Sediment transport in the proglacial Fagge River (Kaunertal/Austria)

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Abstract The fluvial system in proglacial areas is more-or-less continuously fed with sediment by glacial melt water and infrequently supplied with sediment by landslides, debris flows, rock fall or fluvial transport from the coupled slopes. A part of the sediment input is temporarily stored in intermittent sinks (river bed, bars, braid plains). These stores can be reworked and then become sources for fluvial sediment transport during floods. Sediment transporting processes are highly variable in both the temporal and spatial scale. In consequence of this high variability, field-data based detailed knowledge of sediment fluxes and the interrelated geomorphological processes in proglacial areas is lacking. The present work is part of the research project "High-resolution Measurements of Morphodynamics in Rapidly Changing Proglacial Systems of the Alps", that is set up in the Kaunertal, Austrian Alps. The project is focused on the quantification of fluvial sediment transport. Suspended sediment load and bed load are measured at different locations in the proglacial Fagge River. Surface changes of sediment sources are quantified by a comparison of multi-temporal terrestrial and airborne laser scanning data.

Key words proglacial; sediment transport; bed load; terrestrial laser scanning; Kaunertal, Austria

INTRODUCTION

Since the end of the Little Ice Age (LIA) in the middle of the 19th century glaciers in the Alps have been retreating. In their forefields, proglacial areas with specific process characteristics develop over time (Gurnell & Clark, 1987; Embleton-Hamann & Slaymaker, 2012). These proglacial systems show a high geomorphological activity (Price, 1980). High rates of sediment fluxes, the deposition of related accumulations and, hence, landforms are obvious (Warburton, 1990; Marren, 2005). Suspended sediment load is an important but highly variable component of total sediment fluxes within the main proglacial river system is (Orwin & Smart, 2004). The debate about its explanatory power as a proxy for glacial erosion has a long tradition (see Warburton & Beecroft, 1993). Gurnell & Clark (1987, p. xv) point out in the preface of their important textbook that "…*research on sediment transfer in alpine glacier basins is being pursued with enormous enthusiasm…, …. there is still much to discover*". This statement is still up to date. The application of technologies developed and improved in terms of measurement resolution and accuracy in the last few years, for example, airborne and terrestrial laser scanning (among others Heritage & Hetherington, 2007; Heckmann *et al*., 2012), will improve the understanding of sediment transfer processes in geomorphologic research, and particularly in alpine proglacial areas. In a new research package (PROSA, DFG grant PAK 736/1) the application of these approaches, in combination with classic geomorphological, remote sensing and glaciological methods are used to investigate sediment fluxes in a glacierized catchment in Austria (Heckmann *et al*., 2012, this volume). In a subproject, our focus is on the fluvial system of the basin. In accord with the methodological approaches used in our previous research in high mountain basins, we are investigating slope–channel coupling (Bimböse *et al*., 2011), morphological changes of the valley bottom (in the river and on the banks), in order to quantify rates of sediment transfer within the system (Morche *et al*., 2007, 2008) as well as fluvial sediment transport in the main river and the export out of the entire catchment (Schmidt & Morche, 2006; Morche & Schmidt, 2012). The first main field season starts in May 2012; here we present findings of our preliminary investigations on discharge and sediment transport measurements as well as on terrestrial laser scanning of important sediment sources (lateral moraines, alluvial deposits).

STUDY AREA

The Kaunertal valley is located in the Ötztaler Alps in Tyrol/Austria (Fig. 1). The valley is part of the Austroalpine Crystalline Complexes (Geological Survey of Austria, 1999). It is drained by the Fagge River originating from the glacier Gepatschferner. A main tributary (Riffler Bach) drains the water of the glacier Weißseeferner in the western part of the catchment. A gauging station (Hydrographical Survey Austria/Tiroler Wasserkraftwerke AG) operates upstream of the Gepatsch hydropower reservoir at 1895.01 m (above mean sea level, reference Amsterdam). The catchment area above this station is 55 km^2. The study area, ending at the mouth of the Fagge River in the Gepatsch reservoir, is slightly larger (about 62.5 km^2). The watershed includes some of the highest peaks in the Ötztaler Alps (Glockturm 3353 m, Weißseespitze 3518 m, Fluchtkogel 3497 m, Hochvernagtspitze 3535 m, Hintere Ölgrubenspitze 3295 m). Previous rough estimations of solid load, based on averaging the loads of neighbouring rivers, were published by Tschada & Hofer (1990). They estimated an annual solid load in the Fagge River of 58 000 m^3 (suspended sediment load 45 900 m^3, bed load 12 400 m^3) upstream of the reservoir between 1964 and 1989.

