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Composite suspended sediment particles and flocculation in glacial meltwaters: preliminary evidence from Alpine and Himalayan basins

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Abstract:

Research over the last decade has shown that the suspended sediment loads of many rivers are dominated by composite particles. These particles are also known as aggregates or flocs, and are commonly made up of constituent mineral particles, which evidence a wide range of grain sizes, and organic matter. The resulting *in situ* or effective particle size characteristics of fluvial suspended sediment exert a major control on all processes of entrainment, transport and deposition. The significance of composite suspended sediment particles in glacial meltwater streams has, however, not been established. Existing data on the particle size characteristics of suspended sediment in glacial meltwaters relate to the dispersed mineral fraction (absolute particle size), which, for certain size fractions, may bear little relationship to the effective or *in situ* distribution. Existing understanding of composite particle formation within freshwater environments would suggest that in-stream flocculation processes do not take place in glacial meltwater systems because of the absence of organic binding agents. However, we report preliminary scanning electron microscopy data for one Alpine and two Himalayan glaciers that show composite particles are present in the suspended sediment load of the meltwater system. The genesis and structure of these composite particles and their constituent grain size characteristics are discussed. We present evidence for the existence of both aggregates, or composite particles whose features are largely inherited from source materials, and flocs, which represent composite particles produced by in-stream flocculation processes. In the absence of organic materials, the latter may result solely from electrochemical flocculation in the meltwater sediment system. This type of floc formation has not been reported previously in the freshwater fluvial environment. Further work is needed to test the wider significance of these data and to investigate the effective particle size characteristics of suspended sediment associated with high concentration outburst events. Such events make a major contribution to suspended sediment fluxes in meltwater streams and may provide conditions that are conducive to composite particle formation by flocculation. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS glacial meltwaters; suspended sediment; particle size characteristics; scanning electron microscopy (SEM); composite particles; flocculation

INTRODUCTION

Most sediment monitoring programmes in glacierized catchments have focused on suspended sediment concentration/discharge relationships and on the estimation of suspended sediment loads (e.g. Ferguson, 1984; Gurnell, 1995). The particle size characteristics of the suspended load have received comparatively limited attention [see Fenn and Gomez (1989)]. Particle size exerts a fundamental control on the hydrodynamic behaviour of the suspended load, and such data are essential for the application of sediment transport models (Nicholas and Walling, 1996) and for the design of sediment control schemes (Bezinge, 1987; Bogen, 1989). In contrast, there is a much larger database on the particle size characteristics of fluvial suspended sediment in non-glacierized catchments (e.g. Walling and Moorehead, 1989; Walling and Woodward, 2000). It has recently been established that the suspended sediment loads of many rivers in low-relief, temperate freshwater

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environments are dominated by composite particles that commonly exceed the size of their constituent mineral grains by at least two orders of magnitude (Woodward and Walling, 1992, 1999; Droppo and Ongley, 1992; Walling and Woodward, 1993; 2000). Composite particles are also known as aggregates or flocs, and a range of sampling strategies has been developed to monitor the effective or *in situ* particle size distribution of suspended sediment (Walling and Woodward, 2000). We refer to those composite particles derived from erosion of soils and other catchment source materials as aggregates. These particles enter the fluvial system in an aggregated form and retain that structure during transport (Walling and Woodward, 2000). In contrast, flocs are composite particles that have formed *within* the water column due to various physical, chemical and/or biological processes (Petticrew, 1996; Droppo *et al*., 1997). Aggregates may be incorporated into flocs and each may break up to produce smaller composite and discrete particles. The term composite particle affords a useful non-genetic description that embraces all multi-grain suspended sediment particles (Walling and Woodward, 2000).

