Quaternary lacustrine deposits in a high-energy semi-arid mountain environment, Karakoram Mountains, northern Pakistan

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ABSTRACT: Impressive Quaternary lacustrine deposits are present as terrace remnants throughout the Karakoram Mountains, northern Pakistan. They are mainly the result of damming of drainage systems during glacial advances or by catastrophic mass movement deposits. The longevity of most lakes is relatively short, in the order of years to tens of years, but sedimentation rates are extremely high as a consequence of the high sediment loads within the rivers. This results in deposits that frequently exceed 10 m in thickness. The sediments comprise dominantly planar bedded, massive and, less commonly, planar laminated, silts, comprising detrital quartz, feldspar, mica, calcite, chlorite and illite. A facies model for lacustrine sedimentation in a high-energy semi-arid high mountain region is presented, using case studies from a glacially dammed palaeolake (Glacial Lake Gilgit) and a debris-flow dammed palaeolake (Lake Serat). The rapid deposition and absence of organic material restricts the usefulness of these lacustrine sediments as proxies for palaeoenvironmental reconstruction, but they are helpful in reconstructing the former extent of glaciers and illustrating the importance of high-magnitude-low-frequency events, such as landsliding, as formative processes contributing to the evolution of the Karakoram landscape.

KEYWORDS: sedimentology; silts; glaciolacustrine sediments; landslide dammed lakes; Karakoram Mountains.

Introduction

Impressive thick sequences of lacustrine deposits are present throughout Karakoram Mountains, northern Pakistan. Drew (1873), Cunningham (1854) and Thompson (1852) first noted fine-grained deposits in Baltistan and the Gilgit area, but they failed to distinguish between alluvial and lacustrine origins for the deposits. Since then the Karewa beds in the Kashmir basin, which consist of thick lacustrine deposits capped by loess have attracted much interest, especially as they yield valuable information on palaeoenvironments, palaeoclimate and tectonic histories (Gardner, 1989; Rendell et al., 1989; Gupta et al., 1991). Kashmir, however, is structurally different from the Karakoram basins, climatically wetter and, unlike the Karakoram Mountains, was extensively vegetated during Quaternary times. Except for brief notes by Hewitt (1968a, b), Burgisser et al. (1982), Goudie et al. (1984), Derbyshire et al. (1984), Li Jijun et al. (1984), Shroder et al. (1989), Owen (1989a, b, c), Owen and Derbyshire (1993) and Shroder (1993), the origin, sedimentology and significance of lacustrine sediments in northern Pakistan has not been described or discussed in detail. The only modern study of lacustrine sediments in a similar mountain environment has been on the deposits at Lamayuru in Ladakh, northern India (Fort et al., 1988). This paper will, therefore, describe the sedimentological characteristics and genesis of the main types of lacustrine deposits that are present within the Karakoram Mountains of northern Pakistan in order to assess their usefulness as proxies for reconstructing palaeoenvironments.

Geomorphological setting

The Karakoram Mountains are situated at the western end of the Trans-Himalayan Mountains and are the result of the collision of the Asian and Indian continental plates (Fig. 1). The region contains some of the largest rivers with the highest sediment loads in the world, including the Indus, Gilgit and Hunza (Ferguson, 1984; Ferguson et al., 1984). The region also has the highest concentration of 8000 m peaks, including K2 at 8611 m above sea-level. The region is still rapidly uplifting and being intensely denuded (Burbank et al., 1996). Denudational processes include frost shattering (Hewitt, 1968c; Goudie et al., 1984), chemical weathering
by salt crystal growth (Goudie, 1984; Walley et al., 1984),
glacial erosion (Goudie et al., 1984; Li Jijun et al., 1984),
fluvial incision (Ferguson, 1984; Ferguson et al., 1984) and
mass movement (Brunsden and Jones, 1984; Hewitt, 1988).
All these processes produce immense quantities of fine sedi-
ment, which has the potential to be deposited within lacus-
trine environments.

Climatically the region is transitional between central
Asian and monsoonal south Asian types, varying consider-
ably with altitude, aspect and local relief. The Karakoram
valley floors are essentially deserts, with a mean annual
precipitation of less than 150 mm—most of this occurring
over short periods in the summer as heavy storms. In the
valleys, extreme diurnal maximum temperatures in the sum-
mer exceed 38°C, whereas winter temperatures fall below
0°C (Goudie et al., 1984). Dust storms are common, occur-
ring about once a week, and are enhanced in the summer
by katabatic effects.

Three extensive glaciations during Pleistocene times and
at least five minor advances during Holocene times have
been recognised (Derbyshire et al., 1984; Shroder et al.,
1993). These have resulted in deeply eroded valleys and
thick extensive deposits of till. The high supraglacial sedi-
ment loads give rise to large terminal and lateral moraines
rather than subglacial till sheets.

Vegetation is controlled mainly by altitude. It is scarce
along the valley floors and on the lower valley-side slopes,
which are of desert steppe type, and is replaced at higher
levels by temperate coniferous trees and then by alpine
meadow vegetation (Paffen et al., 1956).

