GEOLOGICAL NOTE

Controls on Pebbles' Size and Shape in Streams of the Swiss Alps

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ABSTRACT

Although the size and shape of pebbles reflect the ensemble of sediment supply and transport processes along a stream, neither positive nor negative correlations have been found between the grain size of gravel bars, sediment flux, water discharge, and river flow strengths in Swiss streams. The relative frequency of 20°–30° hillslope angles per catchment is the only variable that positively correlates with the size of the largest clasts (D_{96} percentile). We relate these observations to the detachment-limited states of the Swiss streams where ongoing fluvial dissection steepens the bordering hillslopes, thereby promoting the supply of material through lithology-controlled failure.

Introduction

In mountainous streams, the size and shape of gravels bear crucial information about the transport dynamics and flow strengths of these streams (Hjulström 1935; Shields 1936; Blissenbach 1952; Koiter et al. 2013), the sources of sediment, the mechanisms of erosion and transport (Whittaker et al. 2007; Duller et al. 2012; Attal et al. 2015), and the controlling conditions, such as uplift and precipitation (e.g., Heller and Paola 1992; Robinson and Slingerland 1998; Foreman et al. 2012; Allen et al. 2013; Foreman 2014). Likewise, a stream's bedload material also depends on the bedrock's fabric and the petrological properties of the catchments where the sources of the deposits are (Parker 1991; Paola et al. 1992*a*; Attal and Lavé 2006). Accordingly, grain-size data offer relevant information for disclosing the sedimentary and hydrologic regimes during erosion, transport, and deposition of this material (Krumbein 1941; Paola et al. 1992*a*, 1992*b*; Rice and Church 1998).

The mechanisms by which grain size and shape change from the material source to the depositional site have often been studied with flume experiments (e.g., McLaren and Bowles 1985; Lisle et al. 1993) and/or numerical models (Hoey and Ferguson 1994). These studies have mainly been directed toward exploring the controls on the downstream grain-size reduction in gravel-bed rivers (e.g., Schumm and Stevens 1973; Hoey and Ferguson 1994; Surian 2002; Fedele and Paola 2007). Here, we report data about grain size and shape that we collected from a large variety of mountainous perennial streams situated in the Swiss Alps. These streams originate in basins that differ in terms of their lithological architecture, hillslope and channel morphometries, and ^{10}Be-based basin-averaged denudation rates (Wittmann et al. 2007; Norton et al. 2008; Cruz Nunes et al. 2015), and they have different flow strengths. We analyze the collected data to unravel correlations between these variables and grain size and shape. The ultimate goal is to identify the parameters that have a control on pebbles' size and shape in rivers of the Swiss Alps.

Studied Rivers. The studied rivers are spread over the entire Swiss Alps; their ^{10}Be-based denudation rates have been measured and their hydrologic and geologic conditions have been well established. We analyzed the grain-size population for a total of 18 gravel bars, which we have encountered in 8 different streams situated on the northern and southern sides of the Swiss Alps (fig. 1). For these streams, the measurement sites (table 1) are located at the nearest distance to gauging stations and to where river-borne material has been collected for estimating ^{10}Be-based denudation rates. Gauging sta-

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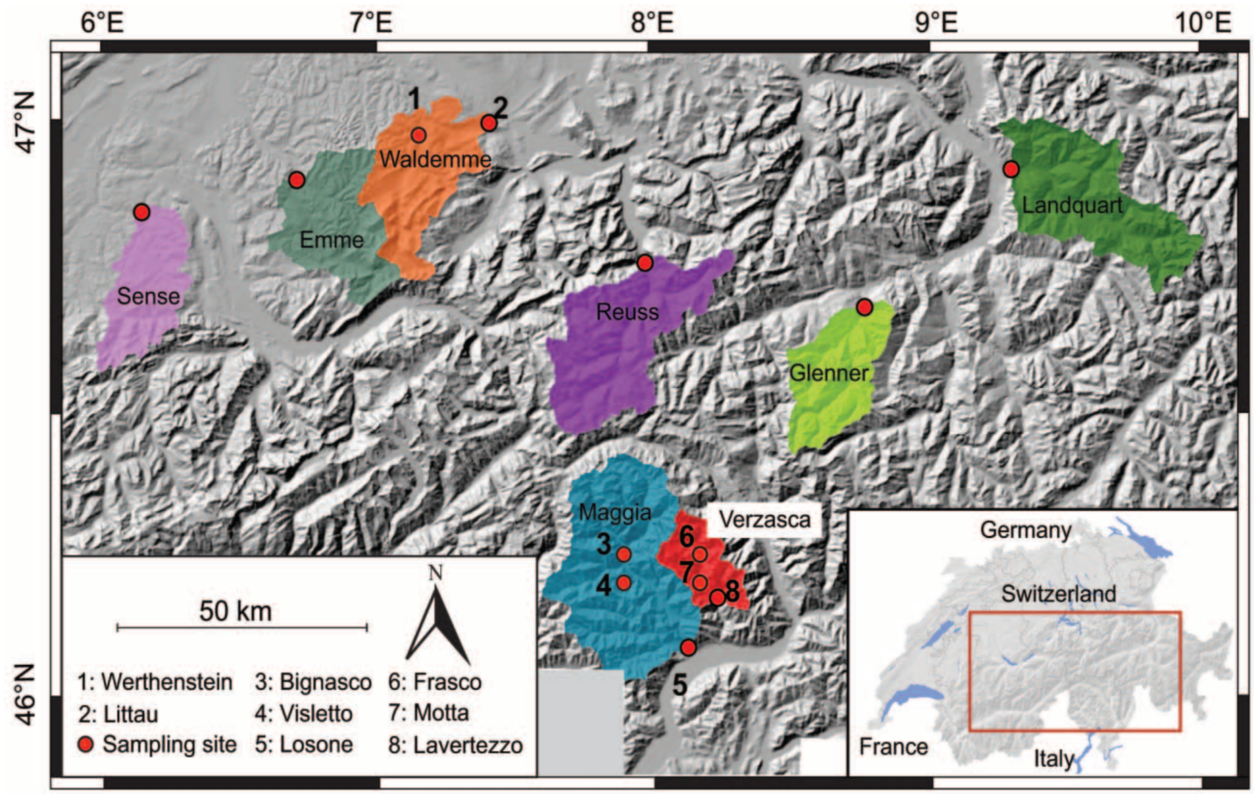