The settling velocities of composite particles may greatly exceed those of their constituent mineral grains. Thus, any attempt to predict sediment deposition using standard numerical models that assume single grain settling is likely to underestimate significantly the proportion of fine-grained particles in the deposited sediment where composite particles are a significant component of the suspended sediment load (Ongley *et al*., 1992; Petticrew, 1996; Droppo *et al*., 1998). For example, Nicholas and Walling (1996) have shown that the presence of composite particles in the suspended sediment load of the River Culm, in southwest England, can be used to explain the poor agreement between theoretical and observed relationships between mean sediment grain size and distance from the main channel that has been reported for the floodplains of many lowland rivers. An improved understanding of the hydrodynamic behaviour of suspended sediment in glacial meltwaters is important for several reasons, including the management of sediment problems in hydroelectric power generation and the accurate prediction of sediment accumulation in proglacial lakes, reservoirs and sediment traps. Existing understanding of composite particle formation within freshwater environments would suggest that glacial meltwater environments are unlikely to be conducive to floc formation because of the absence of organic binding agents. The presence of organic matter in various forms is believed to be an important control on composite particle formation and stability. In many aquatic environments the presence of particulate organic matter is believed to enhance the flocculation process because it is highly cohesive (see Kranck, 1979; Droppo *et al*. 1998). However, the existence and potential significance of composite suspended sediment particles (both aggregates and flocs) in proglacial streams has not been investigated to date. Indeed, Droppo *et al*. (1998) have pointed out that most published work on flocculation processes in cold climates has focused on salt and brackish water environments in fjords (e.g. Syvitski and Murray, 1981; Winters and Syvitski, 1992; Domack *et al*. 1994).

A number of researchers have reported the particle size characteristics of suspended sediment in glacial meltwaters (e.g. Bogen, 1989; Fenn and Gomez, 1989) and proglacial lakes (e.g. Bezinge, 1987) and discussed their significance for the hydrodynamic behaviour of the sediment load. However, all of these studies employed field and laboratory procedures that generated data on the absolute or ultimate particle size characteristics of the dispersed mineral fraction. For example, Fenn and Gomez (1989) analysed their samples using a laser granulometer, following the ashing of sediment-laden filter papers (with 8 μm pores) and screening of residues though a 180 μm sieve. In lowland catchments, such procedures have been shown to produce particle size distributions that contrast markedly with the equivalent *in situ* or effective particle size distribution of suspended sediment that includes composite particles (Walling and Woodward, 1993, 2000). This paper reports the preliminary findings from reconnaissance sampling programmes undertaken during the 1999 ablation season on streams draining one Alpine and two Himalayan glaciers, which together are representative of a range of topographic and glaciological conditions. The primary objectives were to sample sediment-laden meltwaters to establish if composite particles were present in the suspended sediment load of the three proglacial streams, using scanning electron microscopy (SEM), and, assuming such particles were present, to investigate their mode of formation. The sampling technique devised by Woodward and Walling (1992) was employed, since it allows the collection of representative composite suspended sediment particles from aquatic environments for subsequent SEM analysis. We present the results of our SEM analyses, and the need for further work on the effective particle size characteristics of fluvial suspended sediment in proglacial environments is reviewed.

THE STUDY CATCHMENTS

Unteraargletscher, in the Bernese Alps of south-central Switzerland, forms below the confluence of the Lauteraargletscher and the Finsteraargletscher, which flow from the northwest and southwest respectively. The confluence zone is approximately 6·5 km long and is characterized by two large medial moraines running along its length. The regional bedrock is central Aar granite. The glacier terminus lies at *c*. 2000 m above sea level, and its recent retreat has permitted access to the proglacial streams that currently merge into one large stream that drains into the Grimselsee. Samples were taken from this main proglacial stream some 300 m from the glacier terminus (Figure 1a). The Batura and Passu glaciers (Figure 1b) lie in adjacent basins within the Hunza basin of the Karakoram Himalaya in northeast Pakistan [see Ferguson (1984)]. The smaller Passu Glacier is approximately 28 km long with a reasonably clean and highly crevassed surface. The terminus lies at *c*. 2700 m above sea level and approximately 60% of the basin is glacierized (Boyce, 1992). In contrast, the Batura Glacier is one of the largest in the Karakoram Himalaya, with a total length of just under 60 km and a terminus elevation of *c*. 3000 m. Some 48% of the Batura basin is glacierized (Shi and Zhang, 1984) and the surface, particularly in the lower reaches, is heavily mantled with debris. Only a *c*. 700 m wide strip of clean ice is visible along much of its length (Shroder, 1993). Ferguson (1984) reports a mean suspended sediment concentration of 1100 mg l^{-1} for the Batura River for the summer of 1980. The regional bedrock underlying both basins comprises primarily granodiorite, together with Gujhal dolomite and Passu slates (Shi and Zhang, 1984; Collins, 1996). A single proglacial stream exits the terminus of each glacier. Samples were taken as close as practically possible to the portals; direct access was obtained to the portal of Passu Glacier, but at Unteraargletscher and Batura the samples were collected immediately downstream at *c*. 300 m and 500 m respectively from the portal (Figure 1).