Many types of lakes have existed and still exist in the
high mountains of Central Asia. These have formed in a

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**Figure 1** Location of map study areas and known Quarternary lacustrine deposits in the Karakoram Mountains, northern Pakistan.
number of different geomorphological and tectonic settings. The lakes are of three main types:

1. Tettonic lakes.
   (i) Developed within the schuppenstruktur along the southern margin of the Himalayan Range, such as the Kashmir Basin, which formed as the Pir Panjal differentially rose with respect to Great Himalaya (Burbank, 1982).
   (ii) Basins produced by strike-slip faulting. The Nam Co (Co = Lake) and Siling Co north of the Gangdise-Nyaientanglha Range on the North Tibet Plateau are of this type (Zhang Mingtao, 1982).
   (iii) Large-scale crustal subsidence. Many of the small lakes in the Qaidam Basin, for example, are the result of this process (Chen and Bowler, 1986).

2. Glacial lakes.
   (i) Lakes formed by ice damming. Several lakes in the Shaksgam valley, for example, are of this type (Desio, 1980; Burgisser et al., 1982).
   (ii) Lakes formed behind moraines or within moraine fields, for example, the Satpura lake south of Skardu is of this type (Owen, 1989b).
   (iii) Lakes formed within bedrock depressions produced by glacial erosion.

3. Lake resulting from blockage by debris flows, rock falls and landslides. These range in size from several hundred metres (for example, a temporary blockage on the Khunjerab River in 1987 (Owen, 1989a) and on the Kunzha River in 1980 produced lakes of this size), to several kilometres long, as on at Jandardte Nala on the Ghizer River (Nash et al., 1985), to many tens of kilometres long (for example on the Yamzhou Yumco in Tibet (Zhang Mingtao, 1982)).

No tectonically formed lakes have been recognised in the Karakoram Mountains. The orientation of valley systems, however, is strongly controlled by the regional tectonics and many of the valleys either lie long faults or are controlled by rapidly uplifted massifs, such as Nanga Parbat (Owen, 1989c). Examples of the different types of lakes will be described in turn, providing case studies of the two most important types, namely ice dammed and debris-flow dammed.

Methods

The distribution of lacustrine deposits was mapped at a variety of scales ranging from 1:250 000 to 1:10 000 using standard geomorphological techniques (Cooke and Doornkamp, 1990). Good examples of each type of lacustrine deposit were examined using geomorphological and sedimentological techniques. Standard field logging techniques were used to construct both vertical and lateral logs (Tucker, 1982; Eyles et al., 1983; Shaw, 1986). Sediments were classified in the field on the basis of particle size (Wentworth Scale) and shape (Rittenhouse, 1943; Shepard and Young, 1961), together with sedimentary structures. Oriented samples were collected for laboratory analysis using the methods of McGown and Derbyshire (1974).

In the laboratory, particle size distributions were determined by a combination of wet sieving (BS 1377 British Standards Institution 1967) and X-ray size sorting of the < 70 μm fraction using a Micrometics 5000ET SediGraph. X-ray diffractometry (Phillips PS 1729 X-ray diffractometer, using CuK alpha radiation and an Ni filter) was used to establish the mineralogy of the silt and clay content, using air dried, glycolated and heated subsamples in a furnace at 650–700°C for 1.25 h, the interpretation and methodology following Caroll (1974) and Brindley and Brown (1980). The calcium carbonate content was determined manometrically using a Bernard Calcimeter (Avery and Barscombe, 1974). The colour of the bulk sample was compared with a Munsell colour chart.

Preparation of oriented samples for study in a scanning electron microscope (SEM Hitachi S-520) followed the method of McGown and Derbyshire (1974). This allowed natural breakage surfaces to be examined at a range of magnifications from x10 to x50. Qualitative analysis of minerals was determined using energy dispersive X-ray analysis (EDX: Links E5077).

Ablation valley lakes

Ablation valleys (Ablationsschluchten) were popularly believed to result from the melting of the ice margin by reradiation from sparsely vegetated terrain and steep valley walls adjacent to the glaciers (Oestreich, 1906). Hewitt (1989, 1993), however, showed that they are very complex, involving ice-marginal processes (with lateral moraine and kame terrace development being an important component) as well as slope processes, and they should be more appropriately named ice-marginal landforms. Wide and long depressions are frequent and occasionally contain small lakes and ponds. Remains of sediments deposited in these lakes are less common and their former existence is not well preserved. However, remnants are present along the east and west sides of the Gilgit valley south of the Bagrot valley confluence approximately 200 m above the valley floor. Two lacustrine units are present interbedded within glacial diamictons. The lacustrine deposits comprise planar bedded, planar laminated silt lenses that can be traced laterally for about 0.5 km and have a maximum thickness of 8 to 10 m. The sediments consist of poorly sorted, positively skewed silts with loosely packed and isotropic fabrics, although large platy grains may be orientated subhorizontally (Figs 2(A and B) and 3). No diagenetic alteration has been recognised in any of the samples, which consist of detrital grains of quartz, feldspar, muscovite, illite, kaolinite and chlorite.