Figure 1. Hillshade map of the study area showing the studied watersheds and the sampling sites.

tions and the ^{10}Be sampling sites for erosion-rate estimates were situated at different locations along the rivers. Therefore, our sampling strategy was to take pictures between the two sites. In addition, the basins represent various tectonic properties and bedrock lithologies. While streams on the northern and northeastern sides have mainly been derived from basins that host sedimentary and metasedimentary rocks (Emme, Waldemme, Sense, Landquart, and Glenner), rivers that either originate in the core of the Alps (Reuss) or have their sources in the southern part of the orogen (Maggia and Verzasca) are situated in crystalline domains (fig. 2). In particular, the Sense River, which originates on the northwest-

Table 1. Altitude and Location (Latitude and Longitude in the CH1903 Projection) of the Sampling Sites

Site	Altitude (m asl)	Latitude (m)	Longitude (m)
Emme	260	623690	200213
Glenner	779	735989	178532
Landquart	621	766305	205045
Maggia Bignasco	429	689969	132386
Maggia Losone oben	215	702055	114958
Maggia Losone unten	210	702967	114022
Maggia Visletto	403	690200	129321
Reuss Ertfeld	476	692521	185758
Sense	550	593358	193019
Verzasca Frasco	866	704898	132845
Verzasca Lavartezzo	517	707977	123821
Verzasca Motta	633	705594	125830
Waldemme Littau	480	661902	211410
Waldemme Werthenstein bank 1	632	647868	209349
Waldemme Werthenstein bank 2	632	647868	209349
Waldemme Werthenstein bank 3	632	647868	209349
Waldemme Werthenstein bank 4	610	647836	209793