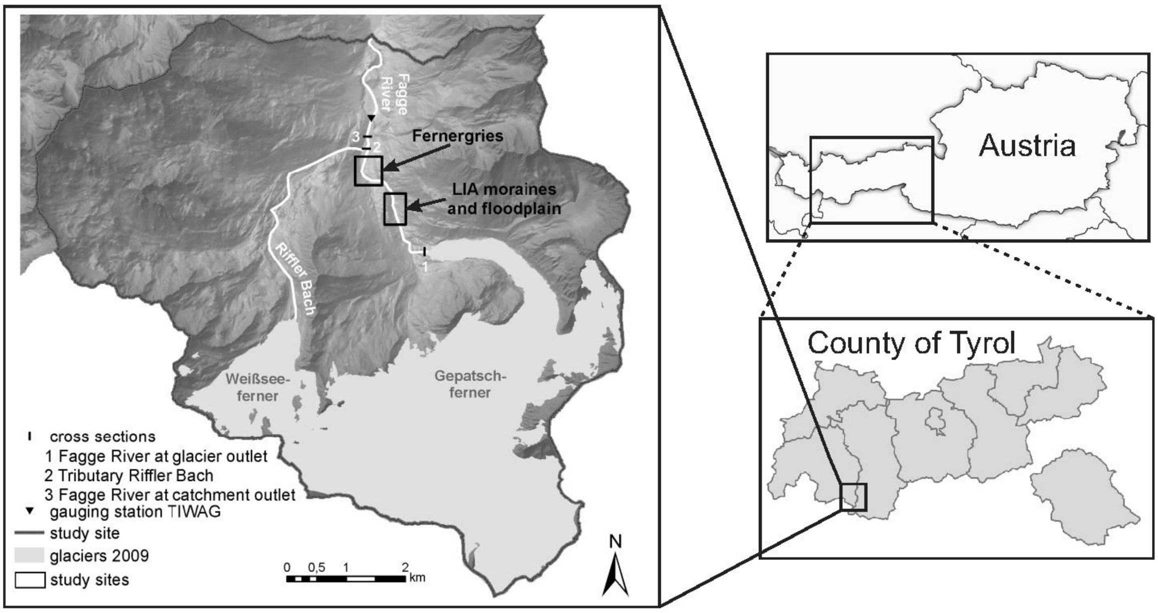

Fig. 1 Location of the study area in the Ötztaler Alps/Tyrol; shaded relief from 10 m DEM (data source: www.tirol.gv.at, http://de.wikipedia.org/wiki/Datei:Austria_map_modern.png, http://alt.tirol-travel.com/img/karten/karte-von-tirol-nur-schweiz.png).

MATERIALS AND METHODS

A multi-method approach will be used to quantify sediment transfers on a catchment scale. Important steps towards the establishment of a holistic sediment budget are: (1) to measure the fluvial sediment transport in the Fagge River, and (2) to detect the changes of important sediment stores by terrestrial and airborne LIDAR (LIght Detection And Ranging).

Sediment transport and discharge measurements Discharge and sediment transport were measured at three different locations: immediately proximal to the glacier outlet, at the mouth of the main tributary (Riffler Bach) and at the outlet of the catchment near the gauging station Gepatschalm (Fig. 1). Discharge measurements are carried out by using current meters in cross-sections near the recording stations. Suspended and dissolved sediment concentration will be determined from regular and event-triggered water samples. Turbidity will be used as a proxy for suspended sediment concentration (SSC) and electrical conductivity for the total dissolved solids (TDS). Water level, turbidity and electrical conductivity will be recorded in short intervals (5 to 15 minutes) over the ablation periods during the next few years. Bed load is measured during wadable stages with a 3 × 3 inch Helley-Smith bed load sampler (Fig. 2). The sampler is placed in several verticals on the river bed for 1 minute. Before snowmelt the water level of the Gepatsch Reservoir will be lowered, enabling the survey of fluvial delta deposits. The annual surface changes will be monitored by terrestrial laser scanning. The resulting net volume changes, which are assumed to be positive, can be compared to the measured fluvial loads of the upstream gauging station. During a first short field trip in September 2011, discharge and bed load were measured at three locations (Figs 1 and 2).

