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Himalayan glacial sedimentary environments: a framework for reconstructing and dating the former extent of glaciers in high mountains

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Abstract

Reconstructing paleoenvironmental change from glacial geologic evidence in the Himalayas has been difficult because of the lack of organic material for radiocarbon dating and the problems of correctly identifying the origin of highly dissected landforms. Studies of the contemporary glacial depositional environments, and ancient landforms and sediments in the Hunza valley (Karakoram Mountains), the Lahul and Garhwal Himalaya, and the Khumbu Himalaya illustrate the variability in processes, landforms and sediment types. These studies can be used to interpret ancient landforms and sediments for paleoenvironmental reconstructions, and aid in forming strategies for sampling sediments and rocks for the developing techniques of cosmogenic radionuclide (CRN) surface exposure and optically stimulated luminescence (OSL) dating. Many Himalayan glaciers have thick covers of supraglacial debris derived from valley sides, and such debris-mantled glaciers exhibit important differences from 'clean' glaciers, both in terms of debris transport processes, and the depositional landforms that they produce. Analysis of sediment-landform associations can be used to reconstruct processes of sediment transport and deposition, and the relationship between moraines and other landforms and climatic forcing cycles. Such analysis is of fundamental importance in guiding sampling and interpretation in CRN and OSL dating work. © 2002 Elsevier Science Ltd and INQUA. All rights reserved.

1. Introduction

The Himalaya and Transhimalaya mountains contain the highest concentration of glaciers outside of the Polar Regions, constituting about 50% of the total extra-Polar glaciated area (Nesje and Dahl, 2000). Glaciers in many parts of the region have undergone significant retreat in the last century (Mayewski and Jeschke, 1979; Mayewski et al., 1980; Ageta et al., 2001), a trend that is likely to continue in the coming years in response to human-induced global warming (Houghton et al., 1990, 1992, 1996). Glacier recession will alter the hydrology and rates of sediment transfer within these glaciated catchments, and increase the frequency of glacier lake outburst floods and other hazards (Yamada, 1998; Reynolds, 2000), and is thus likely to have profound affects on the densely populated areas within and adjacent to these catchments.

Much can be learned about the nature of climate change, glaciation, hydrology and sediment transfer in the high mountains of Central Asia by examining the thick successions of valley fills and landforms that are widespread within the Himalaya and Transhimalaya. In particular, the reconstruction and dating of the former extent of glaciers in these areas is essential for paleoclimatic modeling and for testing the validity of General Circulation Models (GCMs) that are used to predict future climate change. However, relatively little work has been undertaken on paleoclimatic change in Himalayan environments because of the inaccessibility of these regions and the difficulty in obtaining reliable glacial chronologies. Where studies have been undertaken, much controversy exists over the extent and timing of former glaciations in the Himalaya and adjacent mountains (Owen et al., 1998), and in particular Tibet (Zheng and Rutter, 1998). These disagreements are mainly due to conflicting interpretations of landforms that may either be of glacial or mass movement origin. These different interpretations arise partly because intense fluvial and glacial erosion often

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destroys diagnostic morphologies of glacial and mass movement landforms, making their identification difficult. Furthermore, the sediments that comprise mass movement and glacial landforms are very similar and without due care they can be easily misinterpreted, particularly because little has been published on the nature of Himalayan glacial sedimentary environments. These differ from the well-studied alpine and polar glaciers due to high relief, high activity and dominance of supraglacial processes and sediments. Some misinterpretations, however, result from a lack of geomorphic and sedimentological analysis and a desire to assign landforms to either a glacial or non-glacial origin to support a hypothesized model for glaciation. If glacial reconstructions are to be accurate then researchers must support their interpretations with convincing geomorphic and sedimentologic data to enable landforms to be confidently assigned to glacial or non-glacial processes. The main papers that discuss the nature of Himalayan glacial geomorphology and sedimentology include those by the Batura Glacier Investigation Group (1976, 1979, 1980), Gardner (1986), Gardner and Jones (1993), Goudie et al. (1984); Hewitt (1961, 1967, 1969), Shi and Zhang (1984), Zhang (1984), Zhang and Shi (1980), Higuchi (1976, 1977, 1978, 1980, 1984), Owen (1994), Owen and Derbyshire (1989), Shroder et al. (2000) and Owen et al. (2002b), and Ph.D. theses by Hewitt (1968), Owen (1988), Scott (1992) and Sharma (1996).

Dating of Himalayan glacial sequences has long been hampered by the low preservation potential of organic deposits in high-energy environments. Significant progress has been made in recent years by the application of optically stimulated luminescence (OSL) and cosmogenic radionuclide (CRN) exposure dating (e.g. Phillips et al., 2000; Richards et al., 2000a, b; Owen et al., 2001, 2002a, c; Tsukamoto et al., 2002), which allow the direct dating of glacial sediments and landforms. Both techniques, however, have associated problems (Richards et al., 2001). Some of these are inherent to the methods themselves, but others are related to site-specific factors and may be overcome by careful sampling design. Examples include the question of whether the luminescence signal in sedimentary grains has been zeroed prior to burial, and the stability of moraine surfaces chosen for CRN exposure dating. Successful application of these techniques and interpretation of the results, therefore, requires an understanding of glacial debris transport paths and the processes that form and modify glacial landforms.

In this paper we examine the nature and variability of glacial sedimentary environments in the Himalaya and Transhimalaya, drawing upon examples from throughout the region to develop lithofacies and land system models. These models can then be used to aid in identifying, dating and interpreting ancient landforms and sediments, to provide a firm foundation for paleoenvironmental reconstructions.

2. Himalayan glacial environments

The Himalaya and Transhimalaya stretch for 2000 km from Burma to Afghanistan and comprise several main ranges including the Siwaliks, Lesser Himalaya, the Greater Himalayas, Karakoram Mountains, and the Hindu Kush (Fig. 1). These ranges are influenced by two major climatic systems: the mid-latitude westerlies and

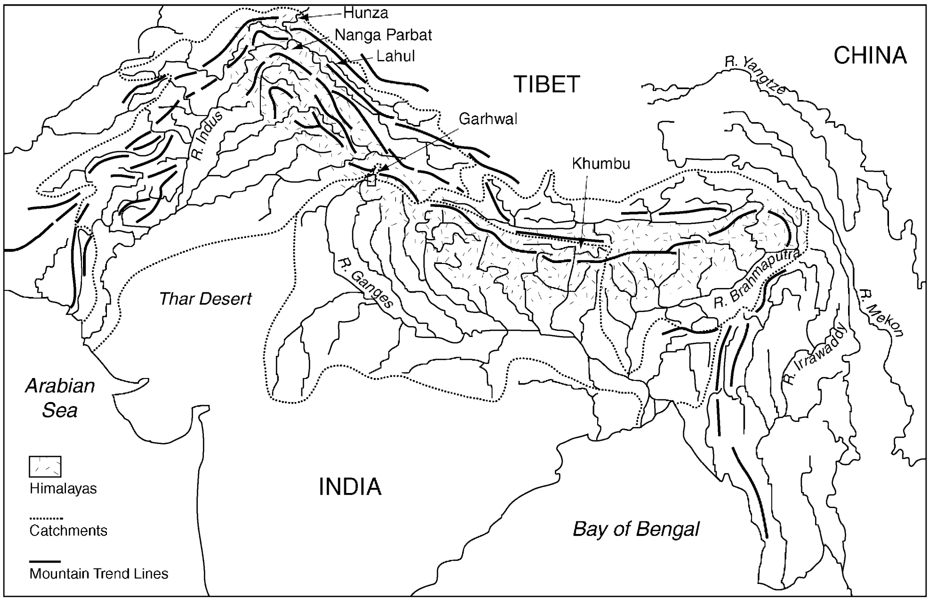


Fig. 1. Location map of study areas.

the South Asian monsoon, and significant interannual climatic variability in the region is associated with El Nino Southern Oscillation (ENSO). The relative importance of the mid-latitude westerlies and South Asian monsoon varies throughout the region (Benn and Owen, 1998). The monsoonal influence is greatest on the eastern and the southern slopes of the Himalaya, which experience a pronounced summer maximum in precipitation (and, at high altitude, in snow accumulation). In contrast, the more northern and western ranges such as the Karakoram Mountains receive heavy snowfalls during the winter with moisture supplied by the mid-latitude westerlies. The regional firn limit varies in altitude, and is 4600–5600 and 6000–6200 m a.s.l. south and north of Everest, respectively (Müller, 1958; Shi et al., 1980), 5200–5700 m in the Garhwal (Grinlington, 1912), 4500–4700 m around Nanga Parbat (Finsterwalder, 1937), 4600–5300 m on the south side of the Karakoram Mountains, and 5200–5700 m on the northern side of the Karakoram (Visser and Visser-Hooft, 1938; Su et al., 1998). Benn and Owen (1998) discussed the nature of past and present glaciation in the Himalaya in terms of the relative roles of these climate controls.

The pronounced summer precipitation maximum in the Himalaya reflects moisture advection northwards from the Indian Ocean by the southwest monsoon. Summer precipitation, however, declines sharply from south to north across the main Himalayan chain and is much higher at the eastern end of the mountain chain than in the west. Only in the extreme west is there a winter precipitation maximum, due to the influence of winter westerly winds bringing moisture from the Mediterranean, Black and Caspian Seas. Snow and ice accumulation may also vary across the Himalaya as a consequence of changing lapse rates, related to a reduction in the moisture content of air masses as they are forced over the Himalaya. These air masses have a major influence on glacier formation both regionally and on a local scale. The seasonal distribution of precipitation results in the maximum accumulation and ablation occurring more or less simultaneously during the summer (Ageta and Higuchi, 1984; Benn and Owen, 1998). These meteorological and glaciological characteristics play a large role in influencing the nature of debris transport and the depositional systems of Himalayan glaciers.

Most glaciers within the region occupy steep, high relief catchments, and have cold (mean monthly winter temperatures of $<-40°C$) high altitude ($>5,000$ m) accumulation areas and temperate ablation zones (mean monthly temperatures in the summer of $>20°C$) (Batura Glacier Investigation Group, 1976, 1979, 1980). Himalayan glaciers are highly diverse, including avalanche- and snowfall-fed cirque and valley glaciers, and very steep hanging glaciers (Benn and Lehmkuhl, 2000). On many glaciers, snow avalanching from precipitous slopes forms an important component of accumulation, and glacier ablation areas can be separated from source areas by steep icefalls or avalanche tracks. Basin topography, therefore, plays an important role in determining glacier geometry and mass balance. As early as 1856, Adolf Schlagintweit (cited in Kick, 1962) used the term "*firnkessel*" glaciers that are fed predominantly by avalanche from high cliffs in the high mountains of Asia as opposed to the *firnmulden* types in the Alps that are nourished by slow ice flow from a firn field, and a comprehensive glacier classification scheme based on mass balance and topographic criteria was proposed by Schneider (1962). Benn and Lehmkuhl (2000) provide a recent review of the mass balance characteristics of Himalayan glaciers.

3. Debris entrainment and transport

Many Himalayan glaciers have extensive mantles of supraglacial debris on their ablation zones, whereas others have little or no supraglacial debris. The latter are sometimes termed 'clean' (or C-type) glaciers, to distinguish them from debris-mantled (or D-type) glaciers (Moribayashi and Higuchi, 1977), although a spectrum of glacier types exists between these end members. The distinction between debris-mantled glaciers and glaciers with less extensive debris cover, however, remains a useful one. The amount of debris cover on glacier surfaces is controlled by a number of factors, the most important of which is the distribution of steep slopes in the glacier catchment, from which avalanches can deliver rock debris, either from bedrock or pre-existing glacial and paraglacial sediments. Other factors influencing debris cover include: (1) precipitation, which governs the amount of snowfall relative to rock inputs, and hence the debris concentration in the ice; (2) glacier size (long valley glaciers are most likely to have extensive debris mantles); and (3) bedrock erodibility (resistant, massive rocks such as granite will yield much less debris than highly fractured schists and sedimentary rocks).

The nature of supraglacial debris on Himalayan glaciers has been examined by several workers who have concentrated their efforts on the glaciers in the Himalaya and Karakoram Mountain in Northern Pakistan (Kick, 1962; Owen, 1988; Scott, 1992; Bishop et al., 1995, 1999) and the Khumbu Himal of Nepal (Inoue, 1977; Moribayashi and Higuchi, 1977; Iwata et al., 2000). Bishop et al. (1995, 1999) and Shroder et al. (2000) highlighted the importance of supraglacial debris cover in the glacial system using SPOT panchromatic imagery to map the surface of the Rakhiot Glacier distinguishing debris-free zones, and areas of shallow debris on white ice, moisture-laden debris, thick debris on topographic highs and thick debris on topographic lows. Scott (1992) and Owen et al. (2002b) illustrated how debris is modified by mass movement and glaciofluvial processes as it is transported supraglacially, and they provided measurements of the thickness and texture of the supraglacial debris on the Rakhiot. Figs. 2–4 illustrate the extent and characteristics of supraglacial debris on the Rakhiot and Bahzin Glaciers.