FIELD AND LABORATORY METHODS

Glacial meltwater streams are usually characterized by high suspended sediment concentrations resulting from processes of glacial erosion (Ferguson, 1984; Gurnell, 1987). In order to isolate composite particles from a turbid meltwater sample for subsequent SEM analysis, the filtration technique described in detail by Woodward and Walling (1992) was utilized. This involves collection of a water sample in a Perspex settling tube (15 cm high), and allowing a short period of time (between 5 and 10 s) for the larger particles to settle out of suspension directly onto a filter membrane. The sampling technique and apparatus are shown in Figure 2. We used Whatman cellulose nitrate filter membranes with 5 μm pores to allow reasonably rapid filtration of water, while retaining the particles of interest. Importantly, this method avoids the need for vacuum filtration, which can result in sediment compaction and artificial grain adherence (Whalley, 1979). In addition, the Woodward and Walling (1992) method also ensures an essentially 'clean' sediment-free filter membrane background, such that individual composite particles and discrete particles are readily identifiable.

Samples were taken as far away from the river bank at each of the three field sites as was safely possible. However, in practice, because of the size of the rivers concerned, this often involved taking samples some distance from the centre of the proglacial stream. We do not, however, view this as an issue for concern, since studies conducted at the Haut Glacier d'Arolla have shown no significant difference in the size characteristics or concentration of suspended sediment samples taken at the same time from different positions in the cross-section of the proglacial stream (Gurnell *et al*., 1992). Samples were taken in the afternoon at each site during periods of high discharge. The filter papers were stored in plastic petri dishes for transport back to the laboratory, where they were placed in a desiccator to dry. Small sections (approximately 0·5 cm^2) were