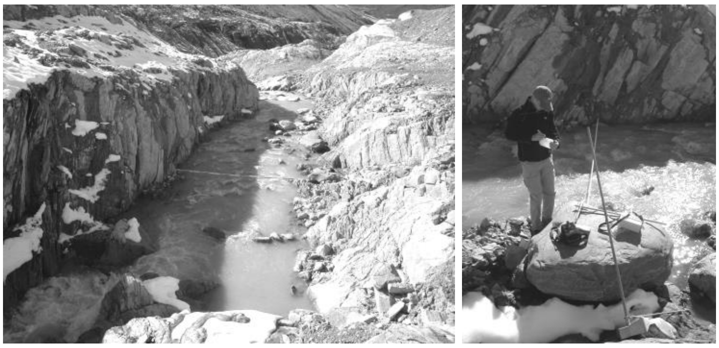

Fig. 2 The cross-section for discharge and bed load measurements in a small gorge near the glacier snout during low flow in September 2011 (the left photo views downstream, Photos David Morche).

Granulometric and geochemical analysis of bed load samples After drying the bed load samples were sieved using meshes in half-phi intervals (Udden-Wentworth-Scale). Grain size distributions as well as characteristic grain sizes (D_5, D_{10}, etc.) were calculated and the sorting coefficient after Folk & Ward (1957) was determined. The geochemical characteristics of the bed load samples were analysed by X-ray fluorescence using a Bruker SRS3000 x-ray spectrometer.

Ground based LIDAR

Data acquisition Large parts of the distal river reach (Fernergries, see Fig.1 for location) of the river Fagge were surveyed using the terrestrial LIDAR system ILRIS 3_6-D in September 2011. Two different positions above the river reach were chosen to scan the whole area. Additionally, a more detailed scan of the channel bed was carried out from one of the positions. One scan sequence of the entire study site consists of multiple single scans. For all scans the last pulse mode was adjusted. At a second upstream test site (beneath the LIA moraines see Fig. 1 for location) the laser scanner Riegl LMS Z420i was used from three different scan positions. A detailed description of the scanner system and the field work can be found in Haas *et al.* (2012).

Fig. 3 Terrestrial laser scanning of the distal Fernergries area using ILRIS 3_6-D (September 2011, photos David Morche).

Data processing and accuracy of the measurements TLS-data of the ILRIS 3_6-D were analysed with the software package PolyWorks. For data processing all scans were transformed into the pif-file format. The single scans were aligned to each other by using at least three manually-selected common points. Afterwards, an ICP algorithm, implemented in the Polyworks software, was used to merge the point clouds automatically. Different authors (e.g. Bellian *et al*., 2005; Abellan *et al*., 2006; Heritage & Hetherington, 2007; Rabatel *et al*., 2008; Hodge *et al*., 2009) gave a detailed description of the merging procedure and the ICP algorithm. In a subsequent step all unused points were deleted. The final point cloud was exported to an ASCII file for further investigation. This file was used to create a DEM of the channel bed reach (Fig. 7). The alignment of the three scan positions of the Riegl scans was done using the software Riscan Pro. The further processing steps were carried out in special LIDAR software (LIS). The accuracy of the measurements was derived by the "repeat surveys of unchanged surfaces" approach (Wheaton, 2008) and amounts to 0.234 m (2 SD). A detailed description of the processing steps and the calculation of the accuracy of the measurements as well as the calculation of the surface changes can be found in Haas *et al.* (2012).

RESULTS AND DISCUSSION

Morphodynamics of sediment stores and channel reaches In August 2011 the Fagge River was hit by an extreme flood event (Fig. 4). The gauging station Gepatschalm recorded the highest peak discharge (57.7 $m^3 s^{-1}$) in the last 24 years. Only during the important 1987 flood event more water (59.2 $m^3 s^{-1}$) was discharged (BMLFUW, 2010).

