aspect of Baintha Brakk (7,285 m) viewed from 4,100 m on Biafo Glacier giving an impression of a massive peak (Hewitt 2010)

Plate 2.7 Baintha Brakk, the right-hand peak, viewed from the east on the upper Choktoi tributary of Panmah Glacier, showing how narrow the mass is (Hewitt 2005)

Plate 2.8 Baintha Brakk viewed from the west and Hispar Pass, showing the precipitous north flank draped with snow and ice (cf. Fig. 2.5) and narrow, highest pinnacles of rock (Hewitt 2006)

of the whole trans-Himalayan upper Indus Basin is involved, about 30 % of the Indus flank of the Karakoram, and more than 50 % of its Yarkand flank. Conversely, almost 90 % of the two basins between 4,000 and 6,000 m have no perennial snow or glacier ice. This comprises lesser mountains and the high, relatively subdued, arid basin areas in the eastern part adjacent to the Tibetan Plateau. The bulk of glacier masses are found only where the highest mountains occur and descending into their immediate surrounds. Most of the ice is situated in narrow zones immediately beneath mountains that rise above 6,500 m and, overwhelmingly, above 7,500 m. This makes the true high mountain areas profoundly important in flows of the two rivers, despite a small share of the entire basin. In the hypsometric profile, the great array of high interfluves reduces to a single narrow spike, their plan areas being relatively tiny. Their significance in relation to large glaciers and the most concentrated ice cover is out of all proportion to their share of the whole Indus and Yarkand Basins.

In sum, verticality involves some seemingly contradictory features in the perennial snow and ice cover. Most of it, and the largest glacier basins, are associated with the highest watersheds. Watersheds above 6,000 m are decisive for a substantial ice cover and above 7,000 m for the larger ice masses. They are associated with glaciers having the greatest elevation ranges and lowest reach in their part of the mountains. Yet, even in these areas, the largest part of the snow and ice cover is confined, vertically, within a relatively narrow band, or less than a third of basin elevation ranges. In terms of actual glacier area and ice storage, the zone between 4,000 and 6,000 m is crucial. The next chapter explores this by looking more closely at the extent and character of glacier ice.

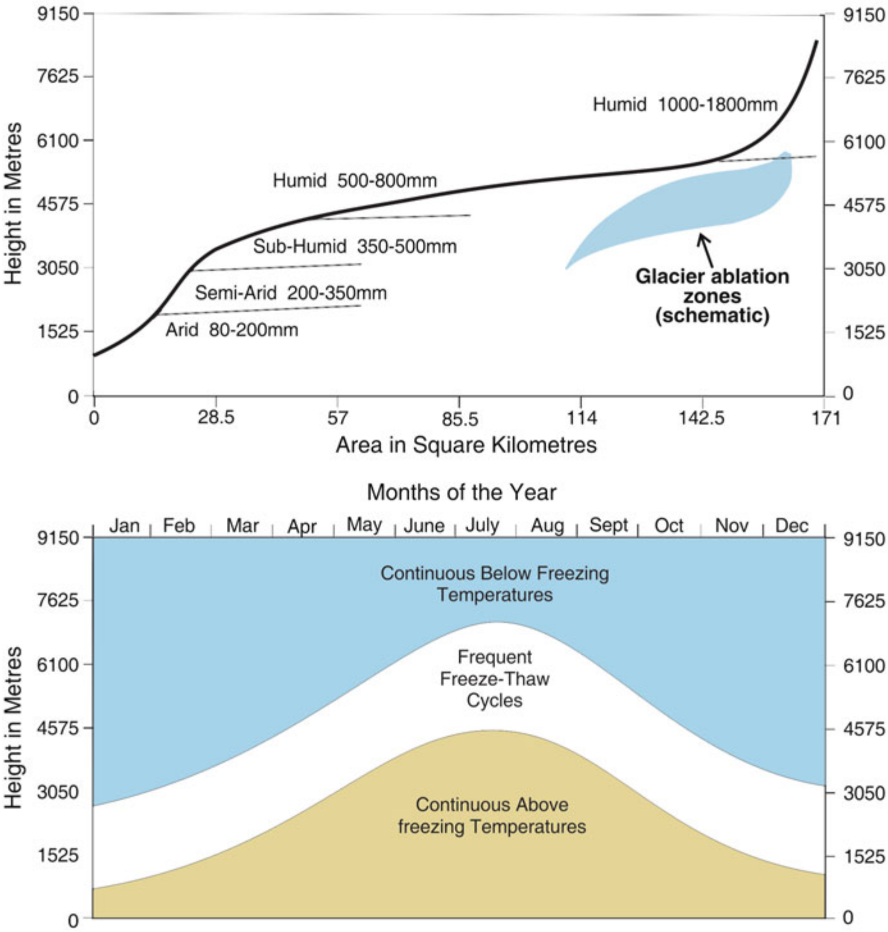

Fig. 2.6 Schematic relations of precipitation to upper Indus basin hypsometry and glacier ablation zones (above); and relations of temperature and freeze-thaw cycles to elevation (below). Both need to be considered as controls over the seasonal and perennial snow and ice cover (After Hewitt 1993)

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