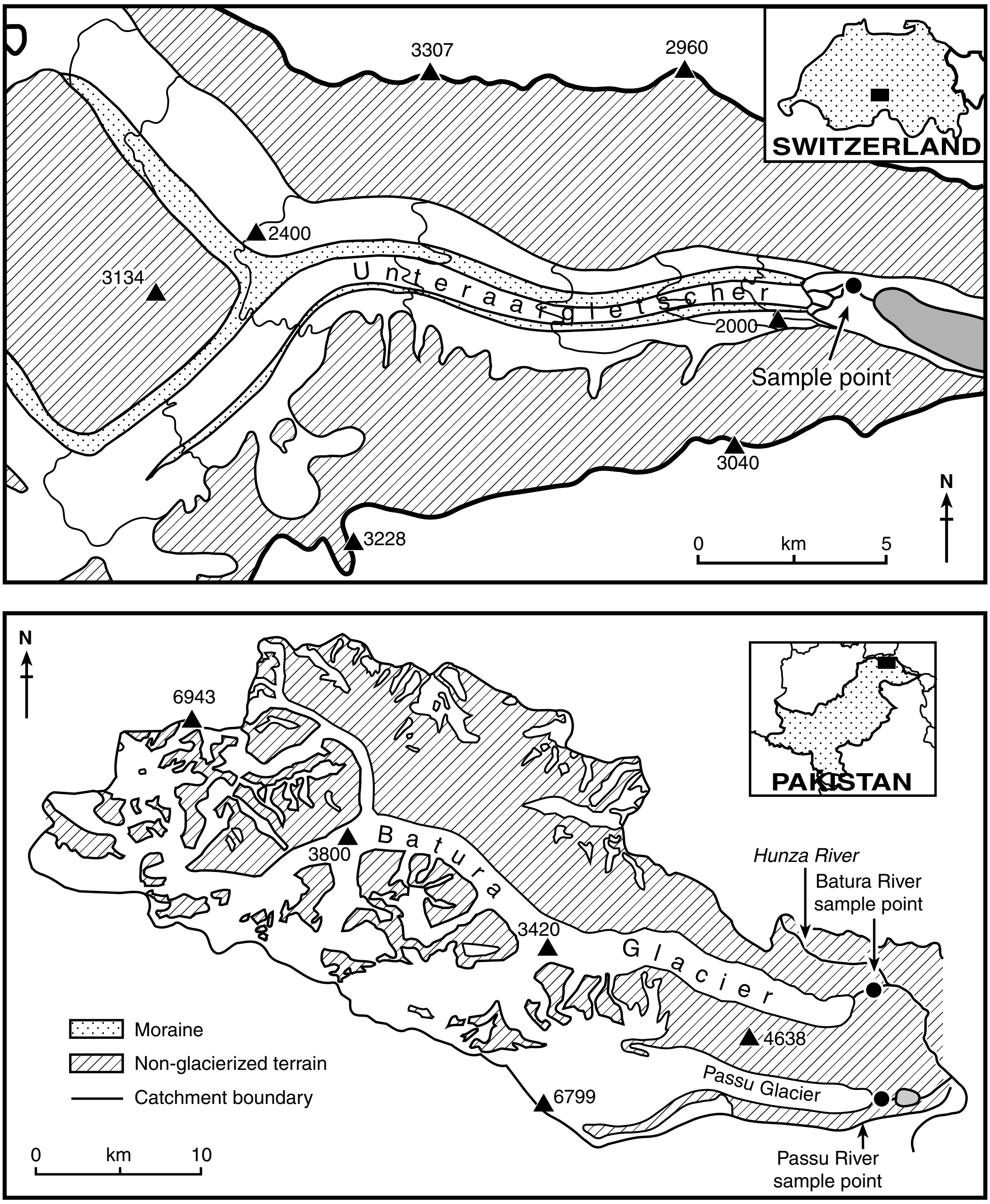

Figure 1. Location maps of the three glacierized basins sampled in this study: (a) Unteraargletscher, Bernese Alps, Switzerland; (b) Batura and Passu glaciers, Hunza Basin, Karakoram Himalaya, Pakistan. The sampling points on each of the proglacial streams are shown