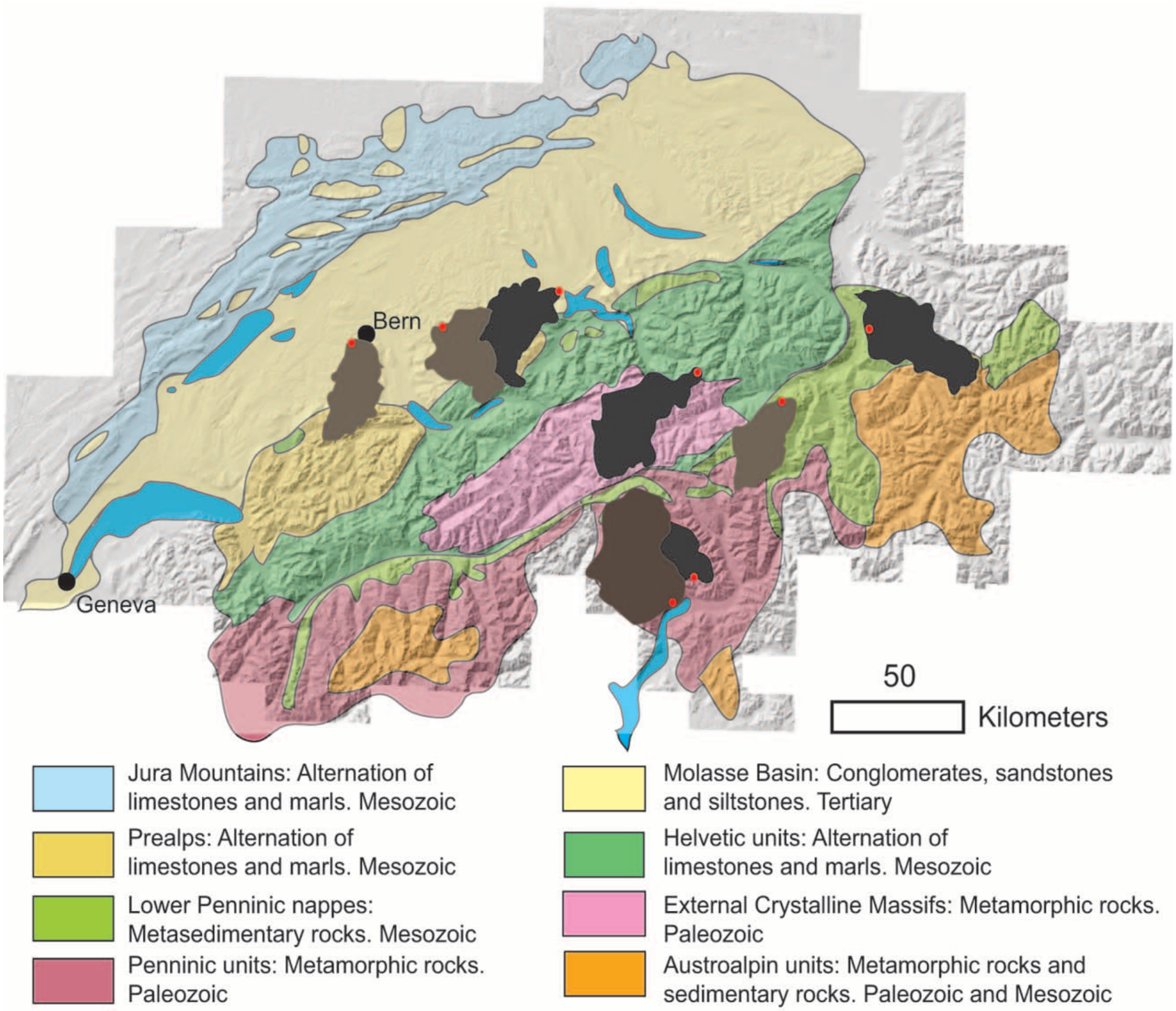

Figure 2. Simplified geological map of Switzerland showing the location of the rivers' catchments. A red circle marks the lowermost sampling site for each river.

ern margin of the Swiss Alps, takes its sources in Prealps sedimentary units that comprise alternated limestones, mudstones, and dolomites. The stream then crosses flysch nappes composed of sandstones and marls and flows in a ca. 150-m-deep inner gorge bordered by Oligo-Miocene sandstone suites of the Molasse Basin and Quaternary fluvioglacial material. The material of the Emme River is made up of recycled Oligo-Miocene conglomerates of the Molasse Basin and material derived from the Helvetic thrust nappes, where Cretaceous suites of limestones form the major lithology. The bedrock lithologies of the Landquart and Glenner basins, located in the northeastern margin of the Swiss Alps, are made up of Mesozoic low-grade schists and gneisses, while the bedrock of the Reuss basin comprises medium-grade granites and gneisses of the Aar Massif. On the southern side of the Alps, the Maggia and Verzasca basins mostly host high-grade leucogneiss of the Penninic crystalline nappe stack.

These basins are also characterized by different sizes and display a large variation in landscape properties. Among these, the hillslope gradient is presumably the most relevant variable, as it conditions, to a large extent, the mechanisms of erosion on the hillslopes (Ouimet et al. 2009), where most of a basin's sediment sources are situated.

Methods

Grain Size and Shape. Grain-size measurements were performed on digital images (e.g., fig. 3). At