Much of the supraglacial debris on Himalayan glaciers is derived from valley sides, either falling directly onto the glacier ablation zones, or undergoing intermediate englacial transport following burial by snow or ice or entrainment in crevasses (Fig. 5). However, debris of basal origin is locally important in the supraglacial debris load of some glaciers. Fig. 6 shows summary clast form data from Batal Glacier, a debris-mantled glacier in the Lahul Himalayas, India. Much of the debris on the glacier surface is coarse-grained, and angular or very angular (A + VA = 94–98%, where A and VA are the angular and very angular clasts, respectively), with mainly slabby or elongate forms (C40 = 90–98%, where C40 is percentage of clasts with a *c*-axis:*a*-axis ratio $\leqslant 0.4$), and no striated clasts (Fig. 5), characteristics typical of passively transported rockfall or avalanche debris (Benn and Ballantyne, 1994). In places, however, discontinuous longitudinal ridges of diamictic debris occur on the glacier surface, reflecting the melt-out of medial debris septa (cf. Boulton and Eyles, 1979). This debris contains fewer

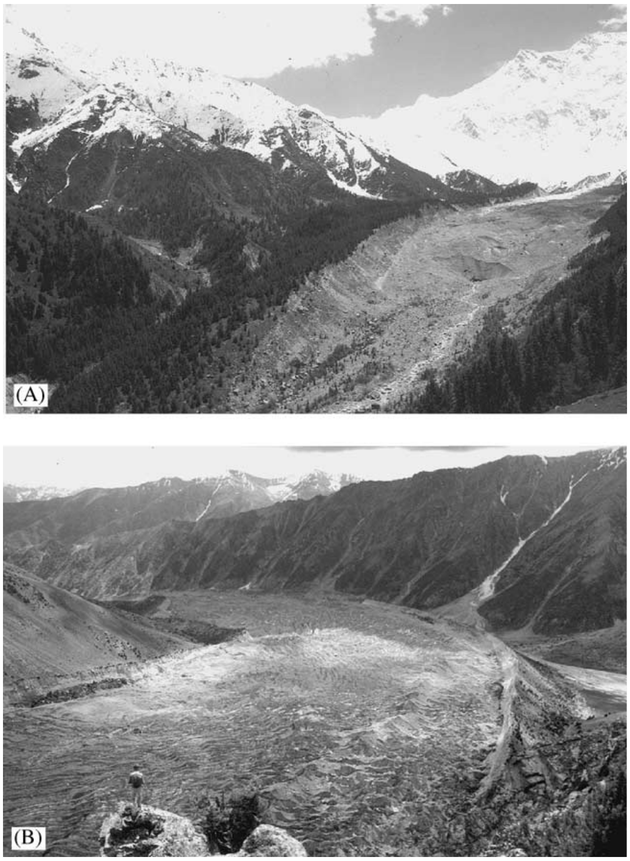


Fig. 2. Views of Nanga Parbat Glaciers. (A) View looking south at the Rakhiot Glacier showing the thick lateral moraines and abundant supraglacial debris. (B) View looking SW down the Bahzin Glacier showing the extensive supraglacial debris cover and impressive lateral moraines.

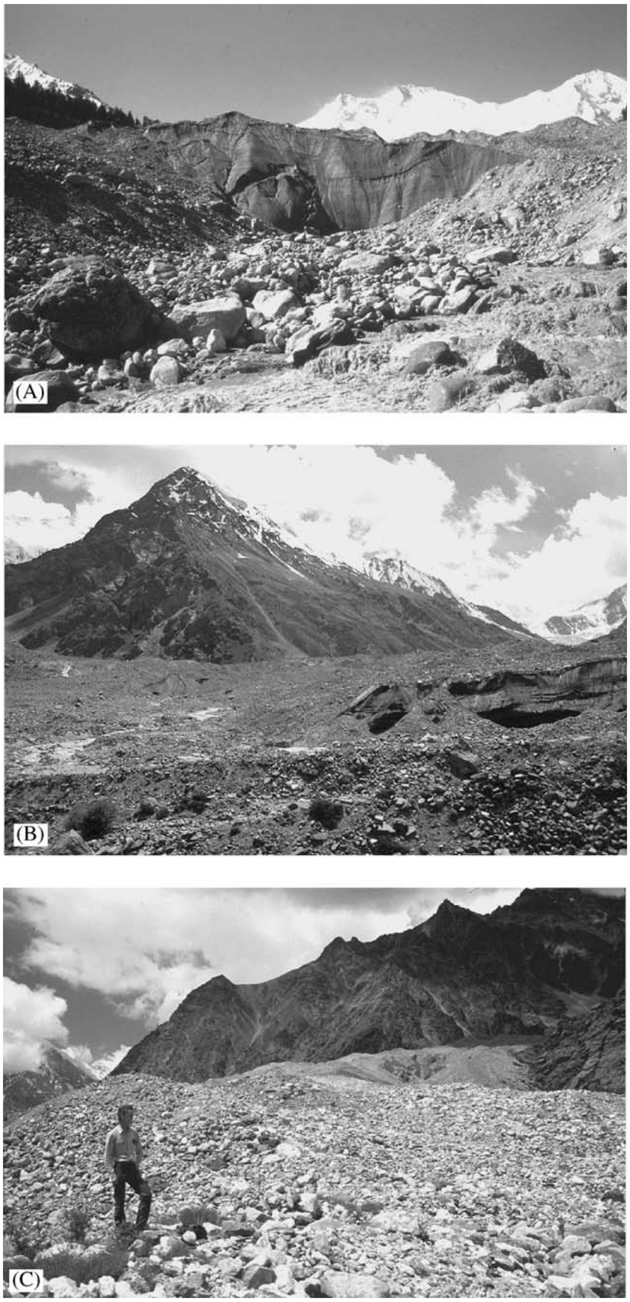


Fig. 3. Views of supraglacial environments on Nanga Parbat Glaciers. (A) View looking south at the snout of the Rakhiot Glacier showing the debris cones that are produced as the ice melts and glaciofluvial reworking. The width of the exposed ice in this plate is about 120 m. (B) Supraglacial debris on the surface of the Bahzin Glacier. The field of view in the middle of the plate is several hundred meters. (C) Close-up view of supraglacial debris on the Bahzin Glacier.

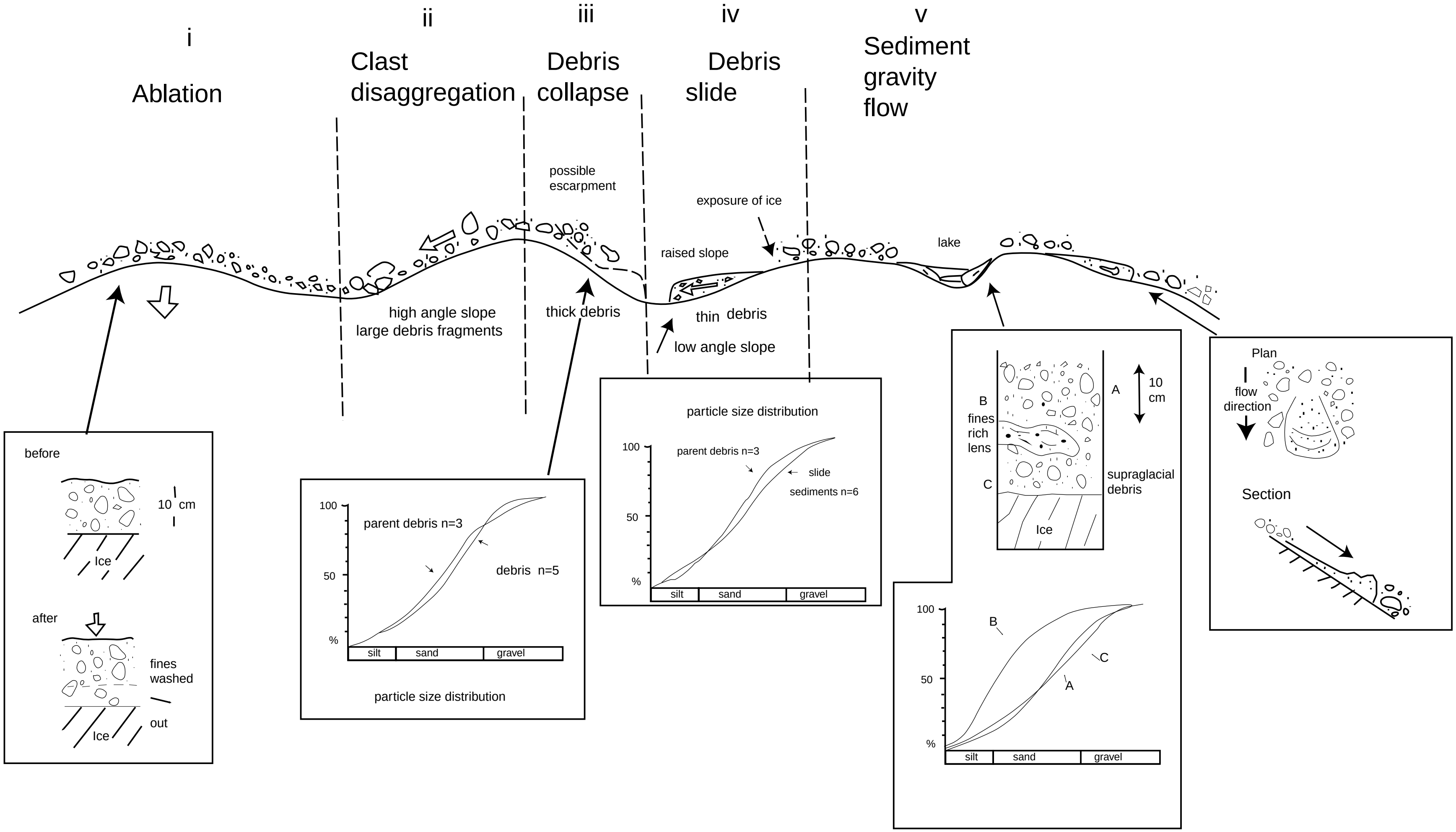


Fig. 4. Processes, particle size characteristics and sedimentary facies associated with supraglacial environments on a Nanga Parbat Glacier. After Scott (1992).

Fig. 5. Englacial debris bands, parallel to the sedimentary layering of the glacier, melting out to form a supraglacial debris mantle, Ngozumpa Glacier, Khumbu Himal. The supraglacial debris layer is c. 2 m thick.

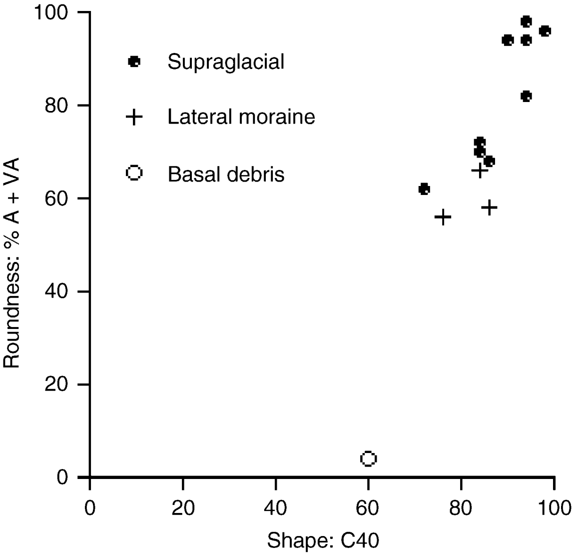


Fig. 6. Summary clast characteristics of debris from Batal Glacier, Lahul. C40 is the percentage of sample with a *c*-axis:*a*-axis ratio $\leqslant 0.4$ (slabby and elongate clast shapes); % A + VA is the percentage of angular and very angular clasts in the sample. Each point represents 50 clasts.

angular and very angular clasts (A + VA = 62–82%), fewer slabby and elongate clasts (C40 = 72–94%), and varying amounts of striated clasts (6–14%), indicating that it represents mixtures of rockfall/avalanche debris with debris of basal origin, probably elevated along medial flowlines (cf. Boulton, 1978; Benn and Evans, 1998). A sample of basal debris from the glacier (see below) is shown for comparison (A + VA = 4%, C40 = 60%, striated clasts = 68%). Clast samples from the north lateral moraine of the glacier also appear to be mixtures of actively and passively transported debris. Lateral moraines are likely to contain more actively transported debris than the supraglacial debris mantle as a whole, due to the occurrence of bed-parallel debris septa around the glacier margins.