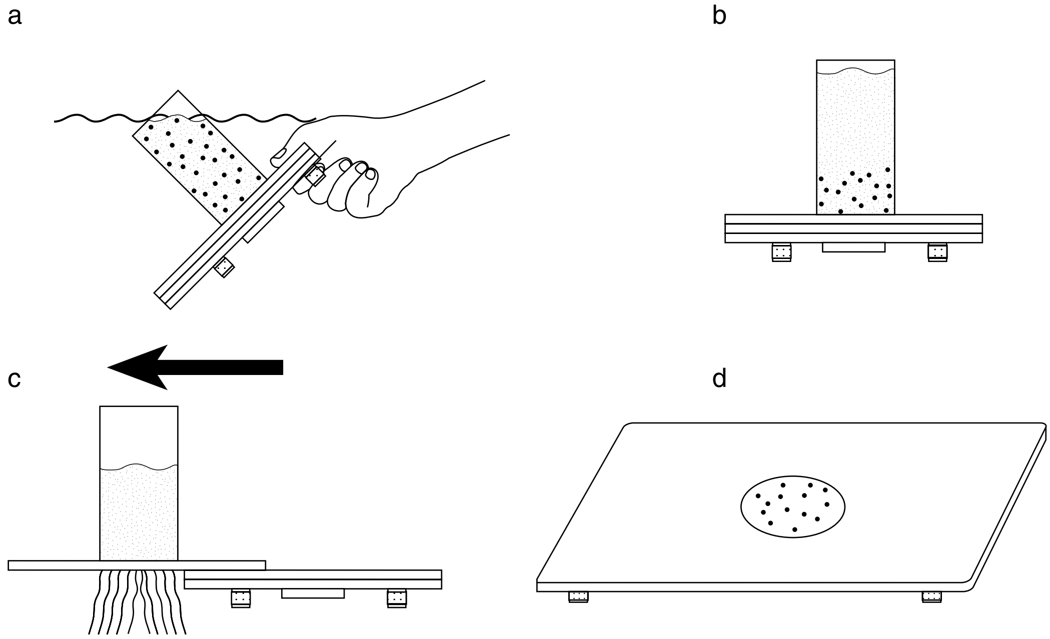

Figure 2. The procedure used to collect the suspended sediment samples: (a) the filtration assembly is held at an angle beneath the surface of the water; (b) the assembly is removed from the water and held in a vertical position long enough to allow the largest particles to settle out onto the filter paper without allowing membrane overcoating; (c) the settling tube is then moved away from the plate housing the filter membrane, leaving a small volume of water containing those particles with the highest fall velocities on the filter membrane surface; (d) any remaining water is left for a few minutes until filtration is complete

cut from the filter membranes, mounted on SEM stubs using self-adhesive conducting carbon pads, and gold coated (Woodward and Walling, 1992). A CamScan Series 4 scanning electron microscope was used to study the composite particles collected on the filter membranes.

RESULTS AND DISCUSSION

Background

SEM analysis has been used to identify surface textures for quartz sand grains that are characteristic of comminution and transport processes in glacial environments (Krinsley and Doornkamp, 1973) and different parts of the glacial debris system (Eyles, 1978). SEM studies have also been carried out on till microfabrics to investigate glacial depositional processes (e.g. Derbyshire, 1978). Conchoidal fractures and sharp edge breakages are commonly associated with silt- and sand-sized particles transported in a glacial environment. Such features are clearly visible on many of the discrete particles and constituent particles in the SEM micrographs shown in Figure 3. It is important to note that the surface of the filter membrane is clearly visible in the background of each sample, demonstrating the effectiveness of the sampling and separation method in preventing fines settling onto the membrane and creating artificial composite forms (Woodward and Walling, 1992). In contrast, previous SEM studies of the properties of suspended sediment from glacial meltwater systems have used vacuum filtration to trap bulk samples on filter papers for subsequent analysis; see Richards, (1984) and Fenn and Gomez (1989). It is important to point out that those studies were not explicitly designed to isolate composite particles, and the procedures employed tended to result in the entire filter paper surface being covered with sediment and in discrete fine particles being deposited on the surfaces of coarser ones; see Richards, (1984).