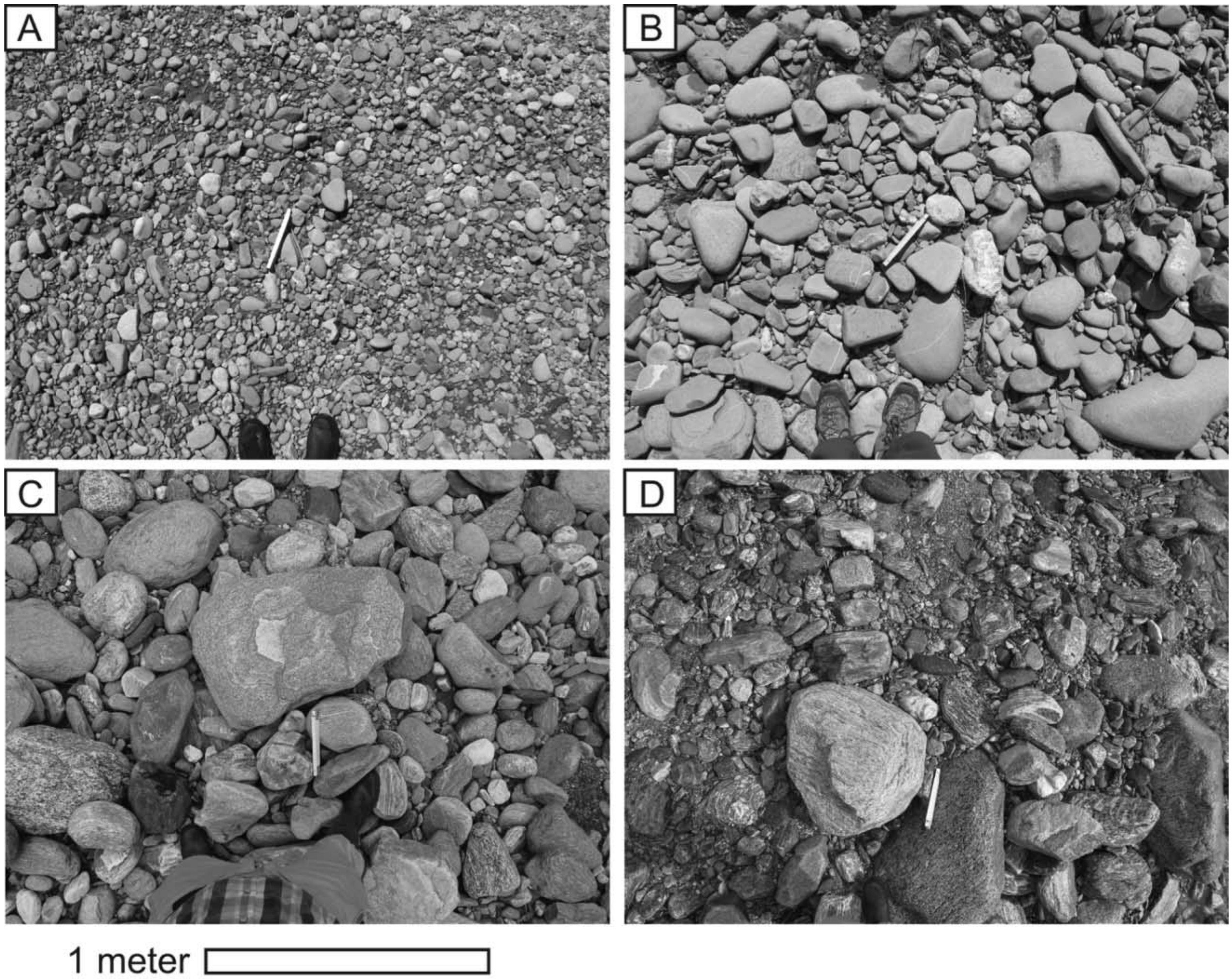

Figure 3. Digital images of sampling sites: *A*, Emme; *B*, Sense; *C*, Maggia Visletto; *D*, Verzasca Frasco. A color version of this figure is available online.

each site, the *b* (intermediate) axes of 500 pebbles were measured, and 200 additional pebbles were used to estimate the ratio between *a*- (long) and *b*-axes. A total of 200 measurements has been considered sufficient for reliable estimations of grain-size distributions (e.g., Rice and Church 1998). At each site, digital images were taken at five to seven different locations within an area of c. 200 m^2. The pebbles were characterized on the basis of their median (D_{50}), coarse (D_{84}), and maximum (D_{96}) fractions. On a gravel bar, pebbles tend to lie with their short axes perpendicular to the surface, thus exposing the section that contains the *a*- and *b*-axes. Therefore, it was not possible to measure the short (*c*) axis, which could be used to determine the pebbles' sphericity. Note, however, that the principal limitation is the inability to accurately measure fine (<3 mm) particles (see also Whittaker et al. 2010). While we cannot resolve this problem with available techniques, we do not expect that this adds a substantial bias in the grain-size distributions reported here because their relative contributions to the results are minor (i.e., <5%, based on visual inspection of the digital images). From a visual estimate, the shape and particularly the roundness of the pebbles were analyzed.

Channel and Basin Morphometries. The stream's gradient at the sampling site was averaged over a 500-m-long reach, and the upstream size of the watershed was extracted from a 2-m digital elevation model provided by Swisstopo (http://www.swisstopo.admin.ch). Hillslope angles were categorized into 10° classes, and related percentages of occurrence were extracted for these classes. Also, at each site, we measured the stream channel widths, on orthophotos, along the same 500-m-long reach used for the stream's gradient. These variables were used to estimate the flow strength at the sites where the grain-size data were collected. Sediment flux was calculated by multiplying the upstream size of the basin and the ^{10}Be-based denudation rates.

Flow Strengths. Water shear stress was compared to the critical shear stress required to entrain the material. Following Hancock and Anderson (2002), which has been modified by Litty et al. (2016), water shear stress was computed through

$$\tau = 0.54\rho g\left(\frac{Q}{W}\right)^{0.55} S^{0.935}, \quad (1)$$

where $\rho = 1000$ kg/m^3 is the water density, g is the gravitational acceleration, Q is the water discharge (m^3/s) that we obtained at the gauging stations operated by the Swiss Federal Office for the Environment (http://www.hydrodaten.admin.ch), W is the channel width (m), and S is the channel gradient (m/m). The critical shear stress τ_c (N/m^2) for the entrainment of sediment with a particular grain size can be obtained through Shields criteria. Shields (1936) showed that for near-uniform grains, represented best by the D_{50} percentile, the Shields variable attains a constant value of c. 0.06 in the case of rough turbulent flow over a narrowly graded sediment bed coarser than sand:

$$\tau_{cD50} = 0.06(\rho_s - \rho)gD_{50}, \quad (2)$$

where $\rho_s = 2700$ kg/m^3, which corresponds to the densities of quartz, feldspar (slightly lower), and carbonate minerals, is used as bulk sediment density because a large portion of pebbles are abundant in these constituents. However, subsequent studies showed that values of related Shields parameters vary considerably, depending on the relative grain size (i.e., percentile) under consideration and the sorting of the material (e.g., Buffington and Montgomery 1997). According to Church (2002), using a value of 0.03, which is commonly found for higher percentiles such as the D_{84} and the D_{96}, appears to be a conventional approach for individual, well-exposed gravel, cobble, or boulder clasts. We thus followed Church's suggestion for the use of the D_{96} grain-size percentile, where

$$\tau_{cD96} = 0.03(\rho_s - \rho)gD_{96}. \quad (3)$$

Results

The measurements of the grain sizes reveal a large spread for the *b*-axis, where the values of the D_{50} range from 0.75 cm at Verzasca Frasco to 2.88 cm at Glenner (table 2). Likewise, values for the D_{84} vary between 2.3 cm at Emme and 12 cm at Glenner, while the sizes for the D_{96} reveal the largest spread, ranging from 5.2 cm at Emme to 30 cm at Verzasca Lavertezzo. The sizes of the largest clasts encountered in the gravel bars range from 30 cm at Glenner to 32 cm at Verzasca Lavertezzo.