Few occurrences of basal debris-rich ice have been reported from the Himalaya, in part due to the obscuring effects of supraglacial debris mantles. Two examples are shown in Fig. 7, from Batal Glacier, India, and Naktok Glacier, Khumbu Himal, Nepal. The Batal example consists of a series of discontinuous, subhorizontal bands of debris-rich ice that crop out at the glacier terminus, between 1 and 11 m above the bed. The bands cut across the primary (sedimentary) foliation of the glacier. Some are arranged *en echelon* and are overhung by the superjacent ice, suggesting differential motion has occurred along them. The presence of primary ice foliation below the debris bands indicates that they were not elevated from the bed by basal freeze-on processes, but that they consist of basal debris elevated along thrust planes. Fig. 7b shows the margin of the north-facing Naktok Glacier, at c. 5200 m. The basal zone of the glacier consists of stratified debris-rich ice, which is typically 1 m thick but is locally folded and thickened to c. 3 m. At the time of observation (October 1998) the basal debris was frozen, and the glacier margin (which is very steep) is thought to be perennially frozen to the bed. The basal debris, therefore, is likely to have originated by subglacial freeze-on. Although these two examples are by no means comprehensive, they do show that basal debris contributes to the sediment budget of some Himalayan glaciers, although the contribution is typically small compared with the supraglacial component.

Supraglacial debris significantly modifies the mass balance of many Himalayan glaciers (Batura Glacier Investigation Group, 1980; Nakawo and Rana, 1999; Benn and Lehmkuhl, 2000). Debris thicker than ~5 cm reduces ablation of the underlying ice below that for clean ice, and below thick debris (> 1 m) ablation rates are very small. Therefore, ablation in debris-covered areas tends to be focused where bare ice is exposed, particularly in slump scars around moulins and crevasses, or around the margins of supraglacial lakes (Sakai et al., 1998, 2000; Benn et al., 2001). The growth of temporary supraglacial lakes, by a combination of melting and calving, is a particularly important process of ablation on many glaciers. The predominance of ice-face retreat (or *backwasting*) as an ablation mechanism has important implications for supraglacial sediment dynamics. During ice-face retreat, supraglacial sediment exposed at the top of the slope is destabilized, and falls, slides or flows down the ice and accumulates at the slope foot (Fig. 5). Measured backwasting rates lie in the range 2–14 cm day^{-1} (Sakai et al., 1998; Benn et al., 2001). Because almost all of this ablation occurs during daylight hours, there is a high probability that sediment grains in the supraglacial debris mantle will be exposed to light optically bleached during backwasting. Indeed,

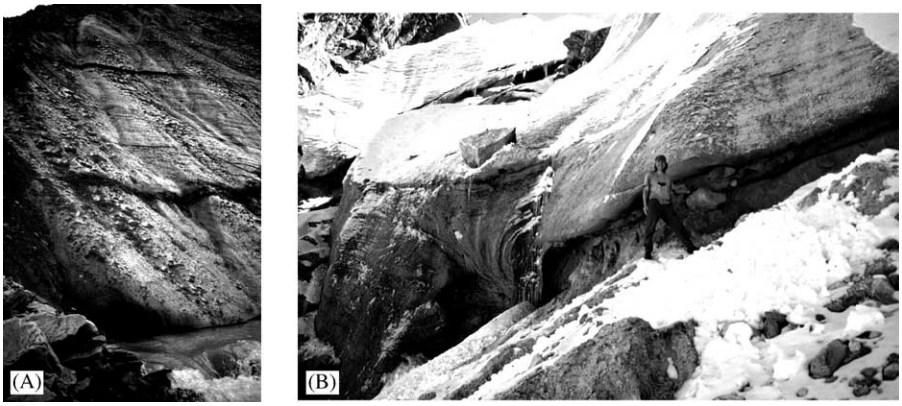


Fig. 7. Examples of basal debris. (A) Batal Glacier in the Lahul Himalaya; (B) Naktok Glacier in the Khumbu Himal.

debris may undergo several cycles of backwasting and topographic inversion during transport over the glacier, further increasing the suitability of sediment deposited by debris-mantled glaciers for OSL dating.

4. Depositional environments and facies

Deposition at and close to the margins of Himalayan glaciers results in a wide range of sediment-landform associations (Li et al., 1984; Owen, 1988, 1994; Owen and Derbyshire, 1989). An important distinction exists between (1) glacier systems dominated by extensive, thick mantles of supraglacial debris, which typically produce massive, complex latero-frontal moraines and steep outwash fans, and (2) relatively 'clean' glaciers, which typically deposit smaller moraine loops and outwash plains superimposed on subglacial bedforms such as roches moutonnées and flutes. Owen and

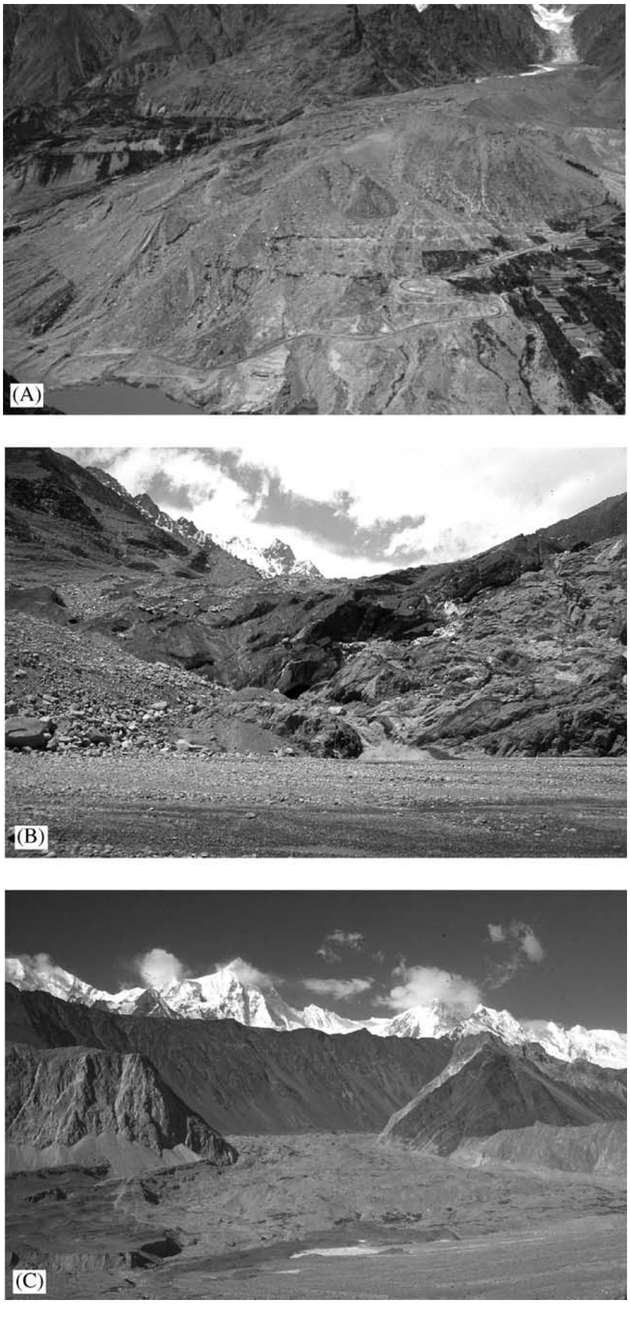


Fig. 8. Views of debris-covered glaciers in the Karakoram Mountains. (A) Oblique aerial view of the Ghulkin Glacier in the Hunza valley showing the main characteristics of latero-frontal dump moraines and ice-contact fans. The active glacial ice can barely been seen under the thick supraglacial debris. Note the large glaciofluvial outwash fans and large debris flows and slides that constitute much of the landform. Fig. 10 shows a lithofacies and land systems' model based on this glacier. The glaciofluvial meltwater channels peroidically switch back and forth across the front of the Ghulkin Glacier. The most recent and active channels and fan when this photograph was taken is present in the upper right corner. A spring line is apparent along the ice-contact fan picked out by the occurrence of vegetation below. The Karakoram Highway, which runs along the margin of the ice-contact fan, provides a scale. (B) View looking west at the snout of the Pasu Glacier showing ice scoured bedrock to the right and a minor terminal moraine to the left. The view of field is approximately 250 m. (C) View looking west–northwest at the Batura Glacier flowing into the Hunza valley. The limit of active glacial ice is approximately coincident with the exit of the tributary valley and the rock buttress on the left. The hummocky light colored debris in the foreground is essentially dead ice covered in thick supraglacial debris. The glacier is about 1.5 km wide at this location.

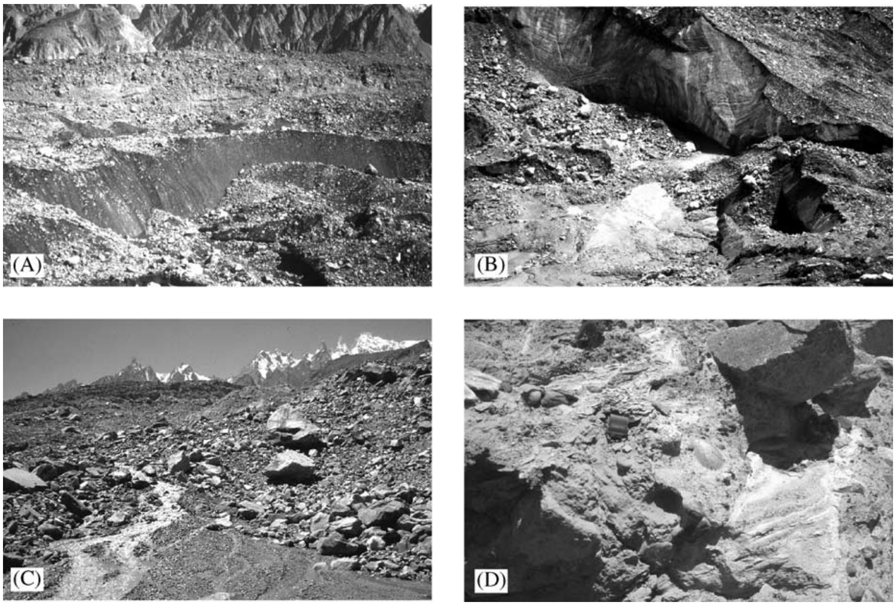


Fig. 9. Glacial sediments on and adjacent to the Ghulkin Glacier. (A) Supraglacial debris on the surface of the Batura Glacier. The field of view in the lower part of the frame is approximately 30 m. (B) Supraglacial meltout, debris flows and lacustrine sediment on the surface of the Ghulkin Glacier. The field of view is about 20 m. (C) View of an active glaciofluvial channel eroding thick supraglacial till that comprises the main frontal moraine. Note the steep gradients and angular nature of the cobble and boulders. The stream is about 3 m wide at this location. (D) Section in part of a lateral moraine showing supraglacial till and a small glaciofluvial channel fill. The roll of sticky tape is about 4 cm in diameter.

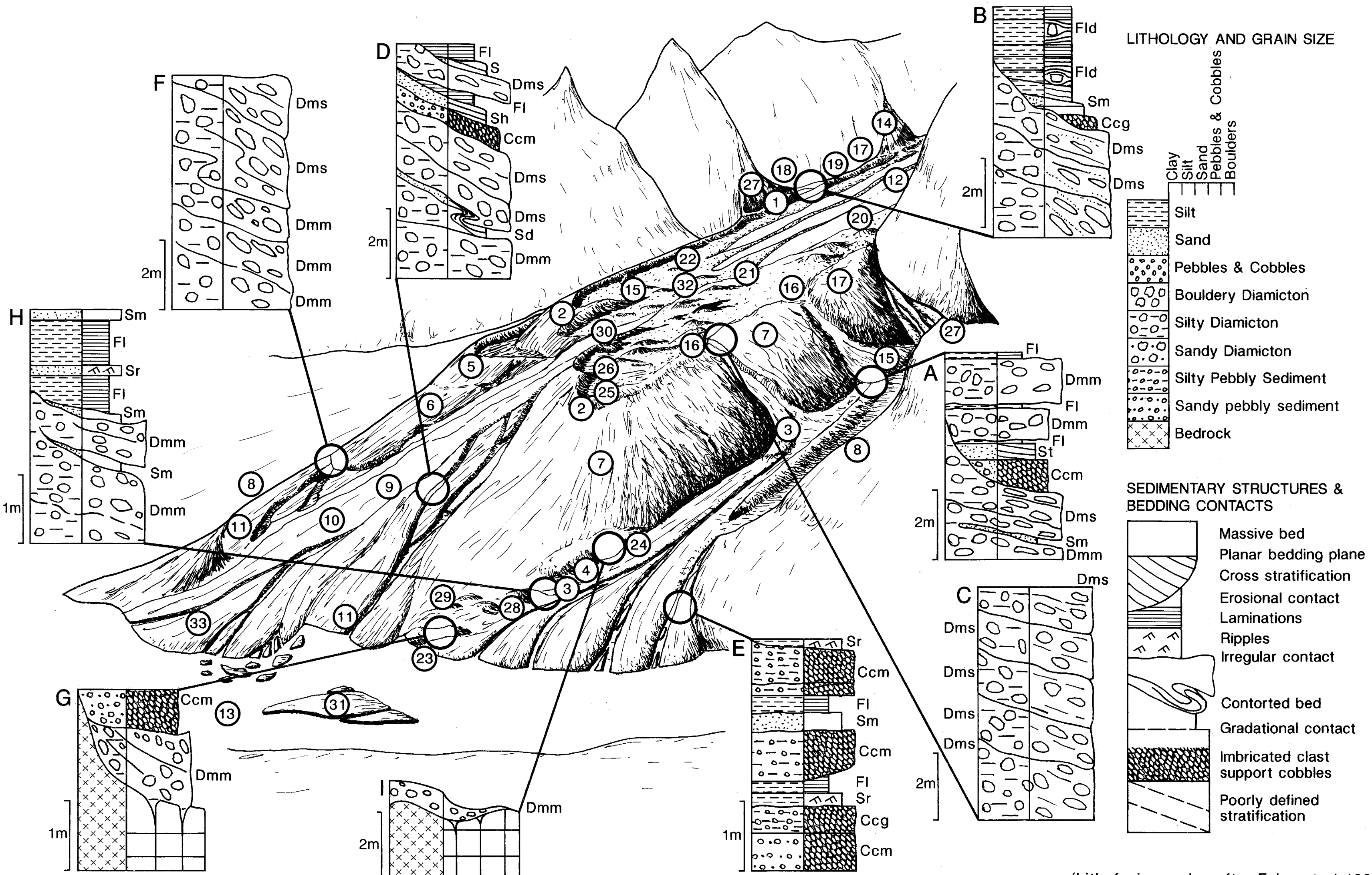
Derbyshire (1989) identified type localities for these two end-members in the Hunza valley of the Karakoram Mountains, Northern Pakistan, naming them *Ghulkin type* and *Pasu type* glaciers, respectively (Fig. 8). A continuum of forms exists between these glacier types. Additionally, the gradient and topography of glacier forelands exert an important control on depositional landforms: with increasing gradient there is a transition between moraines and glacier-fed avalanche fans. Glaciers that terminate in deep gorges tend to produce impressive alluvial fans. In all cases, glaciogenic deposits are subject to rapid reworking by mass-movement and glaciofluvial processes, producing widespread paraglacial deposits.