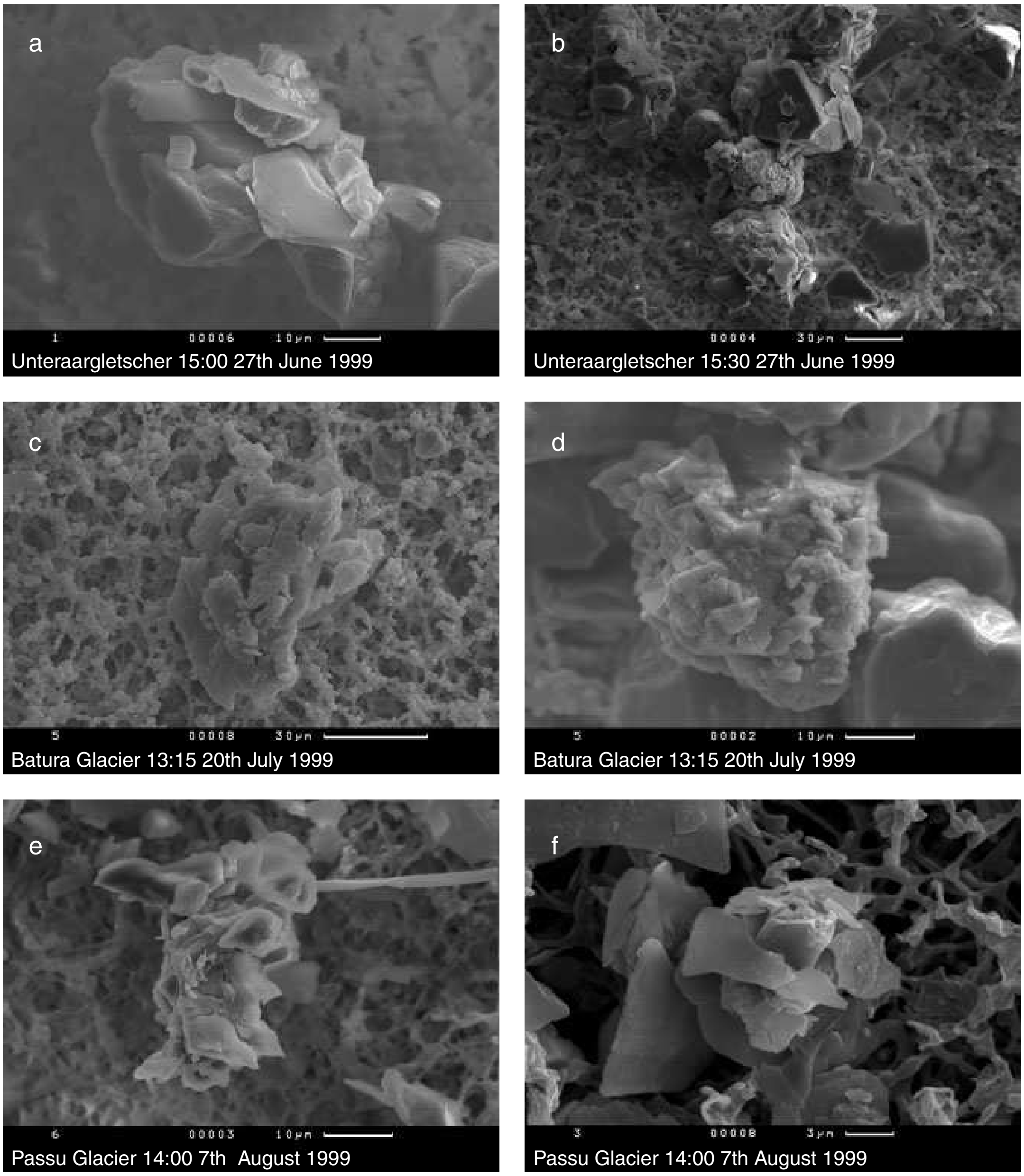

Figure 3. SEM micrographs of composite particles obtained from proglacial streams: (a) Unteraargletscher, 15:00, June 27, 1999; (b) Unteraargletscher, 15:30, June 27, 1999; (c) Batura Glacier, 13:15, July 20, 1999; (d) Batura Glacier, 13:15, July 20, 1999; (e) Passu Glacier, 14:00, August 7, 1999; (f) Passu Glacier, 14:15, August 7, 1999

The SEM results: composite particle form and genesis

During SEM analysis, a representative sample of between seven and nine composite particles was identified from each filter membrane section (Figure 3). The size of each of the composite particles was recorded by measuring the intermediate axis length from the SEM micrographs, assuming that this axis lies uppermost and is visible. These data are listed in Table I and indicate that the intermediate axes of the composite particles

Table I. Estimates of composite particle size for samples collected during the summer of 1999 from the three proglacial streams

Glacier	Date and time of sample collection	Mean size of particle intermediate axis μm	Intermediate axis size range μm	*n*
Unteraargletscher	June 27 (15:00)	44	21–55	9
	June 27 (15:30)	63	30–107	8
Batura	July 20 (13:15)	41	16–62	9
	August 8 (12:00)	33	12–82	7
Passu	August 7 (14:00)	27	17–41	7
	August 7 (14:15)	23	11–42	9

range in size from approximately 10 to 110 μm (fine silt to fine sand). Some examples are described below and shown in Figure 3a to f.

Figure 3a and b shows several composite particles collected from the proglacial stream exiting from the Unteraargletscher on June 27, 1999, at 15:00 and 15:30 hours respectively. The composite particle shown in Figure 3a has a long axis of *c*. 50 μm and comprises loosely compacted platy quartz grains >10 μm in size, with smaller (<5 μm) and more equidimensional particles attached to the surface. The structure of this composite particle suggests that it is the product of in-stream flocculation processes. The two composite particles in the centre of Figure 3b include a wider range of constituent particle grain sizes than the example given in Figure 3a. These composite particles are also more densely compacted, with long axes of 50 to 60 μm. Their structure would suggest that, rather than being the product of post-entrainment flocculation, the tightly packed clay- and silt-rich composite forms represent source-derived aggregates that have entered the proglacial system in aggregated form and have retained this structure during transport. Evidence of flocculation is provided by the two multi-faceted coarse silt particles in the upper part of Figure 3b, where several platy fine and medium silt particles have become attached to their surfaces. Note the 'clean' sediment-free filter membrane background.