The relative grain-size percentiles differ between streams that are derived from basins made up of sedimentary rocks and those where the basins' bedrock mainly comprises metamorphic and crystalline rocks. In streams of the first group, the values of the D_{50} converge to c. 1.84 cm on average, while the mean of the identical percentile for the second group of streams measures 1.44 cm. For the coarser percentile D_{84}, the values converge to a mean value of 5.45 cm for both groups of streams. In contrast, the mean of all D_{96} values is much larger for streams sourced in metamorphic and crystalline rocks, aver-

Table 2. D_{50}, D_{84}, and D_{96} of Each Site and the Ratio between the *b*-Axes and the *a*-Axes

Site	D_{50} (cm)	D_{84} (cm)	D_{96} (cm)	Ratio *b*/*a*
Emme	.9	2.3	5.2	.678
Glenner	2.88	12	27.4	.636
Landquart	2.5	10	13.5	.652
Maggia Bignasco	.85	2.66	12.97	.684
Maggia Losone oben	.79	4	14	.694
Maggia Losone unten	1.12	6	12.65	.676
Maggia Visletto	2.29	9.5	20	.67
Reuss Ertfeld	.88	3.18	6.37	.695
Sense	2.42	6	9.58	.688
Verzasca Frasco	.75	2.5	7	.687
Verzasca Lavartezzo	1.3	5	30	.689
Verzasca Motta	1.44	4.33	18.75	.681
Waldemme Littau	.9	3.52	8.36	.723
Waldemme Werthenstein bank 1	1	3	9	.688
Waldemme Werthenstein bank 2	2.43	8	18	.693
Waldemme Werthenstein bank 3	2.57	5.71	14	.722
Waldemme Werthenstein bank 4	2.68	8.62	18	.722

aging 15.4 cm, while the corresponding value measures 11.7 cm for the streams sourced in sedimentary units. The data show that the grain-size population of rivers where the bedrock is made up of metamorphic and crystalline rocks (second group) has smaller D_{50} but larger D_{96} values, on average, than those that are derived from basins made up of sedimentary rocks (first group; table 2). Accordingly, gravel bars of the first group of streams tend to be better sorted than those of the second group of rivers, where metamorphic and crystalline rocks represent the major lithological constituents. In the same sense, the shape of gravel-bar clasts differs, depending on whether the bedrock of the basins comprises sedimentary or metamorphic/crystalline rocks. The pebbles of the first group of rivers are better rounded and display much smoother surfaces than clasts of the second group of streams (fig. 3). It thus appears that sediment particles have responded differently upon erosion and transport, depending on the fabric of the parent bedrock material.

Remarkably, for all these different pebbles sizes, the ratios between the *b*- and *a*-axes range only between 0.63 and 0.72, without displaying any dependency on the lithology (table 2). This ratio, denoted here as *E*, corresponds to the elongation of the pebbles.

We found no correlation between basin-averaged denudation rates and any of the grain-size percentiles (fig. 4*A*). Likewise, there are no relationships between grain size, the long-stream distance of the streams, and the size of the catchments (table 3). In the same sense, no correlations were found between water discharge recorded by the gauging stations, the streams' shear strengths, sediment flux, and the different grain-size percentiles (fig. 4*B*–4*D*). In addition, also for each stream, we found that flow shear stresses exerted by both the mean and the maximum water discharge are much larger than the critical shear stresses for the entrainment of the corresponding percentile. The D_{96} percentile and the percentage of slopes ranging between 20° and 30° in the catchments (fig. 5) display the only positive correlation (albeit with a low correlation coefficient of $R^2 = 0.29$).

Discussion

Controls of Denudation Rates and the Streams' Hydrology on Grain Size and Shape. While changes in erosion rates all around the globe have been shown to have an impact on the grain size of gravel-bed rivers, including the peri-Alpine region and the Northern Apennine Foredeep (e.g., Peizhen et al. 2001; Attal et al. 2015), we did not find any correlations between these variables. In the same sense, it has been reported that the grain size in streams and related depositional systems tends to decrease downstream (downstream fining; e.g., Paola et al. 1992; Surian 2002), which implies that the downstream distance from one or several potential sediment sources should have an impact on the pebbles' average sizes (Paola et al. 1992*b*; Hoey and Ferguson 1994; Rice 1999; Surian 2002). Furthermore, it has also been shown that the sorting of the material depends on the downstream distance from a sediment source through selective deposition, where finer-grained sediment particles are transported over a longer reach than coarser