In the following sections, we describe examples of sediments and landforms produced by debris-mantled glaciers, glaciers with limited debris-cover, and hanging glaciers, and show how an understanding of Himalayan glacial geologic environments is a vital framework for geochronogical and paleoenvironmental work.

4.1. Debris-mantled glaciers

During the ablation season, large quantities of sediment are released from the margins of debris-mantled glaciers onto glacier forelands by a combination of mass-movement and glaciofluvial processes (Hewitt, 1967). Debris accumulation rates may be sufficiently high that, during periods of positive mass balance, they may prevent forward advance of the glacier, forcing the terminus to thicken in situ. In such cases, very large latero-frontal moraines and ice-marginal aprons can form, which may be >100 m high (Benn and Evans, 1998). Owen and Derbyshire (1989) described large moraine complexes deposited by debris-mantled glaciers in the Hunza valley, termed *Ghulkin-type glaciers*. Large quantities of debris are supplied to the surface of the glaciers by avalanching and the supraglacial debris transport path is dominant (Fig. 9A and B). Debris flows and debris slides originating on the glacier surface build up thick accumulations of sediment around the glacier margin, forming large, steep end moraine complexes (Fig. 8A, 5) that are continuously modified by meltwater erosion and slope failure. Fig. 10 shows a land system and lithofacies model for Ghulkin-type glaciers, and highlights the variety of depositional environments found on latero-frontal moraines and ice-contact fans. Mass movement deposits comprise massive or stratified diamicts which are very poorly to poorly sorted, coarsely skewed and depleted of fines ($<10\%$). Boulders to pebble size clasts are generally subangular to angular and are rarely edge-rounded, faceted or striated.

The ice-distal slopes of large latero-frontal moraines are underlain by stacked diamict, and interbedded sand and gravel deposits, dipping at about 10° away from the former ice margin (Fig. 11C). Diamict units are typically massive and matrix-supported, may be several dm to several m thick, and record debris flow and slide events. Debris-flow units can sometimes be distinguished on the



(Lithofacies codes after Eyles et al 1983)

Fig. 10. Facies model for a debris-covered glacier with latero-frontal dump moraines and ice contact fans. This model is based on the Ghulkin Glacier after Owen (1994). The major landforms are listed 1–33. 1. truncated scree; 2. latero-terminal dump moraines; 3. lateral outwash channels; 4. glaciofluvial outwash fan; 5. slide moraine; 6. slide and debrsi flow cone; 7. slide-modified lateral moraine; 8. abandoned lateral outwash fan; 9. meltwater channel; 10. meltwater fan; 11. abandoned meltwater fan; 12. bare ice areas; 13. trunk-valley river; 14. debris flow; 15. flowslide; 16. gullied lateral moraine; 17. lateral moraine; 18. ablation valley lake; 19. ablation valley; 20. supraglacial lake; 21. supraglacial stream; 22. ice-contact terrace; 23. lateral lodgement till; 24. roche moutonné; 25. fluted moraine; 26. collapsed latero-frontal moraine; 27. high-level till remnant; 28. bedrock knoll; 29. hummocky moraine; 30. ice-cored moraines; 31. river terraces; 32. supraglacial debris; 33. dead ice. The lithofacies associations are labled A to H. A. outwash channel sediments and fan associated with a lateral moraine; B. lateral moraine and ablation valley sediments; C. lateral moraine sediments; D. latero-frontal moraine and glaciofluvial outwash fan sediments; E. proglacial outwash fan sediments; F. frontal moraine sediments; G. bedrock, subglacial till and outwash; H. frontal till and proglacial lacustrines; I. exposed bedrock and subglacial till.

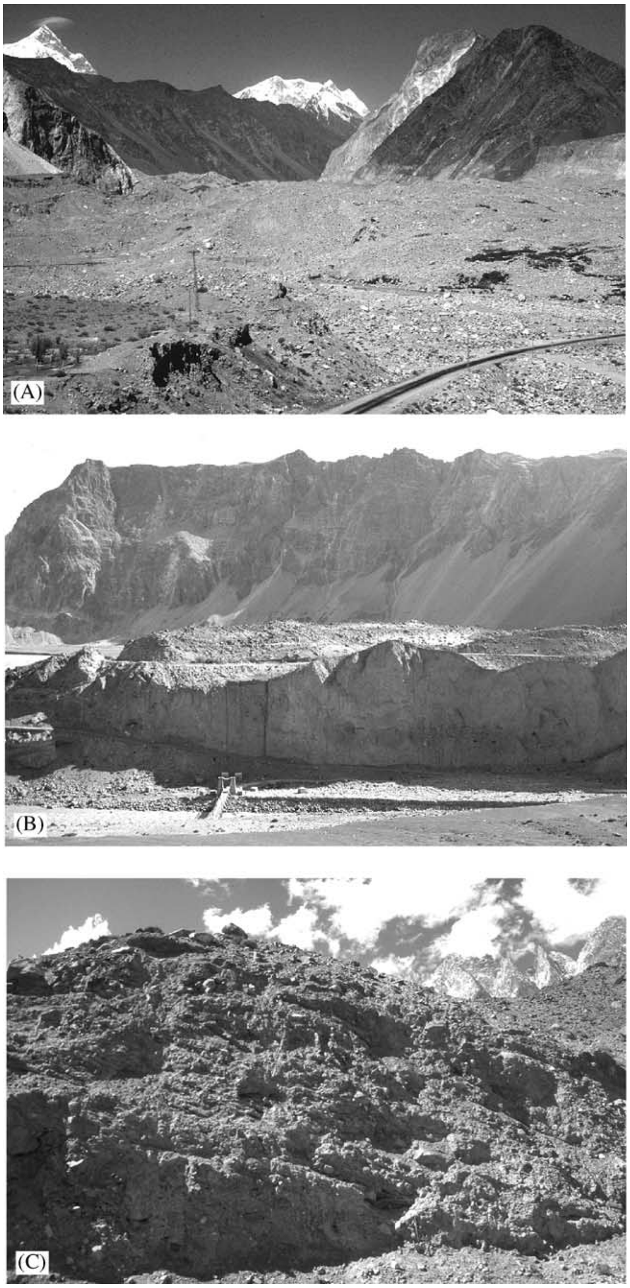


Fig. 11. Landforms and sediments of the Batura Glacier. (A) View looking westward toward the Batura Glacier showing the thick supraglacial debris melting out in the dead ice zone. The highway and telegraph poles provide a scale. (B) Section looking west though a series of ancient latero-terminal moraines of the Batura Glacier helping to illustrate how a thick succession of diamictons may accumulate due to successive accretion of moraines. (C) Section through an ancient terminal moraine of the Batura Glacier. The down glacier side is to the right of the plate. Note that the dip of the stratified diamict is to the right of the plate down the former ice front.

basis of basal clast concentrations (reflecting the sinking of large clasts through weak, saturated sediment), and overlying sand and silt layers or stringers (reflecting dewatering and glacifluvial reworking following deposition). Glaciofluvial sediments tend to become a progressively more important component of latero-frontal moraine complexes with increasing distance from the former ice margin.

The ice-proximal parts of latero-frontal moraines may be underlain by subglacial tills, including melt-out tills, which can be exposed where moraines have been deeply eroded following deglaciation. Subglacial till deposits are typically matrix-supported bouldery diamicts and may form massive and/or stratified meter-thick beds (Figs. 12 and 13). Till sediments are very poorly to poorly sorted and are coarse-skewed, but they tend to be finer grained than the supraglacial tills and mass movement deposits (Fig. 14). Furthermore, the clasts exhibit a greater degree of edge rounding and faceting and have more striations than the supraglacial and mass movement sediments. Diamicts are commonly interbedded with supraglacial lacustrine and glaciofluvial sediments, which typically form meter-size channel fills (Figs. 12 and 13). Structurally, the ice-proximal parts of latero-frontal moraine complexes tend to be complex, due to widespread collapse and reworking following the removal of ice support. Bedding is commonly contorted as a result of the meltout of buried ice or gravitational reworking (Fig. 15). Glacitectonic structures are very rare within large latero-frontal moraines, presumably because massive moraines can accommodate glacially imposed stresses without undergoing large-scale failure.

Large latero-frontal moraine complexes are very widespread in the Himalayas and Transhimalaya, including the Karakoram, Lahul, Garhwal, and Nepal. Figs. 16–19 illustrate the sedimentology and geomorphology of these moraines and Fig. 20 illustrates the particle size characteristics of the supraglacial till. A further example is shown in Figs. 11 and 15, which show sediments and landforms deposited by the Batura Glacier in the Karakoram Mountains.

Latero-frontal moraines in Ghulkin-type landsystems form continuous ramparts right around the glacier margin, and the ice margin may be elevated far above the valley floor. Such land systems tend to develop where meltwater discharges are low relative to debris fluxes, and consequently moraines form predominantly by mass-movement processes. Where meltwater discharges are higher (such as in the warm, humid environments along the southern slope of the Himalayas), glacifluvial processes may keep open a central corridor between separate lateral moraines, preventing a continuous moraine loop from forming (Fig. 21). The presence or absence of a continuous moraine loop around a glacier margin has important implications for the evolution of glacier hazards during periods of negative mass balance. Where a corridor exists between lateral moraines, meltwater can drain away freely as deglaciation proceeds. In contrast, where a continuous moraine loop is present, meltwater can remain ponded