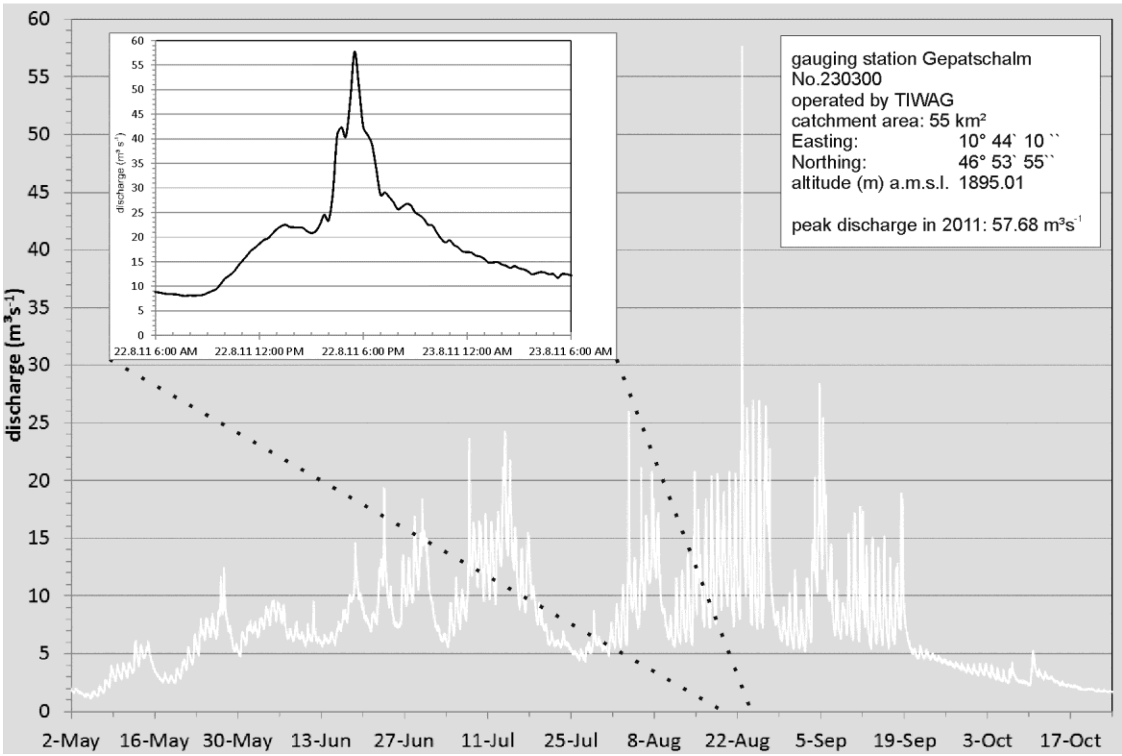

Fig. 4 Hydrograph of the Fagge River at gauging station "Gepatschalm" for the ablation period in 2011; the inset shows the event-hydrograph of the large flood on 22/23 August (data granted by TIWAG).

Measurements of the sediment budget of a flood-plain section of the Fagge River using LIDAR The Fernergries area was scanned for the first time in September 2011, so only photo-documentation of the great surface changes caused by the August 2011 flood can be provided (Fig. 5). A digital elevation model of the Fernergries area was calculated using the first laser scan data. The grid size of the DEM is 1 m. During the August 2011 flood an almost rectangular channel bend of the Fagge River was formed in the Fernergries area (Fig. 6). The channel reach

Fig. 5 Photographic documentation of surface and channel changes in the Fernergries area between July and September 2011. Black arrows mark unchanged surfaces (boulders, trees, building) (left photo by Henning Baewert, right photo by David Morche).