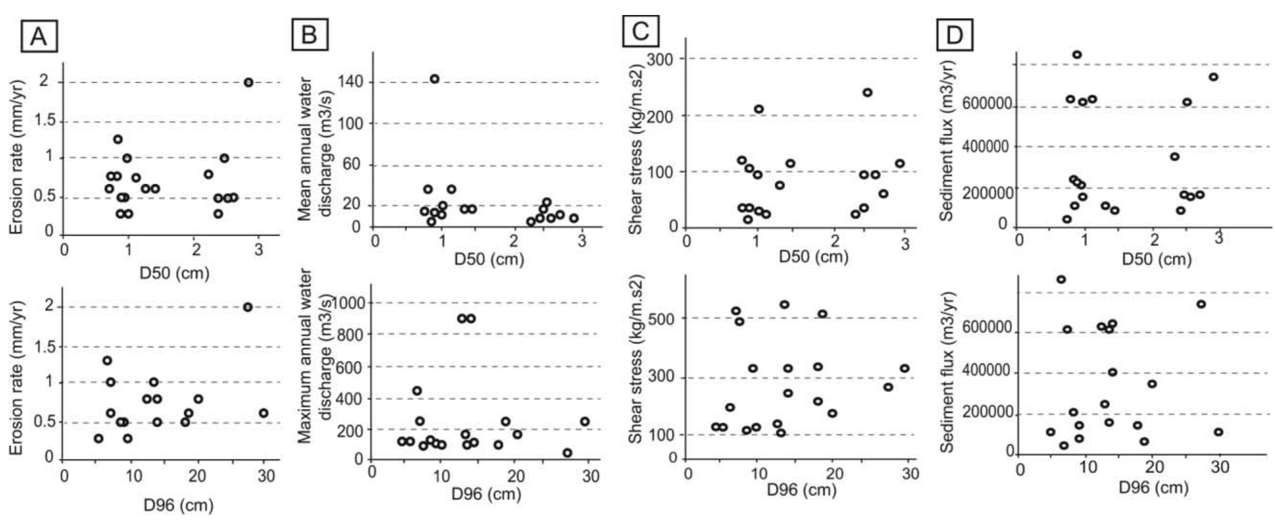

Figure 4. *A*, Erosion rates versus the grain-size percentiles D_{50} and D_{96}. *B*, Mean water discharge versus D_{50} and maximum water discharge versus D_{96}. *C*, Shear stress versus D_{50} and D_{96}. *D*, Sediment flux versus D_{50} and D_{96}.

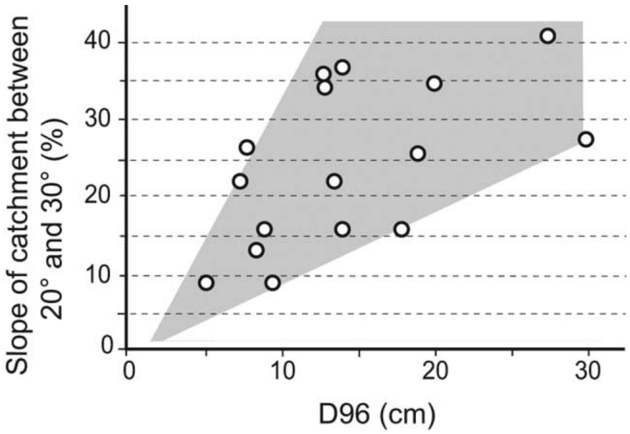

Figure 5. Correlation between the D_{96} percentile and the relative frequency of hillslope occurrence where the corresponding angles range between 20° and 30° in the catchments.

grains during a given flood (Hoey and Ferguson 1994; Kodoma 1994; Paola and Seal 1995). However, in our case, no relationships have been found between the upstream size of the catchment and the grain morphometries or between the upstream lengths of the streams and the pebbles' morphometries. The lack of correlation between these variables suggests that either transport distance has no controlling power on these variables or sediment is not supplied at distinct, and thus spatially constrained, sites (Rice and Church 1998). We rather consider a scenario where sediment has been supplied at multiple sites along the streams' courses, which has most likely been accomplished through a combination of mass-failure processes along the rivers' margins (e.g., Cruz Nunes et al. 2015) and material supply from several tributary torrents (Bekaddour et al. 2013). Apparently, the spatial scale at which sediment is supplied to the trunk streams is shorter than the length of the downstream reach that is required to sort the material.

The hydrodynamic conditions of streams influence the grain size upon entrainment, transport, and deposition (Hjulström 1935; Komar and Miller 1973; Surian 2002). Accordingly, we expect a correlation between the grain-size distribution and the water runoff and related water shear stresses at our surveying sites, because greater flow strengths are required to entrain the coarser fractions of the material that make up the riverbeds (e.g., Ferguson et al. 1989; Komar and Shih 1992). However, this appears not to be case in the Alpine streams, as no relationships have been found between these variables. Furthermore, the calculated water shear stresses are much greater than the critical shear stresses required to transport the bedload (table 3). Our observations are thus consistent with the inferred detachment-limited state of most of the Alpine streams (Habersack and Piégay 2007), where excess stream power, or flow strengths, might explain the lack of correlation between these variables. The question then arises why deposition of gravels occurs, given the finding that discharge on an annual basis can easily transfer some of the material. We consider it likely that these bars accumulate gravel during waning floods, when flow strengths fall below threshold conditions for gravel entrainment.