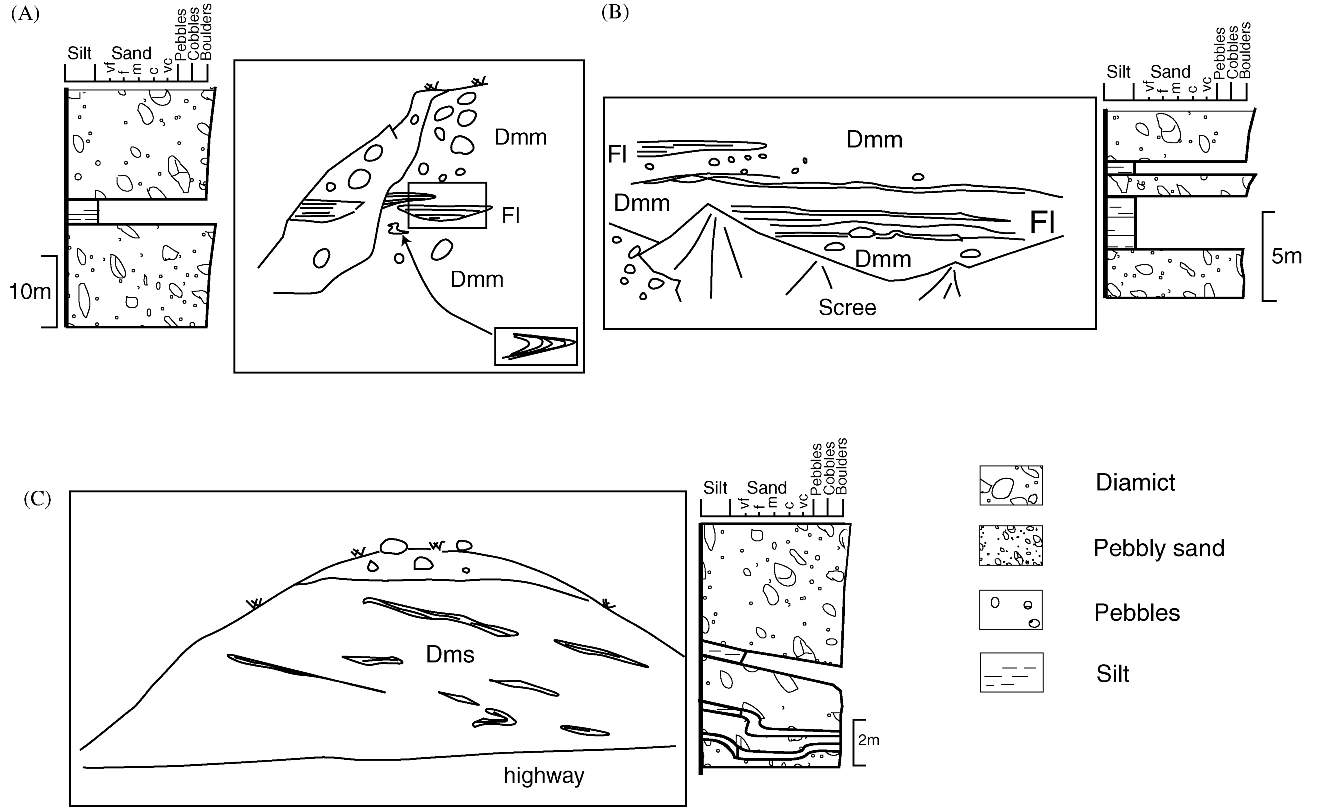


Fig. 12. Views of matrix-supported diamictons of supraglacial tills that comprise latero-terminal moraines associated with the Batura Glacier. (A) Deformed glaciolacustrine within thick massive supraglacial tills (36°29.786′N/0.74°52.381′E). The section shown in this plate is ~3 m thick. (B) Three units of supraglacial till with interbedded glaciolacustrine sediments (36°29.789′N/74°52.380′E) (C) Inclined beds of stratified diamicton and deformed glaciolacustrine silts (36°29.920′N/074°53.103′E).

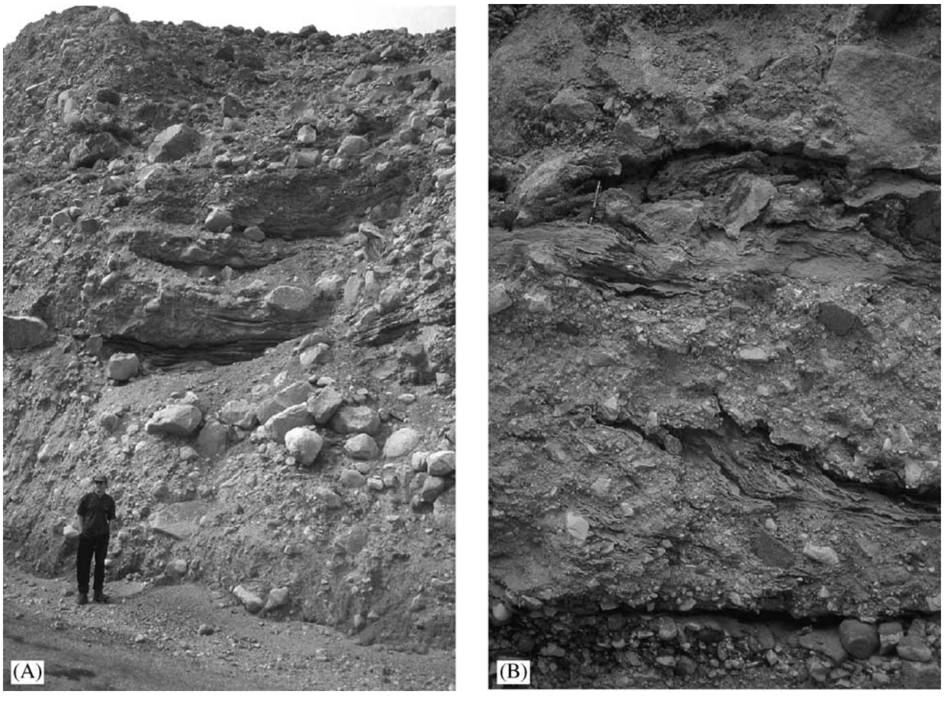


Fig. 13. Sections in latero-terminal moraines near the Batura Glacier showing the associations of channel fill sediments. (A) Supraglacial channel fills within supraglacial tills. (B) Slumped and deformed supraglacial channel fills within supraglacial till. Note pencil for scale.

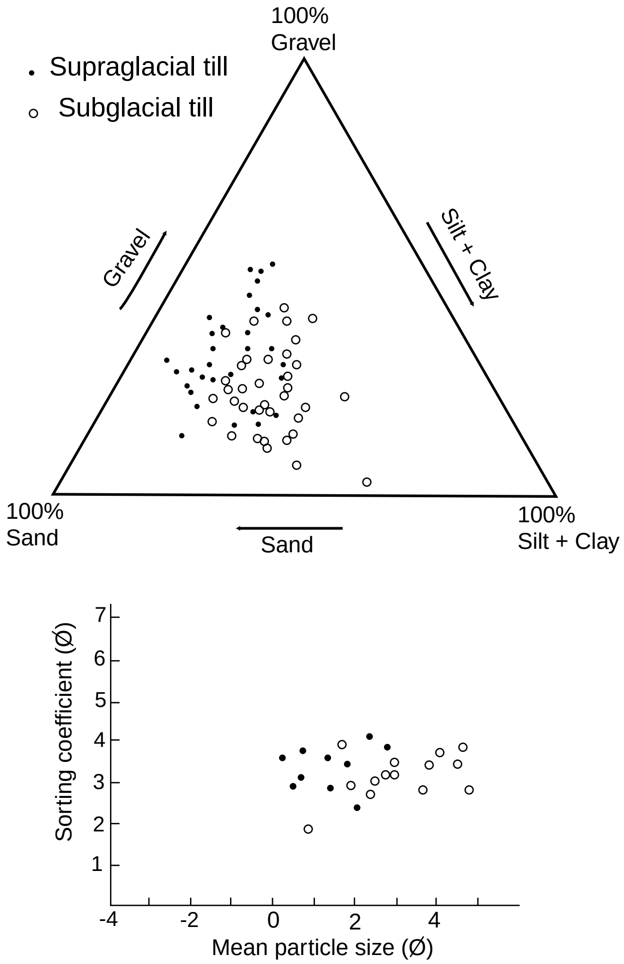


Fig. 14. (A) Ternary diagram and (B) co-plots illustrating the particle size variability of supraglacial and subglacial till from the Hunza valley. Adapted from Owen (1994).

on the glacier surface in moraine-dammed supraglacial lakes, which can attain large volumes before draining catastrophically in glacier lake outburst floods (GLOFs). Supraglacial lakes formed during glacier recession during the last few decades pose serious flood hazards in Pakistan, India, Nepal, Bhutan and China (Yamada, 1998; Reynolds, 2000; Richardson and Reynolds, 2000). Moraine ramparts that have been breached by GLOFs may appear superficially similar to lateral moraines separated by a meltwater corridor. However, sites of former GLOFs are likely to exhibit other signs of large floods downstream of the moraine, such as erosional flood tracks, imbricated outsize boulders, and terraces of bouldery diamict (Coxon et al., 1996).

4.2. Glaciers with limited debris-cover

Moraines deposited by glaciers with limited supraglacial debris cover tend to be smaller than the latero-frontal moraine complexes associated with debris-mantled glaciers, and commonly form sets of nested moraine loops recording repeated glacier advance-retreat cycles. Less extensive debris cover means that subglacial landforms, such as fluted till surfaces and ice-scoured bedrock tend to be exposed, and may form important components of glacier land systems. Owen and Derbyshire (1989) proposed a land system model for Himalayan glaciers with limited debris cover, based on the Pasu Glacier in the Hunza Valley. Landforms include lateral moraines, low-relief hummocky moraine, glacifluvial terraces, fluted moraines, and roches moutonnées. Although supraglacial debris is less abundant by comparison to Ghulkin-type glaciers, mass movement is nevertheless the predominant depositional process. Fig. 22 shows the characteristics of several sedimentary successions that were deposited by the Pasu glacier during Holocene and Pleistocene glacial advances, and highlight the complex sedimentology associated with lateral moraines. Deposition in ice-contact settings and within ablation valleys (valley-side depressions) on the ice-distal side of lateral moraines produces complex successions of supraglacial till interbedded with glaciofluvial and lacustrine sediments.

The land systems represented by the Ghulkin and Pasu models really form end members in a landform continuum, and numerous examples exist of intermediate systems. Additionally, individual glaciers may switch from Ghulkin- to Pasu-type depositional systems during glacier retreat, due to changes in glacier activity or as shrinking glacier margins become decoupled from sources of supraglacial debris.

4.3. Hanging glacier tongues

The precipitous character and large relative relief of many Himalayan catchments mean that glaciers may terminate in hanging tongues perched high above valley floors (Fig. 23). In such cases, debris released from glacier ice can only accumulate far below the glacier terminus in glacier-fed avalanche cones. The sedimentology of such cones is dominated by diamict units dipping downslope, parallel to the surface of the cone, similar to those of snow-avalanche modified talus cones. Accordingly, it may be difficult to distinguish relict glacier-fed avalanche cones from debris cones deposited by non-glacial or paraglacial processes. Other elements of the landscape, such as ice-scoured bedrock upslope, may provide useful diagnostic criteria. However, even if correctly identified as evidence of former glaciers, glacier-fed avalanche cones are likely to be poor palaeoclimatic indicators, because the equilibrium-line altitudes of hanging glaciers are difficult to determine, and may bear very complex relationships with climate (Benn and Lehmkuhl, 2000).