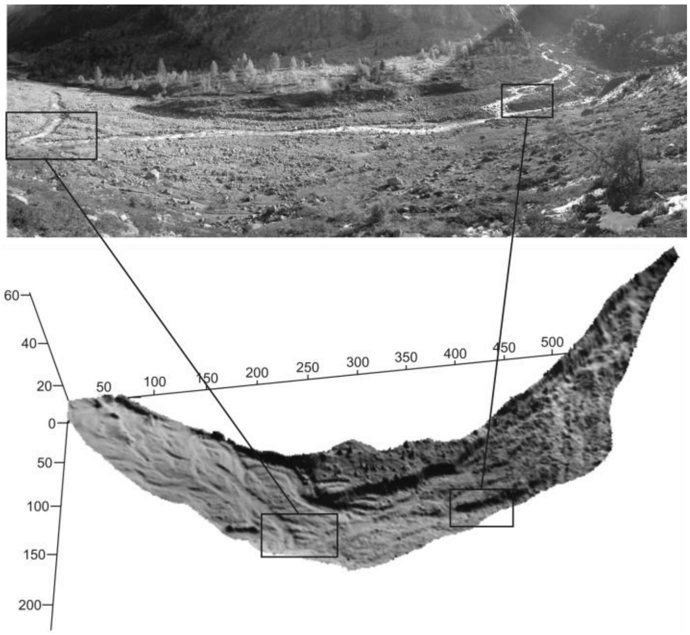

Fig. 6 Digital elevation model of the Fernergries area.

will be monitored in great detail as we assume that this bend is a very unstable fluvial landform. In contrast to the Fernergries, a few hundred metres upstream there are multi-temporal LIDAR data available for the braided river system at the base of the LIA lateral moraines (Haas *et al.*, 2012).

Figure 7 shows a cut and fill analysis of this part of the Fagge River. It is clearly visible that the Fagge River heavily eroded the slope by undercutting. This erosion adds up to 2749 m^3 of sediment, by a maximal lateral erosion of approx. 20 m (Haas *et al.*, 2012, this volume). As Haas *et al.* (2012) describe, in addition several slope-type debris flows were triggered on the slopes of the LIA moraines and provided 1033.5 m^3 sediment to the Fagge River. Summing the lateral erosion and debris flows, 3782.5 m^3 was delivered to the flood plain in this section of the Fagge River. At the flood plain itself, mainly accumulation (4944.1 m^3), and only very slight erosion (196.9 m^3) was measured. In the absence of data for the sediment input of the upstream parts of this flood plain and the sediment output from the flood plain, the sediment budget is certainly incomplete. Nevertheless, this incomplete budget shows that the flood plain at the moment acts as a sediment storage. The material will probably be remobilized during forthcoming events (e.g. snow melt in spring) and the surface of the flood plain then will again be remodelled.

Sediment transport The discharge at the glacier snout was very low (~1 m^3 s^{-1}) in September 2011. The tributary Riffler Bach supplied ~1.2 m^3 s^{-1} to the Fagge River. At the outlet of the catchment, a discharge of more than 2.8 m^3 s^{-1} was measured. During the concurrent Helley-Smith bed load measurements, only small amounts of sediment were sampled in all three surveyed cross-

Table 1 Results of discharge and bed load measurements at three different cross-sections (MBW – measured bed width, Q – discharge, HR – hydraulic radius).

Sample	Date	Dry weight (g)	MBW (m)	Unit bed load (g m^{-1} s^{-1})	Bed load (g s^{-1})	Q (m^{3}s^{-1})	Channel width (m)	Active channel width (m)	Cross-section area (m^2)	HR (m)	Mean channel depth (cm)	Mean velocity (m s^{-1})
Fagge River at glacier outlet	2011-09-23	19.5	0.76	0.43	2.54	1.03	5.95	5.95	1.11	0.17	18.70	0.92
Tributary Riffler Bach	2011-09-24	12.0	0.38	0.52	3.15	1.23	7.10	6.00	1.27	0.18	17.86	0.97
Fagge River at catch-ment outlet	2011-09-24	23.0	0.76	0.50	5.53	2.85	12.40	11.00	2.93	0.23	23.66	0.97