Controls of Hillslope Angles and Bedrock Lithology on Grain Size and Shape. The only relationship we found is a correlation between the D_{96} and the percentage of slopes in the basin ranging between 20° and 30°. It has been shown that this slope range corresponds to the conditions where hillslopes are at at-yield mechanical strength for failure, particularly in the Swiss Alps (Schlunegger and Norton 2013). We thus propose a scenario where detachment-limited streams tend to incise into bedrock, thereby (over) steepening the bordering hillslopes and causing failures. Indeed, Korup and Schlunegger (2009), Valla et al. (2010), and Dürst Stucki et al. (2012) showed the occurrence of multiple bedrock inner gorges in the Swiss Alps where streams have dissected into the bedrock and where hillslopes are at threshold conditions for failure. As the hillslope angles between 20° and 30° most likely reflect threshold conditions for mass failure, the positive correlation (albeit with a poor correlation coefficient, $R^2 = 0.29$) between the relative frequency of this variable per basin and the sizes of the largest clasts suggests that mass-failure processes along the streams possibly have a large impact on the grain-size population through the supply of coarse-grained material. In this context, we interpret that a higher relative frequency of hillslopes in a presumably limited state is likely to result in an increase in the supply rate (i.e., the volume per unit time) of large material (meter-scale bedrock blocks) through mass-failure processes, which, in turn, might explain the increase in the relative abundance of the largest clasts. It is thus likely that this geomorphic situation, most likely conditioned by the glacial inheritance (Norton et al. 2010; Dürst Stucki et al. 2012), may provide an explanation for the observed correlation here. Indeed, landscapes with a strong glacial inheritance (Brocklehurst and Whipple 2002, 2004) tend to result in a situation where the hydrological conditions of a stream do not necessarily have to comply with erosion, sediment transport, and thus the sediment properties of streams' gravel beds. In the case of the Central Alps, Valla et al. (2010) and Norton et al. (2010) have provided evidence to argue that a large portion of the

Table 3. Morphometric Properties of Basins and Rivers

	Area (km^2)	Local gradient	Channel width (m)	Long distance (km)	Slopes (S, %) 0–5°	5–10°	10–20°	20–30°	30–40°	40–50°	>50°	Erosion rate (mm/yr)	References
Emme	436	.0078	30	39	11.7	27.6	49.6	8.5	2.1	.5	.0	.25	Wittmann et al. 2007
Glenner	370	.0255	20	35	1.0	4.6	28.8	40.9	21.8	2.9	.0	2	Cruz Nunes et al. 2015
Landquart	619	.0486	32	39	3.7	11.2	61.0	21.6	2.6	.0	.0	1	R. Delunel, personal commu-nication
Maggia Bignasco	322	.0074	46	25	1.7	3.3	17.0	34.3	30.8	11.9	1.0	.78	Wittmann et al. 2007
Maggia Losone oben	819	.0042	22	49	2.4	3.4	18.2	36.3	30.9	8.0	.7	.77	Wittmann et al. 2007
Maggia Losone unten	819	.0050	84	49	2.6	3.6	18.3	36.1	30.8	7.9	.7	.77	Wittmann et al. 2007
Maggia Visletto	441	.0075	22	29	1.7	3.3	18.9	34.7	29.3	11.0	1.1	.78	Wittmann et al. 2007
Reuss Ertfeld	662	.0081	48	41								1.29	Wittmann et al. 2007
Sense	350	.0081	24	33	19.8	32.0	37.9	8.3	1.9	.0	.0	.25	Wittmann et al. 2007
Verzasca Frasco	64	.0245	31	11	.8	2.3	8.4	25.9	40.5	22.0	.0	.6	Wittmann et al. 2007
Verzasca Lavartezzo	184	.0148	31	22	.7	2.4	10.2	27.0	40.5	19.1	.0	.6	Wittmann et al. 2007
Verzasca Motta	125	.0226	27	18	.7	2.9	8.8	26.0	41.7	19.9	.0	.6	Wittmann et al. 2007
Waldemme Littau	461	.0067	27	49	13.5	24.6	44.5	13.2	3.6	.6	.0	.48	Wittmann et al. 2007
Waldemme Werthenstein bank 1	316	.0223	25	32	8.9	22.9	48.1	15.6	4.5	.1	.0	.48	Wittmann et al. 2007
Waldemme Werthenstein bank 2	316	.0223	25	32	8.9	22.9	48.1	15.6	4.5	.1	.0	.48	Wittmann et al. 2007
Waldemme Werthenstein bank 3	316	.0223	25	32	8.9	22.9	48.1	15.6	4.5	.1	.0	.48	Wittmann et al. 2007
Waldemme Werthenstein bank 4	316	.0142	25	32	8.9	22.9	48.1	15.6	4.5	.1	.0	.48	Wittmann et al. 2007

	Erosion rate sampling site[a] (m)		Sediment flux	Annual mean discharge	Annual maximum discharge	Position of the gauging station[a]		Shear stress (water discharge)		Critical shear stress		Main	
	E (m)	N (m)	(m^3/yr)	(m^3/s)	(m^3/s)	E (m)	N (m)	Mean	Maximum	Using D_{50}	Using D_{96}	lithology	Main rocks
Emme	615000	209000	109,000	12	130	623610	200420	38	129	9	26	Sedimentary	Sandstone
Glenner	735889	181908	740,000	8.9	43	735330	181790	117	261	29	137	Metamorphic	Gneiss
Landquart			619,000	24.4	90	765365	204910	241	553	25	67	Sedimentary and metamorphic	Limestone
Maggia Bignasco	690430	133390	251,160	4	170	690040	132550	16	112	8	65	Metamorphic	Gneiss
Maggia Losone oben	695120	138650	630,630	23.2	900	703100	113860	41	244	8	70	Metamorphic	Gneiss
Maggia Losone unten	691930	128780	630,630	23.2	900	703100	113860	23	137	11	63	Metamorphic	Gneiss
Maggia Visletto	690430	133390	343,980	4	170	690040	132550	24	168	23	100	Metamorphic	Gneiss
Reuss Ertfeld	707940	165830	853,980	140	450	662830	252580	106	201	9	32	Metamorphic	Granite
Sense	591000	186000	87,500	8.6	100	593350	193020	36	128	24	48	Sediment	Limestone
Verzasca Frasco	708830	123470	38,400	10.8	250	708420	122920	120	529	8	35	Metamorphic	Gneiss
Verzasca Lavartezzo	708830	123470	110,400	10.8	250	708420	122920	75	330	13	150	Metamorphic	Gneiss
Verzasca Motta	708830	123470	75,000	10.8	250	708420	122920	118	521	14	94	Metamorphic	Gneiss
Waldemme Littau	659500	211480	221,280	15.7	130	663550	213785	35	116	9	42	Sedimentary	Sandstone
Waldemme Werthenstein bank 1	659500	211480	151,680	11	105	647870	209510	95	333	10	45	Sedimentary	Sandstone
Waldemme Werthenstein bank 2	659500	211480	151,680	11	105	647870	209510	95	333	24	90	Sedimentary	Sandstone
Waldemme Werthenstein bank 3	659500	211480	151,680	11	105	647870	209510	95	333	26	70	Sedimentary	Sandstone
Waldemme Werthenstein bank 4	659500	211480	151,680	11	105	647870	209510	62	218	14	90	Sedimentary	Sandstone