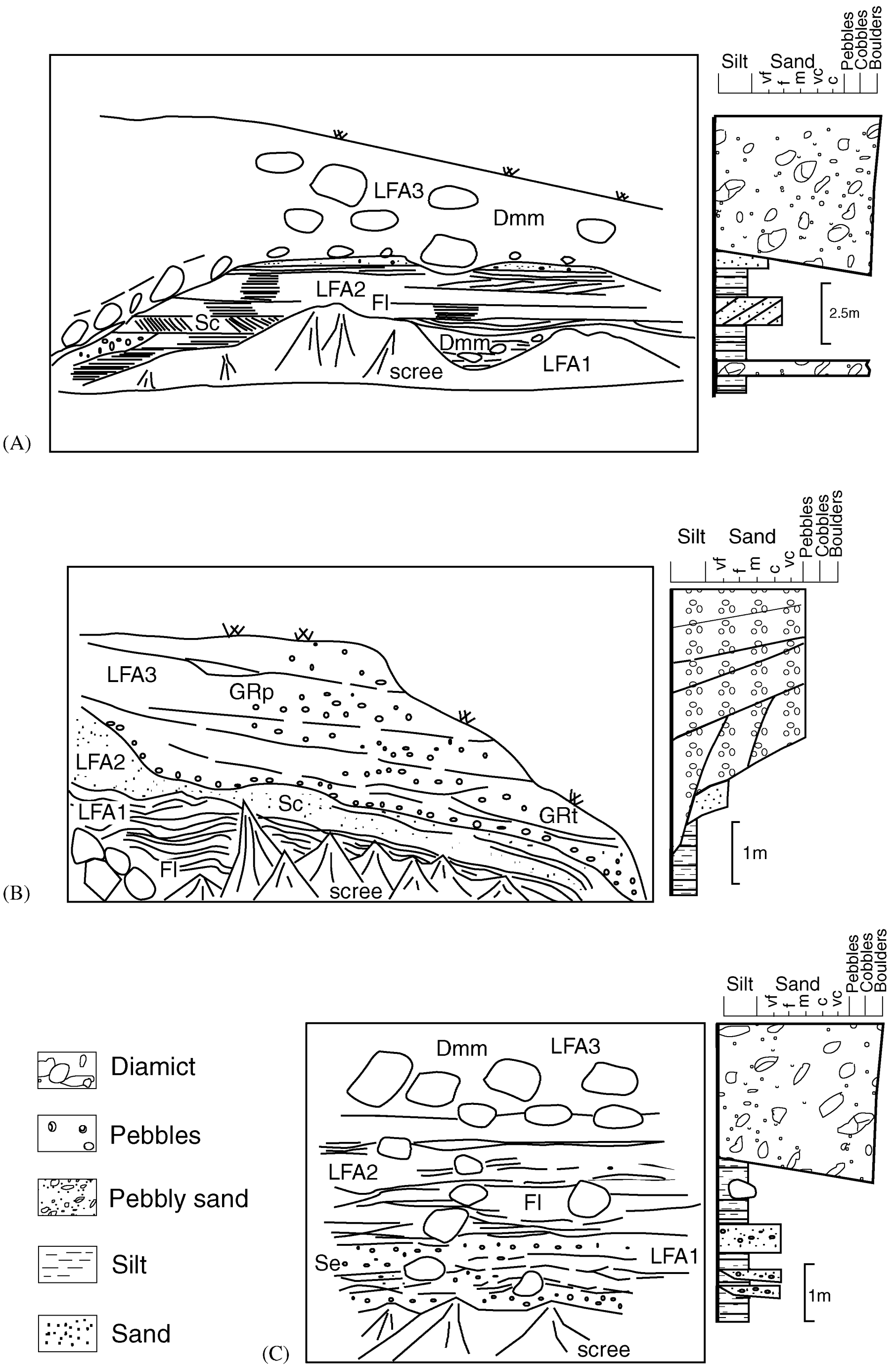


Fig. 15. Lateral and vertical graphic sedimentary logs for sections through latero-terminal moraines associated with the Batura Glacier. (A) Section through an ancient latero-terminal moraines (36°29.942′N/074°52.993′E). LFA1—stratified meter-thick bed of matrix-supported diamict. LFA2—planar cm-thick beds of silts and planar cross-stratified beds of pebbles. Some of the silt beds are slumped. LFA3—massive matrix-supported diamict with meter-size boulders. (B) Section through a historical latero-terminal moraine approximately 1 km from the present day snout of the Batura Glacier illustrating how glaciofluvial and lacustrine sediments can be a very important component of a moraine ridge (36°30.341′N/074°52.003′E). LFA1—deformed planar laminated cm-thick beds of sandy silt with occasional cm- and mm-thick beds of sand. LFA2—ripples and cross-stratified medium sands. LFA 3—cobbly and pebbly trough cross-stratified unit comprising moderately rounded boulders and cobbles in dm- and m-thick beds. (C) Section through a latero-terminal moraine near about 2 km from the contemporary snout of the Pasu Glacier (36°30.296′N/074°51.836′E) LFA1—very irregular beds of stratified subrounded pebbles and sand lenses within irregular cm- and dm-thick beds of silt. LFA2—irregular cm- and dm-thick beds of silts with occasional boulder size dropstones. LFA3—massive matrix-supported diamict comprising angular to subangular meter-size boulders in a silty matrix.

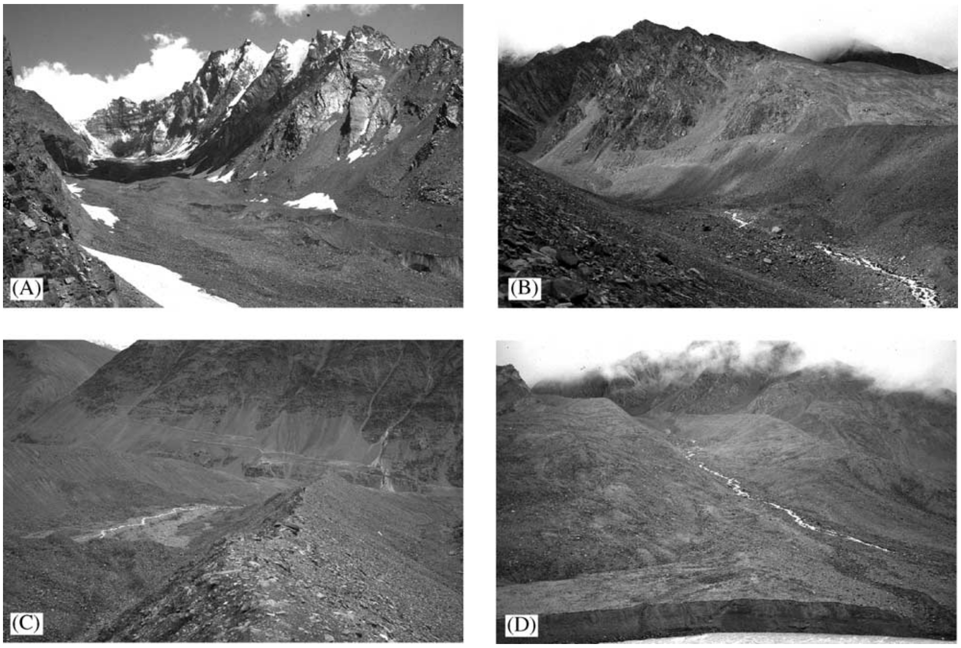


Fig. 16. Views of the Batal Glacier. (A) View looking northwest across the ablation zone showing the thick supraglacial debris. (B) View looking northwest at the snout of the Batal Glacier within lateral moraines. (C) View looking east northeast down a lateral moraine. The debris-covered snout of the Batal Glacier can be seen in the lower left corner of the plate. (D) View of the Batal Glacier inset within large lateral moraines and the prominent proglacial outwash fan that is truncated at its toe by the Chandra River. The active glacial ice is hardly visible in the photograph because of the thick debris cover.

5. Moraine formation and glacier mass balance cycles

End moraines deposited by relatively 'clean' (Pasu-type) glaciers delimit glacier advances, analogous to moraines in familiar mid- and high-latitude settings. The formation of large moraine systems by debris-mantled (Ghulkin-type) glaciers, however, reflects a complex inter-relationship between glacier mass balance and debris flux, and as a result the climatic implications of dated moraine surfaces or depositional units are not always immediately clear. Because of this complexity, it is worth examining the relationship between climatic cycles and moraine formation by debris-mantled glaciers in some detail.

The presence of a thick debris mantle inhibits melting, so that annual ablation totals tend to be highest on the upper part of glacier ablation zones, where debris cover is thin or absent, and decline with altitude as the average debris thickness increases (Nakawo et al., 1999; Naito et al., 2000; Benn and Lehmkuhl, 2000). This reversal of the ablation gradient on the lower part of glacier ablation zones means that, during times of negative mass balance, debris-mantled glaciers tend to lose less mass from the terminal zone than from higher parts of the snout. Consequently, glacier shrinkage can result in a thinning and reduction in the gradient of the snout without significant change in the position of the terminus (Naito et al., 2000). Conversely, times of positive mass balance are associated with thickening and steepening of the ablation zone, not necessarily accompanied by an advance of the terminus. Large latero-frontal moraines play an important role in these processes by acting as major barriers to glacier advance during periods of ice thickening. If the debris flux is large enough, moraine aggradation can keep pace with glacier thickening, so that through time glacier surfaces can become increasingly elevated above the valley floor, hemmed in by their own moraines (Benn and Evans, 1998). Only at times of strongly positive mass balance, when ice flux outstrips the debris flux and moraine growth, can such glaciers overtop their moraines and undergo advance (e.g. Kirkbride, 2000).

Large latero-frontal moraines, therefore, may be composite features formed during successive periods of glacier thickening at the same location (Boulton and Eyles, 1979; Small, 1983). The internal stratigraphy of such moraines may exhibit multiple unconformities separating aggradational sequences (e.g. Richards et al., 2000a). An example from the terminal moraine of the Lhotse-Nup Glacier, Khumbu Himal, is shown in Fig. 24. A deep gully through the moraine exposes stacked diamict units (debris flows) with interbedded sands and gravels (glacifluvial deposits). The sediments form four distinct aggradational packages separated by unconformities (UC1–3). The aggradational sequences are interpreted as episodes of moraine building, associated with periods when the glacier surface overtopped the moraine crest. Because deposition will

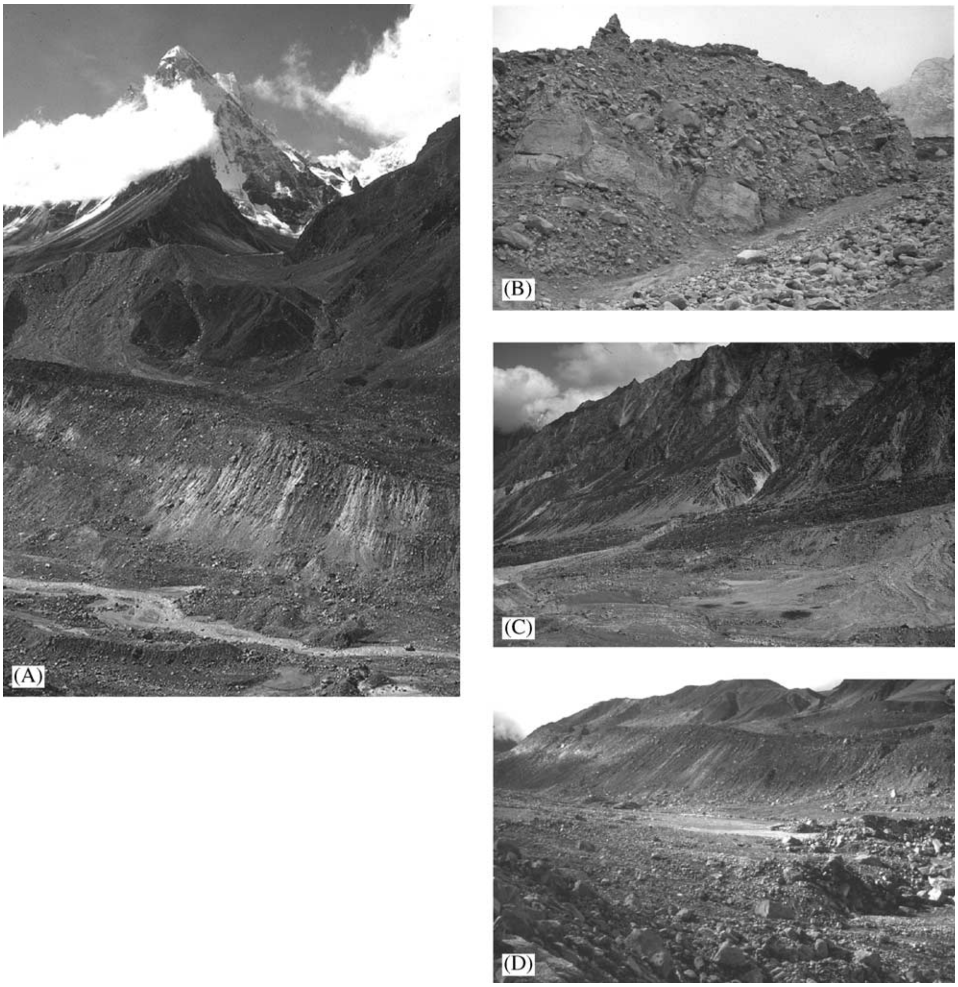


Fig. 17. Views of landforms associated with the Gangotri Glacier. (A) View looking south towards Shivling peak showing moraines produced by the Gangotri Glacier. The small hummocky moraines in the foreground were deposited when ice retreated in the 1970s. The small dots in the pale area in the bottom right corner are tents. (B) Deeply eroded lateral moraines near Gangotri showing supraglacial till interbedded with fluviolacustrine sediments. (C) View looking north at lateral moraines that are being eroded to produce paraglacial fans. (D) View looking south at hummocky moraines and outwash terraces. Large lateral moraines can be seen in the distance.

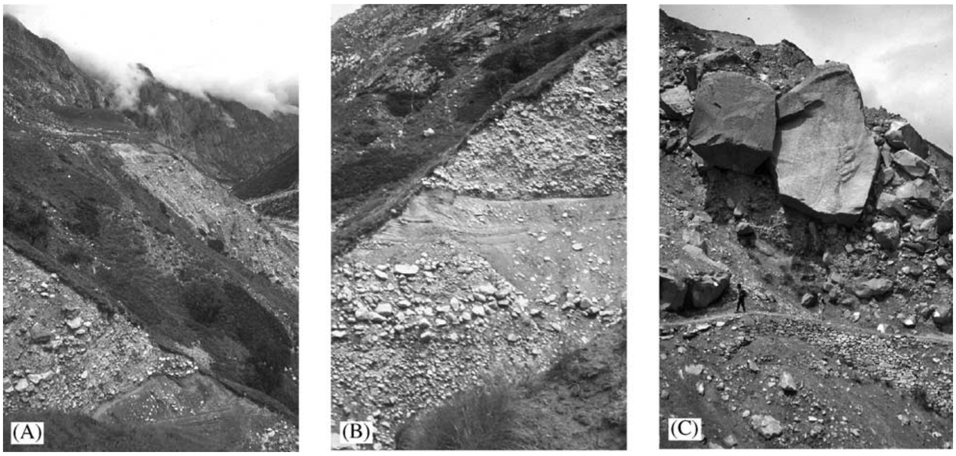


Fig. 18. Sections within lateral moraines produced by the Gangotri Glacier. (A) View looking eastwards at eroded lateral moraines ~5 km west of the Gangotri Glacier. Note how the valley side deposits have obscured morphology of the moraine ridge. (B) Section within the lateral moraines shown in part A showing an important glaciofluvial component to the lateral moraine. The section is about 12 m thick. (C) View looking east at a section in thick supraglacial diamict showing typical angular boulders supported in a silty matrix.