Lakes formed within moraines

These lakes form within moraine depressions behind end moraines or within hummocky moraine complexes. Figure 4 shows an example from within the Dak Choki moraine, approximately 15 km southeast of Gilgit. At Dak Choki the sediments comprise approximately 6 m of planar centimetre-to metre-thick beds of laminated silts, which are capped with cross-stratified sands. The silts are characteristically poorly sorted, positively skewed with laminations of loosely packed silts composed of detrital mineral grains.
Figure 2  Photomicrographs of vertical faces of lacustrine sediments from selected environments. The top of each plate is the top the sample. (A) and (B) Lacustrine sediments deposited against debris flow deposits that constricted the Gilgit River. Note the poor sorting and isotropic fabric. (C) and (D) Lacustrine sediments from the debris flow dammed lake at Serat. Note the isotropic fabric and the vertical disposition of the silts. (E) Silts from an ice-marginal lake deposit at Sakwar. The crude subhorizontal alignment of grains is particularly noticeable. (F) Sediments from an ice-marginal lake deposit east of the confluence of the Gilt and Bagrot valley. The sample is poorly sorted and has a weak fabric.
Figure 3 Envelopes for particle size distribution curves for lacustrine sediments deposited within hummocky moraines (solid line is for sediments from Dainyor; and broken line for sediment from Dak Choki) and ice-marginal sediments (1.3 m in Minawar village).

Lakes formed within bedrock depressions

Borit Jheel is the only example in the study area of a lake that has formed within a bedrock depression. This has formed within a glacially eroded scour in the diffuence col between the Ghulkin and Pasu Glaciers (Fig. 5). The lake is still full of water and therefore it was not possible to collect sediments for analysis within the scope of this study.

Ice-dammed lakes

Ice dammed lakes may be produced by:

1. advances of tributary valley glaciers, which block the main river;
2. trunk valley glaciers that block unglaciated side valleys;
3. blocking by glacier ice of rock enclaves, producing ice-marginal lakes.

Derbyshire et al. (1984) and Goudie et al. (1984) described locations where, during Pleistocene and Holocene glacial advances, tributary valley ice blocked the Hunza valley and deposited lacustrine silts. Although they did not examine the sedimentology in detail, they described the deposits as consisting essentially of planar metre-thick beds of medium silts interbedded with centimetre-thick bedded fine sands. Burgisser et al. (1982) also noted lacustrine sediments in the middle Indus and Gilgit valleys and considered them to be related to tributary valley glaciers that blocked the main Indus valley. The most impressive succession of glaciolacustrine deposits that were produced by ice damming is present in the upper Gilgit valley. Their sedimentology and genesis will be described in detail below.

Glacial Lake Gilgit

Impressive terraces comprising glaciolacustrine sediments are present southwest of Gilgit. These are about 10 km long and consist of two main lacustrine formations, forming two main terraces. They comprise dominantly planar metre-thick beds of massive silt, and near their base and top they are interbedded with sands and gravels (Fig. 6).

The base of the lower terrace is made up of a 2 to 3 m thick bed of westward-dipping, imbricated, well-rounded polymictic clast-supported cobbles with a fine sandy matrix. This unit can be traced along the whole length of the section and onlaps a rock buttress at the westernmost end of the section. There is no apparent stratification, but occasional discontinuities of metre-long sandy centimetre-thick beds can be identified.

Above this bed, planar decimetre- to metre-thick beds of massive silt, which are poorly sorted (sorting coefficient 1.0 to 2.0) and with a mean grain size 5.5 to 7.5 (medium silt), can be seen to attain a thickness of at least 27 m (Table 1, Figs 7–9). Occasional beds are crudely laminated, the laminations being picked out by slight colour changes. This unit thins westwards to a thickness of about 5 m, where it onlaps a rock buttress (Fig. 6). Scanning electron microscopy (Fig. 2C and D) showed that the laminations are not the result of grain size variations, but coincide with
Figure 5  Borit Jheel (Lake) formed within a bedrock depression in the diffluence col between the Pasu and Gshulkin glaciers. This view is characteristic of the Karakoram landscape, dominated by long steep slopes extending down into semi-arid valley floors.

minute discontinuities with a high void ratio, emphasised in the field by a slight colour variation. The bulk fabric has a relatively high porosity (ca. 10%), a loose framework and a preferred alignment of platy minerals with their a-b axis subhorizontally aligned. X-ray diffraction shows that the silt and clay fractions consist of quartz, muscovite mica, orthoclase and plagioclase feldspar, Fe-rich chlorite, kaolinite and illite (Fig. 10). No carbonate cements or authigenic minerals are present, but detrital calcium carbonate constitutes between 5 and 15% by weight (Fig. 9).