Note. "Long distance" corresponds to the distance between the source of the river and the sampling site. The table also presents the percentage of slope occurrence within the basins. The erosion rates were taken from the available literature (see text for references). Please note that for the Waldemme, Maggia, and Verzasca sites, only one erosion rate per catchment has been measured and is available in the literature. Since the ^{10}Be technique averages out major variabilities in local denudation rates, it is safe to assume that the basin-averaged denudation rate is nearly of the same order in the entire basin, as no samples have been taken in the vicinity of knickzone areas. The sediment fluxes were calculated by multiplying the erosion rates by the basins' areas. The annual mean and maximum water discharges were collected from the available gauging records of the Federal Office for the Environment (http://www.hydrodaten.admin.ch). Shear stress values are based on the annual mean water discharge and are calculated through equation (2), while peak shear stresses are based on the annual maximum water discharge and are computed through equation (3). Critical shear stresses were calculated with equation (1) for the different grain-size percentiles. The main lithology corresponds to the main rocks from which the basins are made and therein corresponds to the main lithological source of the sediment.

[a] CH1903 projection.

erosional work is likely to be accomplished in inner gorges, where detachment-limited bedrock channels are bordered by oversteepened bedrock hillslopes. These gorges operate as communication links between hanging tributary and trunk valleys, the situation of which has been conditioned by glacial sculpting during past glaciations (Norton et al. 2010). Accordingly, we relate the positive correlation between the relative abundance of threshold hillslopes per basin and the D_{96}, plus the lack of positive and negative correlations between the grain-size percentiles and any other variable, to (1) the landscapes' transience, characteristic for the Central Alps, and (2) the inferred occurrence of most erosional work in inner gorges. A consequence of this is that ^{10}Be-based denudation rates have to be treated with care (van den Berg et al. 2012).

Studies have shown that lithologies and variation in the grain-size distribution of the supplied sediment play a role in controlling the fining rate within a stream through abrasion and fracturing (Attal and Lavé 2009) and act as a first-order control on the sequence stratigraphic architectures in sedimentary basins (Allen et al. 2015). In particular, pebbles from different geological parent material expose variable predispositions for evolving during erosion, transport, and deposition. This mainly depends on the density, mass strength, and geologic fabric of the parent material and thus also of the clasts in transport (Attal and Lavé 2006). This appears to be corroborated by our observations that gravel-bar deposits of rivers derived from sedimentary lithologies are better sorted than the ones derived from basins made up of metamorphic rocks.

The lithology of the parent material apparently also affects the shape of the pebbles, particularly their roundness. We found that pebbles in streams derived from sedimentary rocks are better rounded and display much smoother surfaces than clasts with sources in metamorphic and crystalline lithologies. Pebbles from metamorphic rocks in general, and from metasedimentary rocks in particular, are less rounded than those derived from sedimentary rocks (Di Capua et al. 2016). Indeed, metamorphic rocks generally host several deformation planes and thus break down during transport in streams by a mechanism different from that for, for example, limestone pebbles, where that lack of distinct horizontal fabric favors the occurrence of abrasion during transport (Drake 1970). We use these differences in lithological conditioning to explain the variable shapes of the river-borne clasts.

We cannot properly address the pebbles' sphericity, as the short axis was not measurable on photos. However, it is likely that the pebbles derived from sedimentary rocks would be more spherical than the ones from metamorphic parents. Indeed, Drake (1970) suggested that anisotropic rocks, like metamorphic rocks with a distinct planar fabric, will fracture into less spherical fragments than isotropic lithologies.

Conclusions

River processes such as erosion and transport affect sediment dynamics. Pebbles' size and shape reflect these and can be used to explore the controls exerted by fluvial processes. Because we have found no correlations between the grain size of gravel bars in Swiss rivers and related water discharge and flow strengths, we consider that fluvial processes appear not to exert the principal controls on the river-borne pebbles' size and shape. Instead, we interpret that the morphology and morphometry of the riverbed material is mainly conditioned by the lithological properties of the parent material and the supply of material through mass-failure processes, at least in the Swiss Alps. Despite this, we identified a constant elongation index, $0.63 < E < 0.72$, that depends on neither the streams' hydrologic properties nor the lithology of the clasts. This constant can thus be used for further studies on grain size in streams to simplify the collection of data characterizing the morphometric properties of river-borne material.

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