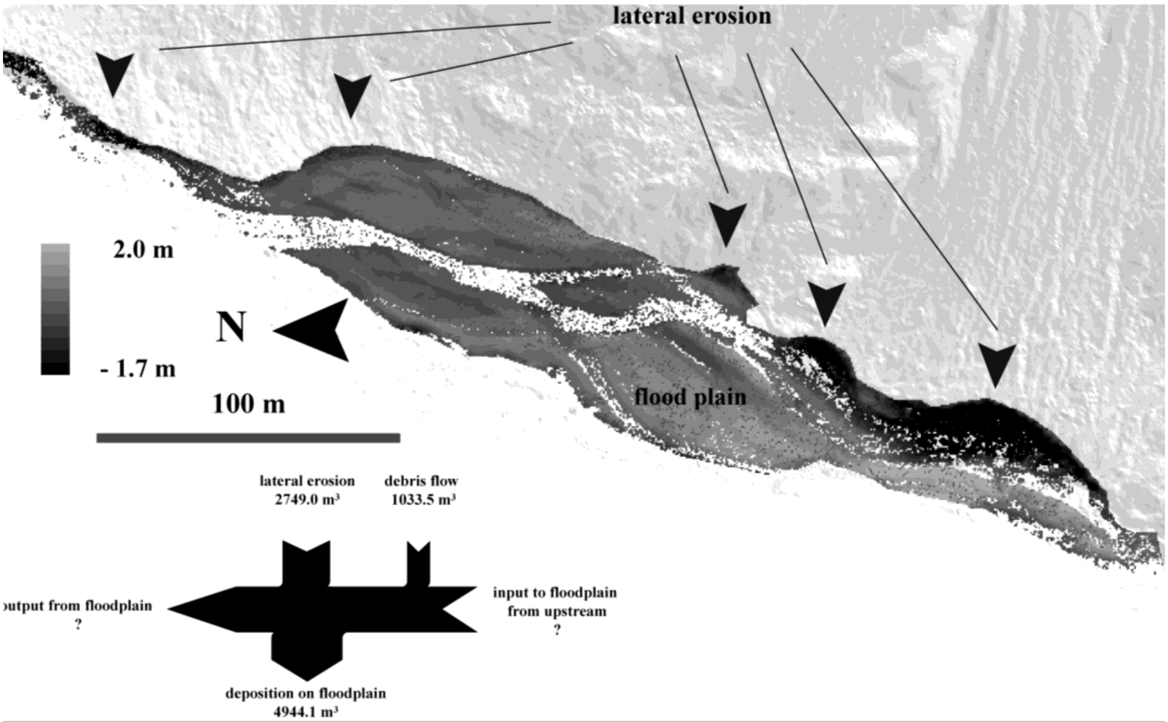

Fig. 7 Cut-and fill-analysis of the flood plain at the base of the LIA moraines draped on a hillside, based on a DEM with a resolution of 0.5 m and sediment budget of the flood plain and the coupled slope.

sections: 19.5 g at the glacier snout, 12 g in the Riffler Bach and 23 g in the Fagge River at the lowermost cross-section (Table 1). The active channel width is the part of the cross-section where bed load was measured. It was also different in all three cross-sections (Table 1). Only near the glacier outlet in the small gorge (Fig. 2) was the whole channel bed width active (5.95 m). In the Riffler Bach and in the Fagge near the outlet bed load occurred only in parts of the channel (width 6 m and 11 m, respectively).

Grain size and geochemical characteristics of bed load material The grain size distributions show clear differences between the materials sampled directly below the glacier and the tributary Riffler Bach or the Fagge River downstream. The sediments supplied by the glacier Gepatschferner are finer with more than 90% sand (Fig. 8, Table 2). The coarsest particles were sampled at the outlet of the catchment with a D_{95} of 8.8 mm. Due to the higher proportion of coarser particles in this sample the sorting is poor (Table 2). The bed load material sampled in the Riffler Bach and proximal to the glacier snout is moderately sorted (Table 2).

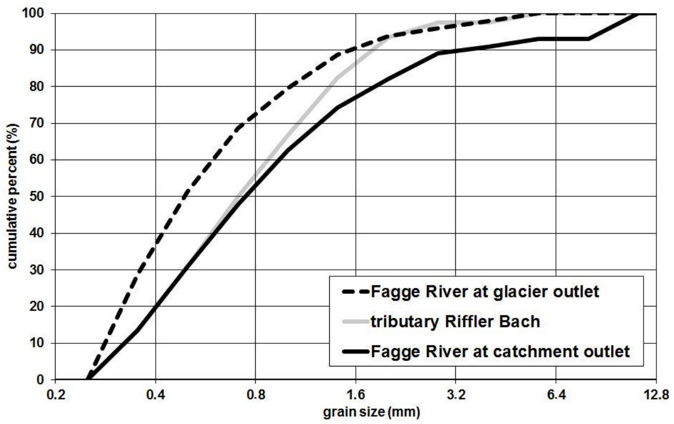

Fig. 8 Grain size distributions of bed load samples in the Fagge River system.