Large sand grains occur within the silt matrix and frequently are aligned with their long axis to the vertical. The silt fabric beneath these grains is sometimes compressed and often the fabric above shows a subvertical alignment. This suggests that the large sand grains are small dropstones. Larger scale examples include pebbles, cobbles and large boulders, which compress the laminations beneath. Frequently, dropstones occur as clusters of pebbles within a scattered sandy matrix.

Few sedimentary structures are present within these silts except where sandy silts and fine to medium sand with centimetre-thick beds are present (Fig. 6). These are often graded and rippled, the latter indicating a westward flow direction. The silts above these beds are often convoluted and load cases are common. Near the base of the lower silt formation, beds of sandy silt, sands and pebbles are present. The sands and pebbles are cross-stratified and the sandy silts are rippled, commonly including climbing ripples, indicating an eastward flow direction. Near the western end of the section 2 to 3 m above the base of the lacustrine silts, imbricated and well-rounded cobbles form an eastward-thinning lens which can be traced for about 100 m. This, in turn, is overlain conformably by the silts (Fig. 11).

A bed of sandy and cobbly, imbricated, clast-supported, well-rounded to subangular polymictic pebbles, 2 to 3 m thick, separates the lower from the upper silt beds. The base of these pebbles is an undulating erosional surface. The overlying upper silt beds are not present at the western end of the terrace, which is marked by a sharp erosional scarp. Here, the outcrop has clearly been eroded away.
The silts of the upper terrace have similar characteristics to those in the lower terrace, but their mean grain sizes are finer (6.7 to 8.7\(\phi\), the norm being ca. 7.5\(\phi\)) and sorting is very poor (>2.0 cf. 1.5–2.0). These silts also contain dropstones and clusters of pebbles and sands. They reach a thickness of 24–30 m and thin towards the west. Metre wide and decimetre deep sandy gravel lenses that fill scours are present throughout the section (Fig. 11).

The top of the upper terrace has been channelled (Fig. 12). The channels vary from gentle concave sections tens of metres to several metres wide to steep-sided channels, some of which are undercut. These are filled with gently dipping, cross-stratified, poorly sorted pebbles, sands, and cobbly well-rounded polymictic gravels with planar metre-thick beds. The sedimentary structures indicate an eastward flow direction (Fig. 11 C and D).

Very poorly sorted matrix-supported polymictic diamictons with angular clasts overlie the gravels. These have a diffuse fabric and a gently-dipping crude stratification subparallel to their surface, which dips at < 10° towards the axis of the valley. At one location three of these units are present and they are interbedded with centimetre-thick beds of fine sandy silts.

Adjacent to these deposits are massive, matrix-supported bouldery diamictons with thicknesses up to several tens of metres. Their upper surfaces dip 10–20° towards the axis of the valley. These are truncated and form cliffs several tens of metres high.

These deposits are the result of sedimentation within a lake that formed when a glacier blocked the Gilgit valley as it flowed down the Hunza valley during the Borit Jheel glaciation of Derbyshire et al. (1984). This produced a glacial lake that backed up the Gilgit valley for at least 20 km (Fig. 13). There is no evidence that the valley was blocked by debris flows; moreover, the Gilgit valley is very wide (ca. 4 km) at its confluence with the Hunza valley and it would have taken an enormous amount of debris to block the valley at this point. The presence of moraines at Dak...
Table 1  Particle size statistics for lacustrine sediments from the terraces near Gilgit and Serat. The values are quoted in phi units.

<table>
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<td>0.45</td>
</tr>
<tr>
<td></td>
<td>9 m up</td>
<td>7.66</td>
<td>1.98</td>
<td>0.22</td>
</tr>
<tr>
<td>Upper terrace</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10 m up section</td>
<td>5.44</td>
<td>1.94</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>6.76</td>
<td>1.67</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
<td>1.54</td>
<td>0.65</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Choki provides evidence for an ice advance down the Hunza valley. High-level glacial surfaces and glacially eroded valley sides provide evidence in support of an early glaciation of the Gilgit valley before ice damming (Shroder et al., 1993). It is likely that ice filled both the Gilgit and the Hunza valley during the Borit Jheel glaciation. Ice retreat occurred in both the Gilgit and lower Hunza valleys, and this retreat was probably punctuated by ice advances in the Hunza valley, sufficient to block the Gilgit valley. However, Gilgit ice did not advance sufficiently to form a confluence with the Hunza ice, as shown by the extensive plain of imbricated outwash cobbles and pebbles flooded during the lake’s formation. These cobble sheets form the basal units of the terrace at Gilgit.
The early flooding that produced the basal lacustrine sediments was initially of moderate flow regimes and probably carried high sediment loads, depositing gravels and cross-stratified sands with climbing ripples above the basal cobbly gravels. Constant sedimentation within the lake after flooding produced the lower planar bedded massive silts. The massive nature of the beds and the regular bed thickness, as well as the isotropic microfabric, suggests that these lake sediments were deposited rapidly, with little or no seasonal influence.