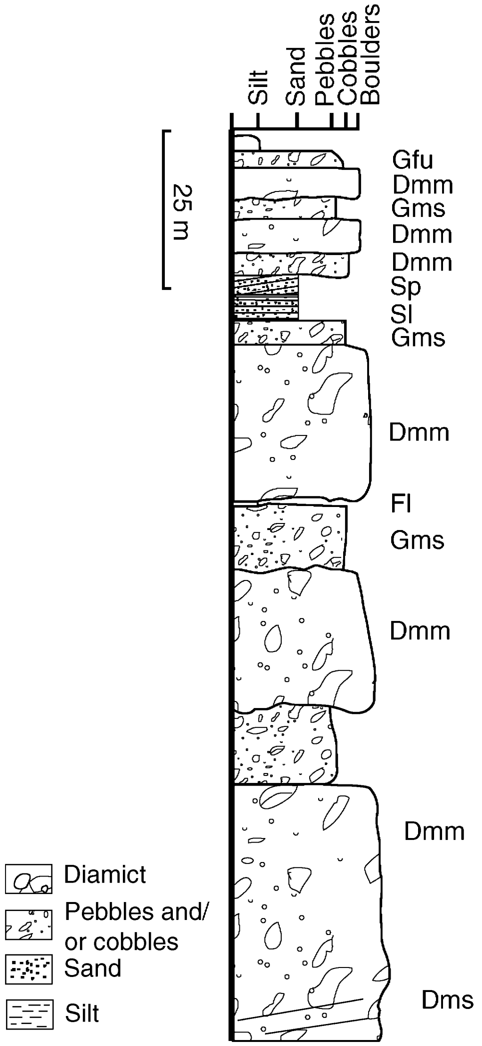


Fig. 19. Graphic sedimentary log showing the typical sedimentology associated with lateral moraines in the Bhagirathi valley.

increase the height of the moraine crest, sustained periods of moraine aggradation are likely to be associated with glacier terminus thickening and positive mass balance. The unconformities represent erosional episodes. These may occur during times when the glacier terminus has pulled back from the moraine crest, and reworking occurs without replenishment from an upslope sediment supply, or may represent localized failure of the moraine slope within a period of aggradation.

6. Dating glacial events

The newly developing techniques of CRN surface exposure and OSL dating are beginning to allow moraines and their associated landforms to be dated. The ages they provide, however, may be misinterpreted if the origin and history of the landforms and/or sediment is poorly understood. The CRN and OSL ages may provide maximum and minimum dates on landforms as is shown in Fig. 25. Each type of dating method is described below to help fully understand the nature of the dating techniques and the limitations.

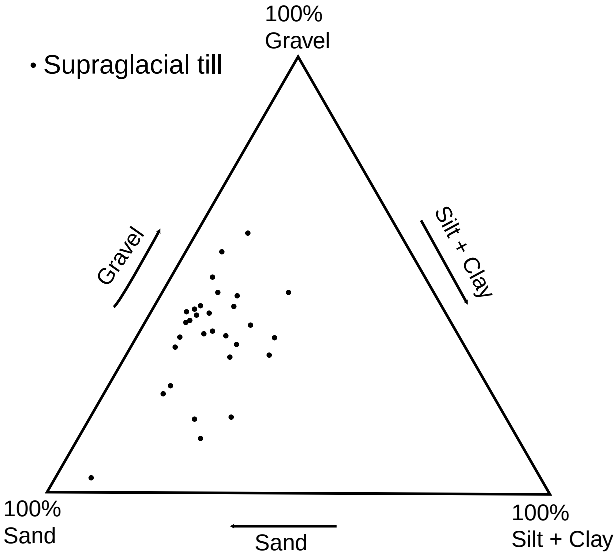


Fig. 20. Ternary diagram illustrating the texture of supraglacial tills from Garhwal. Data from Sharma (1996).

6.1. *Cosmogenic radionuclide (CRN) surface exposure dating*

Previous workers have assumed that CRN ages for boulders on moraine crests should provide reliable dates on the timing of glaciations, on the grounds that valley glacier fluctuations are driven by high-frequency climatic cycles (decadal to millennial timescales) and therefore the construction of moraines occurs over a relatively short period (Gosse et al., 1995a, b; Phillips et al., 1996, 2000). However, it is clear from the above discussion of the formation of large latero-frontal moraine complexes that their duration of formation may be considerably longer than a few millennia and may actually include two or more glacial events. Therefore, CRN exposure dates obtained from boulders on the surfaces of large latero-frontal moraines are more likely to apply to the end of the most recent depositional cycle, that is, the withdrawal of ice from the moraine crest. Furthermore, because the terminal zones of debris-mantled glaciers are relatively slow to respond during periods of negative mass balance, the cessation of moraine building around such glaciers may lag behind the climatic forcing. Thus, exposure dates on moraines mark the onset of deglaciation at the site, and not the timing of full glacial conditions. In the Lahul Himalaya, Owen et al. (2001) showed that CRN exposure ages on latero-frontal moraines were essentially the same as

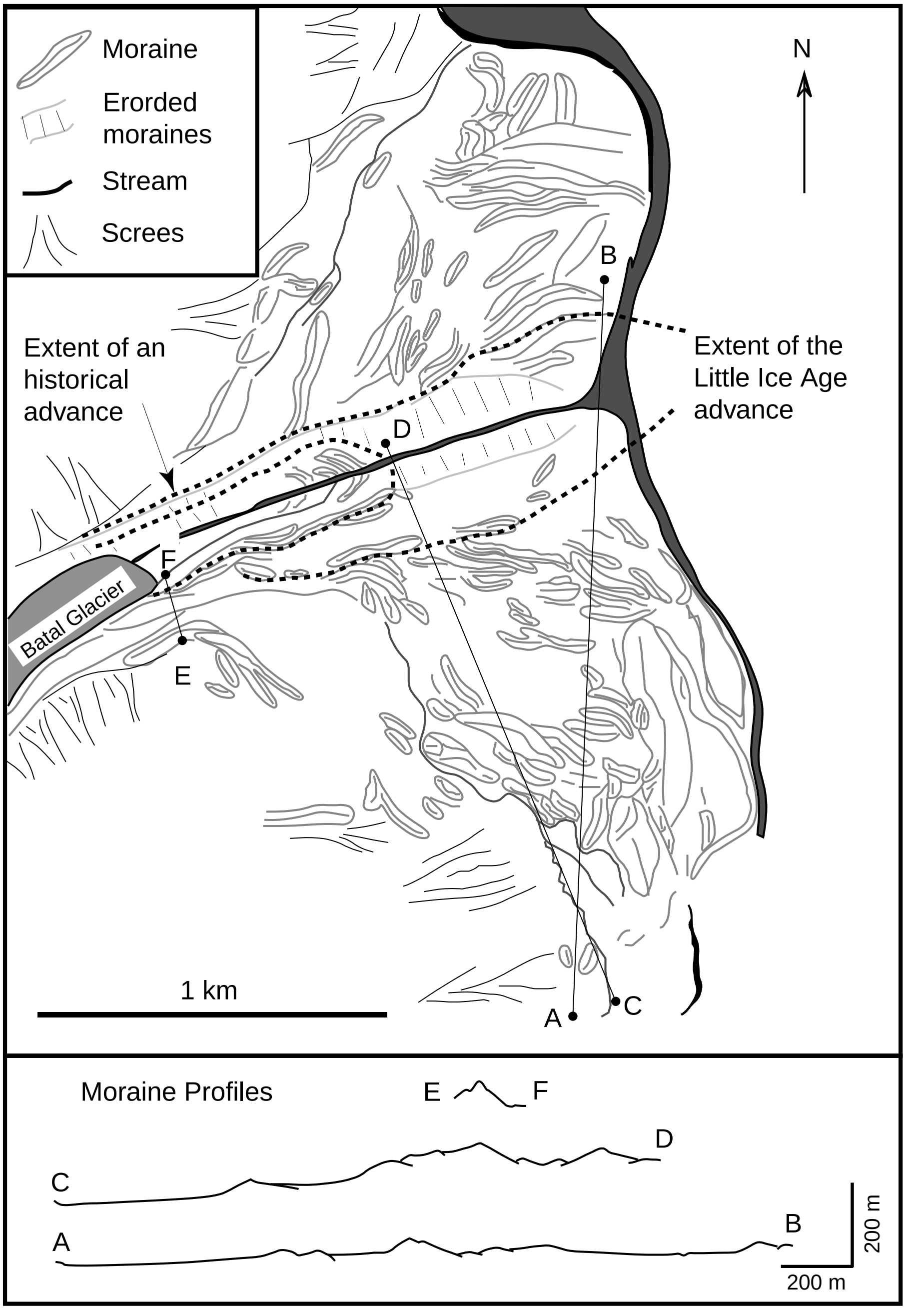


Fig. 21. Geomorphic map of the forefield of the Batal Glacier in the upper Chandra valley, Lahul Himalaya.

boulders from subglacial landforms and glacial eroded bedrock of the same glacial stage. This suggests that either the whole glacial event was rather short lived or that the ages on the moraine ridges are essentially the age of deglaciation. Such considerations do not apply to smaller moraines deposited by relatively 'clean' glaciers.

When applying CRN exposure techniques, it is important to note that several conditions must be met if CRN concentrations in Himalayan moraine boulders are to be used to determine the age of the moraine. Firstly, the CRNs inherited from exposure of the boulder prior to its being incorporation into the moraine must be small. Complex exposures can occur in outcrop, prior to the boulder being incorporated in the flowing ice stream, or during an intermediate stage while the boulder was part of an older moraine. However, glacially transported boulders in Himalayan environments have usually either been severely abraded during glacial transport or have been broken apart by mass movement processes when they were first entrained in the ice. Inherited CRNs are therefore unlikely to occur in most boulders. Secondly, the high activity of glaciers