The examples from the Batura Glacier that were collected at 13:15 on July 20, 1999 (Figure 3c and d), display contrasting internal and external morphologies. The composite particle shown in Figure 3c is composed of platy, fine silt-sized constituent particles within a low-density structure that includes significant voids. This particle may be the product of in-stream flocculation, and it contrasts markedly with what would appear to be a compact source-derived aggregate shown in Figure 3d. The tightly packed composite particle shown in Figure 3d appears to be quite robust and is surrounded by several discrete particles of comparable size. In view of the short settling times employed during sample collection, this association may indicate hydraulic equivalence for these composite and discrete sediment particles, and they may have similar densities.

The fine-grained core of the composite particle shown in Figure 3e (which was collected from the Passu Glacier proglacial stream at 14:00 hours on August 7, 1999) shows a similar form and, therefore, it is likely that this is also a source-derived aggregate. However, this composite particle contains a number of larger particles (between 5 and 10 μm in size) that appear to be loosely bound around the central core. Thus, this composite particle shows evidence of in-stream particle flocculation around a denser source-derived aggregate core (Figure 3e). In contrast, Figure 3f shows a composite form with a much looser overall structure (and a smaller range of constituent grain sizes) with large voids that may be indicative of formation solely by flocculation within the proglacial stream. In the absence of organic binding agents [see Droppo *et al*. (1997)], the composite particles shown in Figure 3a, c and f, the upper part of figure 3b, and the outer section of figure 3e, may result solely from electrochemical flocculation processes. To the authors' knowledge, this mechanism of floc formation has not been reported previously in the freshwater fluvial environment.

Discussion and research needs

Composite suspended sediment particles in glacial meltwater streams may result from three main mechanisms:

(1) in-stream flocculation of suspended primary particles;
(2) entrainment of aggregates derived from sub-glacial, en-glacial or supra-glacial sources, such as clay-rich basal till sediments;
(3) erosion of pre-Quaternary bedrock producing compacted and/or cemented composite particles, the structure and mineralogy of which will be inherited from the parent rock.

The relative importance of each of these processes in the production of composite particles will be controlled by bedrock and glacial sediment properties and sources, as well as a range of water-quality parameters, including temperature, ionic concentration, suspended sediment concentration, and the absolute particle size characteristics (e.g. clay content) of the suspended load. The first of these mechanisms may be expected to produce loosely compacted composite particles (e.g. Figure 3c and f) with a lower density than source-derived aggregates eroded from till sediments or bedrock (e.g. Figure 3d). Compositional analysis of constituent grains and cements, using electron microprobe techniques, may allow the origin (e.g. bedrock or till) of composite particles to be established.

During sample collection with the Perspex sampling tube, 5 to 10 s settling times were employed to prevent both the overcoating of the filter membrane and the formation of artificial composite particles. This means that our samples are skewed towards the coarser end of the effective particle size distribution (Table I). Significant numbers of discrete coarse silt- and sand-sized particles were also present on the filter papers collected from each of the meltwater systems, and further work is needed to quantify the relative importance of composite and discrete particles in different size fractions. Walling and Woodward (1993) have reported the use of a water elutriation apparatus for this purpose. This allows a suspended sediment sample withdrawn directly from a river to be fractionated into five effective size fractions. In lowland fluvial environments this approach has demonstrated that the 8–16, 16–32, 32–63 and >63 μm effective size fractions can be dominated by composite particles and that the proportion commonly exceeds 75% of the total mass (Woodward and Walling, 1999). Our preliminary analyses have demonstrated that composite particles of various sizes and with a wide range of constituent grain sizes are present in the sediment loads of all three proglacial streams (Table I and Figure 3).