The great thickness of the sediment suggesting a moderately large lake with a depth that would have been controlled primarily by ice thickness, which may have been of the order of several hundred metres. The lake probably caused flotation of the margin of the Hunza glacier, inducing calving. These floating ice blocks deposited dropstones and lumps of till, forming clusters of sand and pebbles within the silt. Subaqueous density currents produced the beds of sands and rippled silts, as well as small scour-fill channels which have flow directions indicating a source from the ice margin (Fig. 13A). Larger subaqueous channels have not been recognised, but the absence of deposits at the proximal end of the lake (near the Hunza–Gilgit confluence) may be the result of erosion. Alternatively, it may be that underflows were of only minor importance.

The ice breached and the lake consequently drained. An extensive floodplain developed across the gently eroded surface of the recently deposited silts, on which an imbricated sheet of pebbles and sands was laid down. Major channel fills were not recognised and therefore it may be that the main channel of the river was near the position of the present river (Fig. 13B). The breaching of the ice-dam was probably gradual. Mason (1929) observed ice-dammed lakes in the upper Shaksgam valley and saw that crevassing within the ice can result in waters escaping gradually in the summer, the ice 'healing' in the winter, thus allowing the lake to form once more. A similar situation, but on a different time-scale, may have occurred in the case of the Hunza ice. The balance between drainage and formation may have altered in favour of the latter such that a second lacustrine episode occurred, producing the lacustrine beds of the upper terrace (Fig. 13C). These have a similar sedimentology to the lower beds but the silts are more poorly sorted and finer-grained, suggesting that they may have had a different source from those in the lower terrace, although their mineralogy is the same; detrital quartz, feldspar, mica and kaolinite being derived from granitic rocks and chlorite and illite from metamorphic rocks. It is likely that these silts came mainly from the Gilgit valley because sufficient waters were present during the breaching of the dam to produce an extensive floodplain conglomerate and it may have been that silts derived from the glacier became more important during the deposition of the sediments of the upper terrace. Fluctuations in grain size up-section probably reflects local source changes and fluctuations in the silt supply from the glacier.

After the final breaching of the ice, channels were eroded into the upper silts. These were infilled with imbricated cobbles and pebbles. The sedimentary structures indicate flow of water out of these channels towards the east (Fig. 13D). The steeper channels may have been produced by rapid discharges of water upon breaching of the ice in a manner similar to, but on a very much smaller scale than, the channels in the Channeled Scabland of the Columbia Plateau, USA (Baker, 1978). Migration of channel position and downcutting of the main river resulted in its present position. Unstable till deposits left on the valley sides from...
Figure 9 Vertical variation of particle size characteristics for lacustrine sediments in the terrace of Glacial Lake Gilgit.

the earlier glaciation were reworked by debris flow processes and now cap the terraces (Fig. 13E). The lacustrine sediments were progressively incised to form extensive terraces along the southern side of the Gilgit valley (Fig. 13F).

Landslide and debris-flow-dammed lakes

There are many historical examples of catastrophic debris-flow events in the valleys of the Indus, Gilgit and Hunza rivers (R. B. Shaw, 1871; Cunningham, 1854; Mason, 1929; Brunsden and Jones, 1984; Nash et al., 1985) and their effects have been described in some detail (Henderson, 1859; Obbard, 1860; Butler et al., 1988; Owen, 1995). Frequently, rivers are impounded by debris derived from such events, a recent example observed by the author involved blocking of the Khunjerab river during the summer of 1987. Other recent examples were described by Cai et al. (1980) near the Batura Glacier and Brunsden and Jones (1983) along the Karakoram Highway. A large catastrophic mudflow that blocked the upper Hunza River at Shishkat in 1973, producing a lake 12 km long and resulting in the destruction of a newly completed bridge, is of particular note. Goudie et al. (1984) described the lake deposits that remained after the dam was breached as being of gravelly braid-plain character in the proximal areas and unconsolidated fine sands and silts in the distal areas. Drew (1873) and Mason (1929) described a major landslide off the Lichar Spur on the western flank of the Nanga Parbat massif during December 1841, which blocked the Indus and created a lake that backed 40 km up the valley. Similar examples were described from the upper Hunza and Shyok valleys. Mason (1929) described a lake that formed near Serat village due to a landslide that blocked a gorged section of the Hunza: it was breached within 6 months. A depth of at least 10–11 m of silt was deposited over an area of 1.5 km by 300 m during this time (this example will be considered in detail below). In contrast, there is little evidence of silt deposition behind the Lichar Spur, even though it lasted for a similar length of time and received the combined sediment loads of the Hunza, Gilgit and Indus river systems. However, it was considerably larger, and silt deposition was effectively diluted over a larger area of the submerged sediment fans. Secondly, the breach of the landslide in the Lichar area had catastrophic effects producing a ‘wall of water’ (Henderson, 1859; Obbard, 1860). Shroder et al. (1988)
described mega-ripples of bouldery gravels and sands in the lower section of the palaeolake near Shatial in the middle Indus valley, which they believe to be the result of the flood waters. Given the magnitude of such an event the silts would have been eroded away easily, destroying any sedimentological evidence.