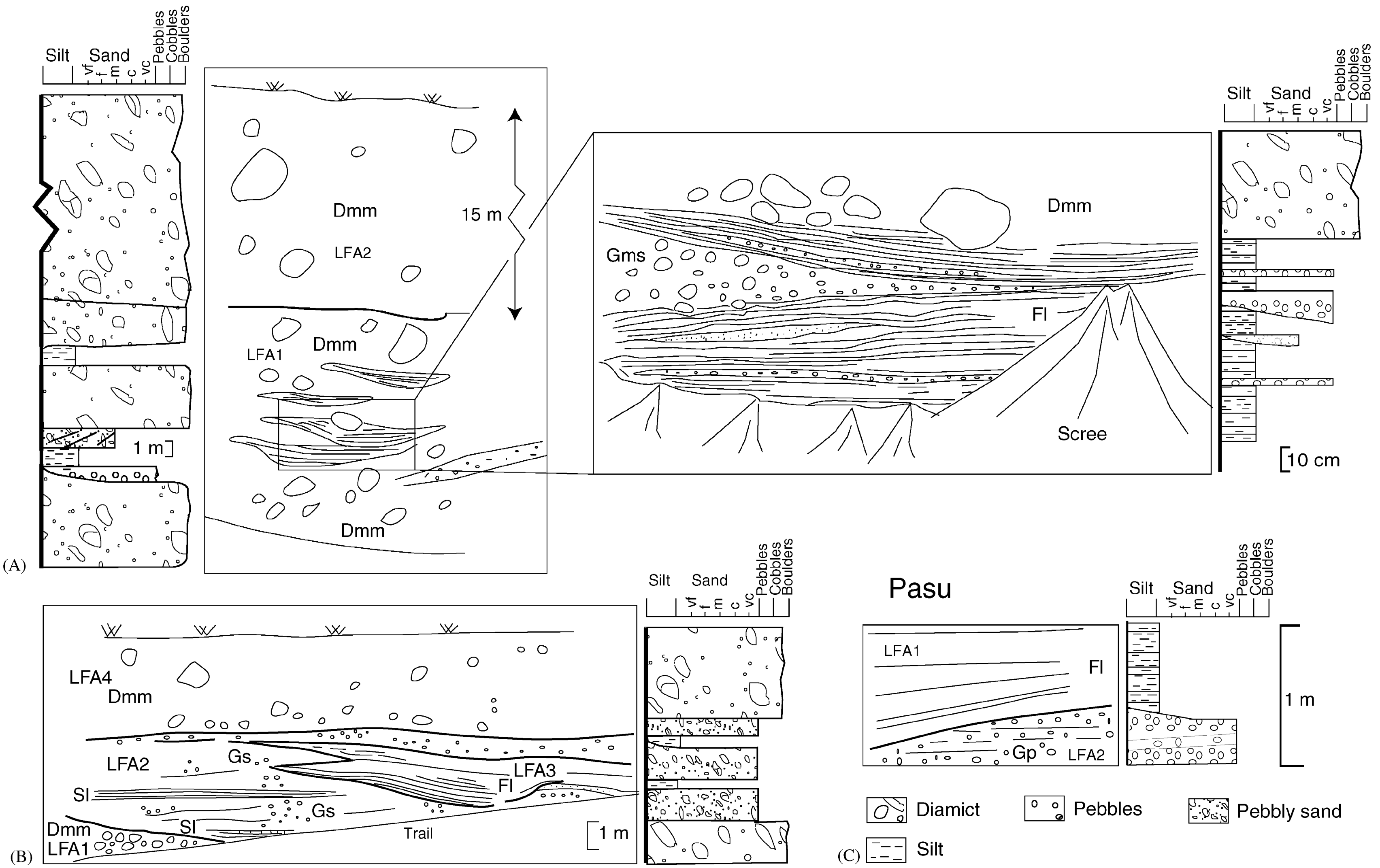


Fig. 22. Lateral and vertical graphic sedimentary logs of sediments associated with the Pasu Glacier. (A) Section within an ancient terminal moraine near the Hunza River south of Pasu village (36°27.272′N/74°54.270′E) showing the relationship between supraglacial lacustrine and glaciofluvial sediments and till. LFA1—massive matrix-supported diamictons incorporating meter-wide and dm-deep channel fills of silts and sands. LFA2—massive matrix-supported diamict containing meter-size boulders in a silty matrix. (B) View looking towards 290° at a section within a lateral moraine above Pasu Bazaar (36°28.159′N/074°53.496′E) showing the association of glaciolacustrine silts with supraglacial till. LFA1—limestone rich diamictons with occasional subangular meter-size granite boulders in a silty matrix. LFA2—crudely stratified moderate to well rounded polymictic cm-size pebbles within channel fills that are dm-deep and m-wide. LFA3—cm- to dm-thick slumped planar beds of massive silt with crude color laminations interbedded with cm-thick bed of sand that is commonly involuted. LFA4—massive matrix-supported diamict comprising polymictic meter-size boulders in a silty matrix. The clasts become smaller towards the northern end of the section. (C) Section showing glaciolacustrine sediments draped over distal glaciofluvial outwash gravels. LFA1—low-angled planar cross-stratified moderate to well rounded polymictic cm-size pebbles. LFA2—planar cm- to dm- bedded massive silts with color laminations. The bedding in the lower part of this unit drapes over LFA1.

Fig. 23. The Rawling Glacier in the Chandra valley, Lahul Himalaya. This glacier has divided in two, with a lower portion separated from the upper hanging glacier by a steep rock face. Ice accumulation in the lower glacier is supported by ice and snow avalanching from the snout of the upper glacier.

in the Himalaya leads to high rates of sediment transport and deposition and thus, accelerates the rate of glacial erosion. These high erosion rates help ensure that boulders and bedrock surfaces are deeply eroded and thus reduce the likelihood of significant CRN buildup while the boulder was exposed in outcrop. The fresh surfaces exposed by boulder break-up also reduce the likelihood that inherited CRNs will be present. Boulders can, however, inherit CRNs if they have been reworked from older deposits, particularly if an advancing glacier overrides previous glacial deposits. In these cases, older glacial debris is redeposited within the younger moraines. Owen et al. (2002a) showed this to be the case in their study of the glacial successions in the Hunza valley. To account for all of these possibilities, Owen et al (2002a) advised that workers should collect multiple samples from each moraine to check the concordance between ages for several boulders from the same moraine to increase the confidence of the dating.

The final remaining issue is the stability of the boulder within the moraine. Hallet and Putkonen (1994) examined the process of boulder diffusion on moraine crests by mathematically modeling the likely age distribution on moraines that were undergoing predictable erosion. They showed that boulders at inflection points along the sides of moraines were less likely to be effected by erosion than those on the crests and foot of moraines. This model needs to be tested, however, using CRN exposure dating of boulders in different positions on moraines before these ideas can be verified and incorporated into moraine dating techniques.

6.2. Luminescence dating

Richards (2000) provided a useful guide to the theory, methods, use and limitations of OSL dating for defining the timing of glaciation in the Himalaya. He outlined the nature of the main types of sediment that are commonly dated, but paid little attention to the details of the depositional environment and sedimentology. However, he emphasized the importance of fully bleaching (zeroing) sediment grains prior to burial as a fundamental requirement of optically stimulated (OSL) dating. In many glacial environments, it has been shown that this condition is commonly not met, due to the transport paths taken by debris within the glacier system. If sediment is derived from beneath the glacier and transported to the margin subglacially (either within basal ice or in the glacial drainage system), bleaching will not take place during transport. Furthermore, many glacial and proglacial depositional processes may not expose sediment grains to sunlight prior to final burial. Such processes include basal or supraglacial melt-out, glaciotectonic processes, and deposition from turbid meltwater streams. Incomplete bleaching, however, is less likely to be a problem in the case of debris-mantled glaciers in high mountain environments. First, the predominantly supraglacial entrainment and transport of debris is highly likely to result in sediment bleaching within the glacier system. Second, the likelihood of bleaching is increased during sediment cycling on the glacier surface, during which debris may be gravitationally reworked several times during repeated topographic inversion. Finally, the deposition of debris in large latero-frontal moraines by gravitational processes provides further opportunities for zeroing. The zeroing problem can be further minimized by sampling from facies that are likely to have been deposited subaerially. For example, Richards et al. (2000b) obtained consistent results by sampling sandy and silty horizons at the top of debris flow units exposed in latero-frontal moraines. The sandy and silty horizons were formed by meltwater activity on the moraine front, probably during dewatering soon after deposition of the underlying debris flows. Thus, grains in such units are more likely to have

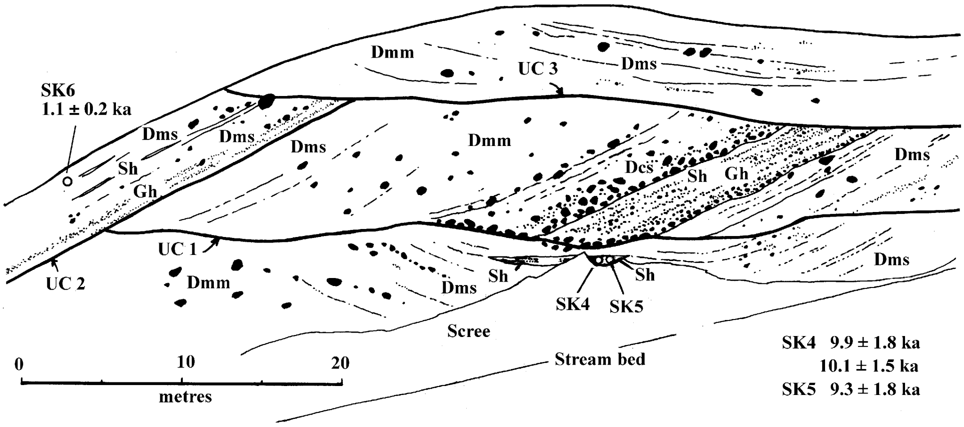
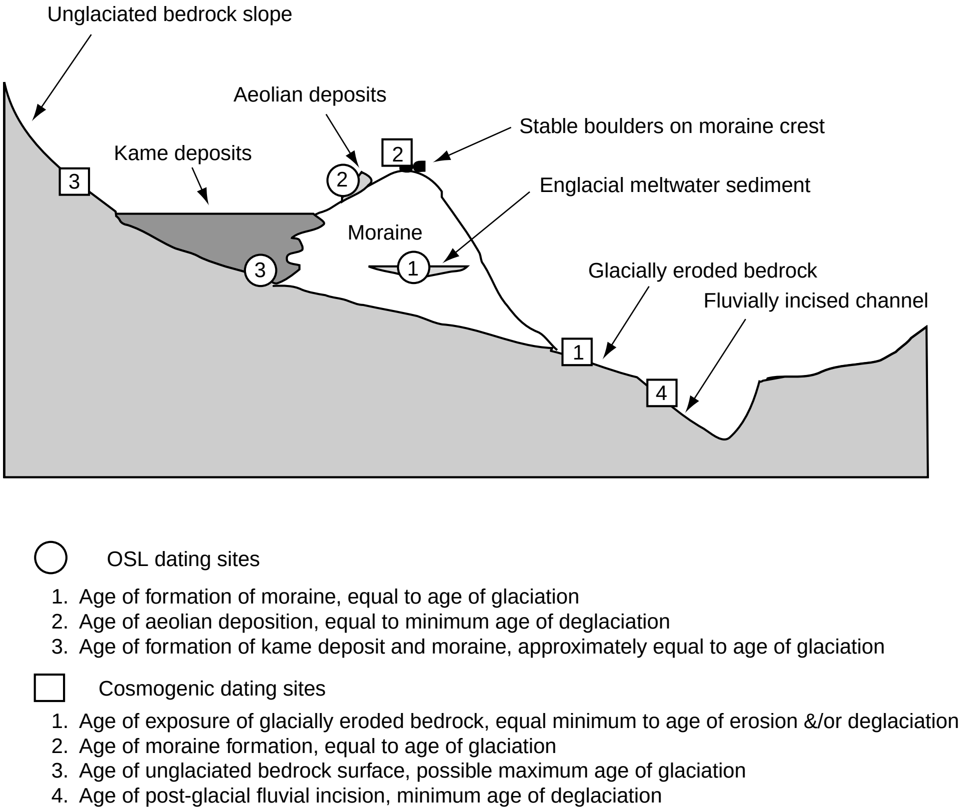


Fig. 24. View of a section through part of the laterofrontal end moraine in front of the Lhotse-Nup Glacier in the Khumbu Himal (after Richards et al. 2000b). UC1, UC2, and UC3 represent three unconformities. OSL dating undertaken by Richards et al. (2000b) is shown on the figure helping to illustrate the long and complex history of this landform. The lithofacies codes of Eyles et al. (1983) are used to describe the sedimentology.



○ OSL dating sites

1. Age of formation of moraine, equal to age of glaciation
2. Age of aeolian deposition, equal to minimum age of deglaciation
3. Age of formation of kame deposit and moraine, approximately equal to age of glaciation

☐ Cosmogenic dating sites

1. Age of exposure of glacially eroded bedrock, equal minimum to age of erosion &/or deglaciation
2. Age of moraine formation, equal to age of glaciation
3. Age of unglaciated bedrock surface, possible maximum age of glaciation
4. Age of post-glacial fluvial incision, minimum age of deglaciation

Fig. 25. Sampling strategies for OSL and CRN dating of moraines and associated deposits and landforms showing the significance of each dating site.

undergone complete bleaching than grains from diamict units, which may have been deposited subglacially, or deep within debris flows.

OSL dating of facies from small lateral moraines deposited by relatively 'clean' glaciers is more likely to be beset by problems of incomplete or non-bleaching of grains during deposition. Grains in such moraines may not have experienced supraglacial transport, and therefore not have undergone bleaching during transport. Furthermore, moraine formation may have involved processes, such as push or glacitectonic processes, that do not expose the constituent sediments to daylight. The dating of such moraines by OSL, therefore, must be subject to the same cautions as glacial landforms in mid- and high latitudes.

OSL dating is potentially more useful than CRN dating for dating the duration of formation of large latero-frontal moraines complexes. This is because CRN surface exposure dating is only really applicable for dating the surface of moraines, which is essentially the time when the glacier started to retreat, whereas when appropriate sediments are dated using OSL methods within different positions in the moraine complex it is possible to determine the full duration of the landforms evolution. A good example of this is provided in Richards et al. (2000b) who dated a latero-frontal moraine in front of the Lhotse-Nup Glacier in the Khumbu Himal. The full potential of this kind of study has yet to be investigated and it is clearly important for determining the environmental and landscape evolution in Himalayan glacial environments.

7. Conclusions

Himalayan glacial sedimentary and geomorphic environments are complex, and include erosional, depositional and deformational processes and vary from debris covered valley glaciers to essentially debris free ice caps. The debris covered glaciers, however, dominate as a consequence of the abundant avalanching of debris and snow from steep long valley sides. The abundance of supraglacial debris helps produce complex latero-frontal moraines that may record one or more glacial cycles. The range and variability of sedimentary and geomorphic environments is well illustrated using examples described above from the Hunza valley, the Lahul and Garhwal Himalaya and the Khumbu Himal. The lithofacies and land systems models presented provide a basis for interpreting ancient sediments and landforms. Furthermore, an understanding of the nature and internal composition and structure of Himalayan glacial landforms is essential for developing strategies to help date the timing of glaciation. Dating the surface of such moraines using CRN surface exposure dating provides a minimum age on the landform and is essentially an estimate of the onset of deglaciation. In contrast, optically stimulated luminescence dating provides an age on the timing of deposition of the sediment and hence when appropriate sections are available it can be used to define the duration of formation of the landforms.

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