The SEM data provide evidence for the presence of both source-derived aggregates (e.g. Figure 3b and d) and composite particles that appear to be the product of in-stream flocculation processes (e.g. Figure 3c and f). It is important to note, however, that the samples discussed in this paper were collected from meltwaters with relatively low ambient suspended sediment concentrations (<200 mg l^{-1}) and these values may increase by two orders of magnitude during outburst events. Kranck (1993) has shown that the flocculation process may be enhanced by high concentrations of suspended sediment in the water column and concentrations in excess of 5000 mg l^{-1} are now known to be a feature of glacial meltwater discharges. For example, Gurnell (1995) has reported meltwater outbursts from the Glacier de Tsidjiore Nouve in southern Switzerland for the 1981 ablation season where suspended sediment concentrations exceeded 3000 mg l^{-1} for several days, and concentrations in short-lived pulses reached 70 770 mg l^{-1}. The combination of low temperatures (and low fluid viscosity) and high suspended sediment concentrations during outburst events may provide optimum conditions in proglacial systems for inter-particle collisions and for composite particle formation by electrochemical flocculation, despite low organic contents and limited bacterial activity. These events represent very significant suspended sediment fluxes, yet the effective particle size characteristics of the associated sediment have not been investigated. Continuous *in situ* measurement of such events using a field-portable laser backscatter probe, such as that described by Phillips and Walling (1995), would allow such controls to be explored further. In addition, monitoring the downstream passage of a glacially sourced suspended sediment pulse may provide further insights into freshwater flocculation processes (including electrochemical mechanisms), since both the proportion of organic matter and bacterial activity are likely to increase downstream; see Petticrew, (1996) and Droppo *et al.* (1997). Equally, information on the mineralogy, structure and abundance of source-derived aggregated suspended particles may provide insights into the nature of the sub-glacial drainage system and sediment sources; see Eyles (1978), Collins (1979, 1989), and Foster *et al*. (2000). Droppo *et al*. (1998) have shown that suspended sediment transport to and within the Mackenzie River Delta in the subarctic zone of Northern Canada is dominated by composite particles (flocs). These workers suggest that water temperature, suspended solid concentration, particulate organic matter and bacteria are important controls on flocculation dynamics in the Delta.

Catchment lithology has been shown to exert a significant influence on the particle size characteristics of suspended sediments in lowland non-glacierized catchments (Walling and Moorehead, 1989; Walling and Woodward, 2000). Thus, variations in bedrock properties and in the clay and silt content and fabric of sub-glacial debris [see Derbyshire, (1978)] are likely to exert an important control on the significance of source-derived aggregates. It is important to point out that all three of the glaciers investigated in this reconnaissance study drain resistant igneous and metamorphic terrains. Catchments with softer, argillaceous sub-glacial strata and sediments may be expected to generate a much greater proportion of source-derived aggregates in the suspended sediment load. For example, from SEM analysis of the microfabric of a flow till from southern Norway, Derbyshire (1978, 46) reports the presence of 'coarse to medium silt grains with irregular clustered coatings of fine silt and aggregates of fine silt and clay particles'.

CONCLUSIONS

The fall velocity of sediment particles is controlled mainly by their size and density. Therefore, an improved understanding of the genesis and role of composite suspended sediment particles—in a range of aquatic systems—is important for the meaningful application of sediment transport models and may provide insights into the nature of ancient sedimentary environments. Existing data on the particle size characteristics of suspended sediment in glacial meltwaters relate to the chemically dispersed mineral fraction (absolute particle size). For certain size fractions, however, such data may bear little resemblance to the effective or *in situ* particle size distribution. The results presented in this paper demonstrate the existence of composite suspended sediment particles in the proglacial meltwaters of one Alpine and two Himalayan glaciers. The presence of loosely bound composite particles points towards the operation of in-stream flocculation in these environments. In the absence of organic material, electrochemical attraction may be an important flocculation mechanism in glacial meltwater systems, especially during high concentration outburst events. Further research is required in a range of lithological and hydrological settings to assess the significance of source-derived aggregates and flocculated particles to the overall suspended sediment load of glacial meltwater streams. This may lead to a better understanding of suspended sediment flocculation processes more generally in freshwater fluvial systems.

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