Small-scale debris flows may temporarily block streams or create slack areas within the main river, producing eddies. Deposition of sandy silts and coarse silts occur within these and the deposits may have climbing and asymmetrical ripple laminations that indicate local upstream flow directions. An example is present on the north side of the Gilgit river opposite Gilgit. The ripple laminations onlap a debris-flow deposit which is now incised by the present southeasterly flowing Gilgit river, indicating a northwesterly to northerly flow direction. By definition, these are not lacustrine silts although they can easily be misinterpreted as such.

Figure 14 illustrates a typical example of lacustrine sediments making up terraces in the Khunjerab valley. These sediments comprise decimetre- to metre-thick planar beds
of medium to coarse silts. Asymmetrical and climbing ripples sometimes occur, especially near the bases and tops of these deposits. Near the top of the section, some silts are interbedded with planar beds of fine sand and scours filled with gravel (centimetre- to decimetre-wide and centimetre-deep). Load structures are often associated with beds of alternating lithologies.

Brunsden and Jones (1984) noted that debris flows and landslide instability were confined to particular areas sensitive to failure within the Hunza valley. This is particularly apparent at Serat (discussed in detail below) and near the village of Hope in the Bagrot valley (Fig. 15). At Hope, the most impressive examples of lacustrine sediments resulting from debris flow processes can be seen, but they are rather inaccessible. Several debris-flow events can be recognised as a result of landsliding of bedrock associated with failure of a highly weathered grossan, and the resedimentation of tills. Three major debris flows dammed the river, forming lakes and allowing lacustrine silts to be deposited, that onlap the debris-flow deposits. The southernmost lacustrine deposit
comprises more than 100 m of planar bedded silts and rippled sandy silts. The other two deposits are composed of planar bedded silts that are tens of metres in thickness. The most assessable example of lacustrine deposits that resulted from debris-flow-dammed lakes, however, is present at Serat and this will be described in detail below.

**Palaeolake Serat**

Three sets of terraces, approximately 1.5 km long, are present along the southern side of the Hunza River near Serat. Each terrace comprises metre-thick planar bedded silts capped by cobbly gravels (Fig. 16). At the western end of each terrace the silt beds onlap poorly sorted monomictic (gneiss) bouldery diamictons which are fan shaped in cross-section (Fig. 17). The diamictons are stacked above each other forming a cedar-tree-like arrangement, the topographically lowest diamicton being the youngest deposit. These represent debris-flow events, the youngest was deposited during the winter of 1857-1858 as a result of heavy falls of rain and snow, which caused the collapse of the northern slopes of Phungurh on the southern side of the Hunza valley (Becher, 1859; Mason, 1929). This dammed the river for 6 months and, when the dam was breached, the resulting flood was referred to by Mason (1929) as the 'Second Great Indus Flood'. It was recorded at Attock as a 16.7 m rise in the level of the Indus River. A deposit of lacustrine silts some 10–11 m thick, now forming the lower terraces, was
Figure 13  Schematic development of Glacial Lake Gilgit.

Figure 14  Typical lacustrine sediments in the Khunjerab valley. Note also the lacustrine deposits several hundred metres up the valley side in the distance.

deposited during the lifetime of this lake. The age of the other debris-flow deposits is not known. They must, however, post-date the last major valley glaciation (Ghulkin Glacial), when the valley was full of ice. This glaciation probably occurred during Late Glacial times, although the dating is poorly constrained (Derbyshire et al., 1984). Given the altitudinal position of the lacustrine sediments on the valley sides (Fig. 16) there must have been considerable incision between depositional events. This suggests that the early debris flows may be early to mid-Holocene in age.

Most of the terraces consist dominantly of decimetre- to metre-thick beds of fine to medium grained silts, which are very poorly sorted to poorly sorted, strongly positively skewed and platykurtic (Table 1). Their cumulative particle
size curves form a very tight envelope and there are no apparent grain size changes within a bed or, indeed, throughout the terrace (Fig. 18). Laminations are rare and, when present, they are the result of colour variations. Scanning electron microscopy shows an isotropic fabric, with platy minerals frequently subvertically disposed (Fig. 2E and F). Porosity is high (20–30%) with an open fabric. Grains are angular and no secondary clay minerals or cements have been recognised. X-ray diffractometry of the silt and clay fraction indicates the presence of illite, chlorite (Fe-rich), muscovite, orthoclase and plagioclase feldspar, kaolinite and quartz (Fig. 20). There is a carbonate content of 5 to 15% consisting of detrital carbonate grains.

Occasionally, massive, planar centimetre-thick beds of moderately to poorly sorted sands are interbedded with the silts. At some horizons metre-wide and decimetre-deep channels have been filled with planar beddings sands and pebbly sands with up rip-up clasts of silt.