Table 2 Characteristic grain sizes and sorting (after Folk & Ward 1957) of the bed load.

Sample	Sorting (ϕ)	D_5 (mm)	D_{10} (mm)	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)	D_{90} (mm)	D_{95} (mm)
Fagge River at glacier outlet	0.98	0.27	0.28	0.30	0.49	1.18	1.54	2.43
tributary Riffler Bach	0.95	0.28	0.32	0.37	0.71	1.48	1.80	2.30
Fagge River at catchment outlet	1.39	0.28	0.32	0.37	0.74	2.19	3.36	8.82

Table 3 The proportions (in %) of the main geochemical components of the bed load, LOI = loss on ignition.

Sample	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	K_2O	CaO	MgO	TiO_2	CoO	Rb_2O	LOI
Fagge River at glacier outlet	70.97	13.72	3.36	3.44	2.14	1.72	1.41	0.44	0.015	0.009	2.05
tributary Riffler Bach	67.91	15.14	3.90	3.61	2.09	2.00	1.56	0.56	0.025	0.007	2.41
Fagge River at catchment outlet	68.00	15.24	3.85	3.69	2.05	2.04	1.55	0.57	0.016	0.008	2.06

The geochemical compositions of the three bed load samples show only small differences (Table 3). The main elements in all three samples are silicon and aluminium, more than 82% of the total.

CONCLUSIONS AND OUTLOOK

The substantial similarity in the geochemical composition of the bed load samples is an indicator for the analogous lithology in both sub-basins of the Fagge River catchment. According to geological mapping in the 1960s the prevailing lithology consists of Paragneiss (mica shist) and to a minor extent Orthogneiss (granite gneiss). The higher proportions of the element cobalt in the bed load sample from the Riffler Bach indicate the presence of amphibolite in the western part of the catchment (Fig. 9) (Geologische Bundesanstalt, 1989). The small grain sizes of bed load transported in the Fagge River and its tributary the Riffler Bach during low flow lead to the hypothesis that both rivers transport particles as bed load that basically originate from the glaciers or subglacial sediment stores. Further measurements are needed as many fine instream sediment stores were recognized during the later field trips. It is not clear whether this is the normal state of the Fagge River or if the river is still in a state of (transient) disequilibrium after the enormous August 2011 flood. The results of the present work clearly show the high potential of LIDAR data to calculate sediment budgets. In conjunction with measurements of the transported material in the channel it will be possible to derive complete sediment budgets of parts of the catchment. A detailed background of the research bundle PROSA is summarized in a companion paper (Heckmann *et al*., 2012).

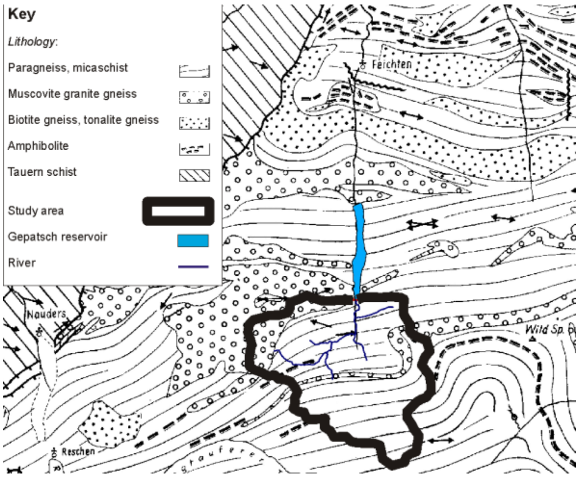

Fig. 9 Geological sketch of the catchment (after Schmidegg, 1964, cited in Purtscheller, 1978).

The field work and equipment will be fleshed out in the coming years in order to obtain highly resolved data sets on fluvial sediment transport dynamics in the proglacial zone of the Kaunertal valley and to derive, in combination with airborne and terrestrial LIDAR data, sediment budgets of sub-catchments of the Kaunertal valley.

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