The lower and middle terraces are capped with very poorly sorted polymictic, imbricated cobbly gravels. Beneath these gravels sandy beds with rip-up clasts of silt and cross-stratified sands are present. At the top of the upper terrace, large channels, with widths 3–10 m and depths 1–5 m, have gently sloping sides. These are infilled with pebbly sands and gravels, with bedding dipping at between 5 and 10° towards the centre of the channel and decreasing in dip up-profile (Fig. 19). The upper sediments exhibit desiccation structures such as scrolls and mudcracks. Overlying these and capping the terraces are decimetre-thick beds of very poorly sorted gravelly sandy diamictons with angular clasts of gneiss. Wind-blown sand forms irregular sheets on the surfaces of the terraces.

There is a cobbly diamicton in the middle of the upper terrace that is fan-shaped, about 5 m wide and trends towards 312°N. The material is mainly gneiss and rip-up clasts of Serat silt. It is very poorly sorted and coarsens upwards. Beds of silt (centimetres thick) onlap the deposit with dips matching the surface of the flow. On the downstream side of the diamicton (western side) the sandy silts are planar rippled indicating flow directions upstream and up the surface of the fan. The base of the silts immediately overlying the diamicton is disturbed and silt blocks have been incorporated into the upper surface of the diamicton.

Wet-sediment deformation structures are also present within the lacustrine sediments at Serat. Decimetre- to metre-diameter oblate spheroids of folded laminated silts and sands are present within the lacustrine sediments (Fig. 21A and B). The ends of the laminations within the cycloids (cycloid structures: see Hempton and Dewey, 1983) are detached from the original beds, ending at either the base or the top of the structures. In places, the cycloids are equally spaced, but close stacking frequently produces irregularities in the oblate form. Confined to some of the laminations within the cycloids are small (2–3 mm diameter) circular holes, which were probably water escape structures. The cycloids are best formed near the top of the middle terrace and can be traced for at least 0.75 km. The silts above and below them show little evidence of disturbance (Fig. 21B). At the western end of the terrace, the lacustrine deposits have dips of between 5 and 10° where they have been deposited on the palaeoslope surface of the debris flow that helped form the lake. Here large cycloids slid down slope after their formation stacking up on each other. Cycloid structures also occur within the large scour fills at the top of the upper terrace (Fig. 21C). The cycloid structures are frequent along many of the beds, but they do not exceed more than 20 cm in diameter, the
The sedimentology of the lacustrine succession is essentially simple. Blockage of the river by debris-flow events produced a large lake on three occasions. The upper terrace represents the oldest lake deposits. Silts were deposited rapidly and settled out as an isotropic mass showing little evidence of any influence of flow, as indicated by the lack of stratification, the massive nature of the beds and the isotropic fabric. The rapid sedimentation is a consequence of the extremely high sediment load of the Hunza River, which is amongst the highest in the world (61 MT year\(^{-1}\); WAPDA, 1979) and is predominantly silt grade. However, small planar beds of sand and small channels filled with sand and rip-up clasts of silt, are probably the result of underflows due to high discharges of the Hunza River perhaps coinciding with peak discharges from the upper Hunza glaciers.

The small diamicton fan in the middle terrace is interpreted as a subaqueous debris-flow deposit which may have been initiated by rock falls from the adjacent valley walls during the deposition of the lacustrine silts. This debris flow was turbulent, producing reverse grading and rip-up clasts of silts, which may have been eroded as the flow advanced obliquely to the valley trend. After deposition, lacustrine silts continued to accumulate, onlapping the debris flow. The topography was sufficient to create flow separation during an underflow event, resulting in rippled sandy silts climbing up the downstream face of the fan. The debris flow was unstable for some time after its deposition, its movement being enough to cause incorporation of blocks of newly deposited silt into its upper surface.

The large channel fills at the top of the upper terrace may represent stream channels from adjacent side valleys, which developed after the first lake was drained during its drainage as a result of floodwater. These channels were filled subsequently during the early stages of the formation of the second lake. The sedimentary structures indicate relatively high flow regimes representing rapid infilling. The middle terrace formed during the existence of the second lake. Its drainage may have produced a pebbly gravel cap and rip-up clasts of silt at its base derived from older silt terraces. However, these gravels do not form mega-ripples which frequently are associated with exceptionally high flow regimes and high-volume events. The lower terrace represents deposits formed after the 1857 debris-flow event, these are similar in sedimentology and form to the middle terrace. They represent exceptionally high sedimentation rates. Breaching of this lake also gave rise to similar cobbly gravels with rippled pebbly sands immediately beneath the cobbly gravels capping the terrace, indicating high flow regimes.

The cycloid structures probably testify to the rapid deposition of sediment, resulting in differences in density and viscosity within the sediment pile (cf. Ramberg, 1981). The
sliding and stacking of cycloids within particular horizons illustrates the fluidity of the sediment soon after deposition. It is tempting to attribute these structures to agitation and liquefaction of the sediment during an earthquake, however, the criteria Sims (1975) used to attribute such structures to seismic events is not satisfied because the sediments at the western end of the terraces were deposited on a palaeoslope and the cycloids are not laterally continuous throughout the whole terrace.

Recently the surface of the upper terrace has been modified by small debris flows and by the accumulation of windblown sands, which overlie both channel fills and massive lacustrine silts.

Discussion

The sedimentology of the different types of lacustrine deposits within the Karakoram Mountains is remarkably similar. They comprise essentially poorly sorted silts that form
Figure 20  X-ray diffractograms of the silt and clay minerals in the lacustrine sediments at Serat. (Sample A was taken from the middle of the lower terrace; B, the top of the lower terrace, C, the middle of the middle terrace; D, the base of the upper terrace; E, the top of the upper terrace.)
massive metre- to decimetre-thick beds. Laminations are rare and usually are due to colour variations—the result of subtle changes in the porosity and the microfabric of the sediment. This may be the result of slight changes in the deposition rate and sediment input into the lakes. The sediment loads within the lakes are so high and the deposition rates are so great that true varved sediments do not form in these high-energy lake environments. Sedimentation within these lakes is a function of sediment load in the river, and the longevity and size of the lake, and this clearly varies dependent on the type of lake formed.

The main mechanism for lake formation in the Karakoram Mountains is damming of drainage systems either by mass movements or advancing glaciers, although ice-marginal lakes and moraine-dammed lakes are present, they are much less common. As a consequence of mass movements and glacier damming, most lakes are short-lived because the dams are easily breached. The high energy and high sediment loads associated with mass movements, glaciers and the main rivers in this region result in high sediment inputs into the lakes. Consequently sedimentation rates are very rapid and thick deposits of silt form in relatively short periods of time. Historical documentation of mass-movement-dammed lakes in the Indus, Hunza and Khunjerab valleys, for example, supports the view that landslide dams are breached within a few months to a few years of their formation. Nevertheless substantial deposition occurs within these short periods to produce lacustrine sediments that are in the order of several metres to tens of metres in thickness. The longevity of glacial lakes, such as Glacial Lake Gilgit, is not known. By analogy, however, with the sedimentation rates in the mass-movement-dammed lakes it is likely that such sediment piles may accumulate within a few to tens of years. However, direct comparisons with mass-movement-dammed lakes must be treated with caution because, during glaciations and glacial advances, meltwaters may have considerably different debris loads compared with the waters infilling debris-flow-dammed lakes.

Figure 21 (A) The characteristic of the cycloid structures; (B) slumped cycloid structures within the middle terraces; and (C) channel fill sediments and cycloid structures in the upper lacustrine terrace at Serat.
Figure 21  Continued.

Figure 21  Continued.
Figure 22  Schematic diagram showing the settings and characteristics of lacustrine environments in the Karakoram Mountains. The graphic sedimentary logs illustrate the type of sedimentary facies that is associated with each type of lacustrine environment. The lithological symbols are shown in the key for Fig. 6.
Figure 22 summarises the main types of lacustrine environments and provides summary graphic sedimentary logs to illustrate the types of sedimentary facies associated with the main types of lakes. This provides a useful model to aid in the interpretation of Quaternary sediments in problematic settings.

As a consequence of these very high deposition rates, the lacustrine sediments in the Karakoram Mountains have limited use as a proxy for reconstructing palaeoenvironments. In addition, the absence of organic material makes them difficult to date using radiocarbon techniques. Furthermore, the rate of deposition may also be problematic for optically stimulated luminescence dating because the sediments may be buried too rapidly to be bleached. They may, however, be useful in reconstructing former ice positions. They also testify to the importance of high-magnitude-low-frequency events, such as landslide damming, as formative processes in the evolution of this high mountain landscape. These temporary lakes are also significant in the landscape evolution of this region because they act as temporary storage for silts. These may be reworked later by fluvial, mass movement and aeolian processes.

**Conclusion**

The majority of Quaternary lacustrine deposits in the Karakoram Mountains are the result of drainage systems being dammed by glacial advances or catastrophic mass movements. The longevity of most of the lakes is probably relatively short, in the order of years to tens of years. The extremely high sedimentation rates, which are a consequence of the high sediment loads within the rivers, result in the deposition of thick lacustrine deposits. These deposits comprise dominantly planar bedded, planar laminated silts, consisting of detrital quartz, feldspar, mica, calcite, chlorite and illite. Figure 22 summarises the main lacustrine facies that are present in the Karakoram Mountains, but these also may be applied to other high-energy semi-arid high mountain regions. The rapid deposition and absence of organic material restricts the usefulness of these lacustrine sediments as proxies for palaeoenvironmental reconstruction. They are helpful, however, in reconstructing the former extent of glaciers and illustrating the importance of high-magnitude-low-frequency events, such as landsliding, as formative processes contributing to the evolution of the Karakoram landscape. These lake deposits are also probably important as a temporary storage for silts, which may later be reworked to contribute to aeolian deposits such as loess.

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