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Downstream fining in a megaclast-dominated fluvial system: The Sabeto River of western Viti Levu, Fiji

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ABSTRACT

Megaclast-dominated fluvial systems have been largely ignored by researchers. Yet megaclasts exert an important control on channel geomorphology, flow behaviour and sediment transport, and such systems are probably far more common than this neglect would suggest. Despite the explicit identification of megaclasts as the products of cataclysmic flow, observation of modern fluvial systems confirms that megaclasts can be entrained by flows that lie within the normal flow regime.

The pattern of fining along the megaclast-dominated Sabeto River of western Viti Levu, Fiji reveals a strong negative exponential relationship between particle size and distance downstream, and a rate of downstream fining comparable with that of other gravel-bed rivers. The downstream fining pattern is straightforward and step-like discontinuities in the fining gradient are absent. This is suggestive of a sedimentary system only minimally disrupted by the supply of sediment from tributaries or the reworking of material from sources such as hillslopes and alluvial terraces. There is evidence, however, of anomalously coarse sub-populations at two sites. These coarser components must pre-date the other deposits at the sites. We speculate that they represent the products of earlier and higher-magnitude events. The bed sediments may thus be composite features, made up of individual components each transported by a specific event of particular magnitude.

Our work confirms the relationship between the rate of downstream fining and particle size. This may arise because the distance over which individual particles are transported is likely to be size dependent. It is also possible that abrasion may be more effective in the case of larger particles than smaller ones, with the result that the coarser fraction of the river's bed sediment fines downstream more rapidly than the finer fraction.

There is a long-standing debate about the relative roles of abrasion and sorting in downstream fining. Our data reveal little evidence for a downstream increase in the roundness of the river's gravels, implying that abrasion is likely to play a minor role in the fining process in this system.

1. Introduction

One of the most notable and conspicuous characteristics of rivers is the tendency of fluvial bed sediments to become finer with distance downstream. This phenomenon exerts a primary control on river geomorphology, playing a critical role in downstream changes in the planform of the river, in the extent of floodplain development and in the nature of the river's long profile (see, for example, Mackin (1948, pp. 481–483) and Seal et al. (1997, p. 874)). It contributes to our understanding of the sedimentary processes that operate in rivers, throwing particular light on the relative roles of sorting and abrasion in generating the size distributions of fluvial sediments. And it has been employed as a tool in the interpretation of the sedimentary record (see, for example, Pelletier (1958, pp. 1053–1056) and Minter and Loen (1991, pp. 71–72)).

Downstream fining has been the subject of numerous investigations, although many of these have been at the reach-scale or have involved the investigation of sedimentary behaviour in laboratory flumes or abrasion experiments and do not deal with the pattern of sedimentation over the entire length of the system. More significant has been the neglect of work on the coarsest components of the river's bedload, with a complete absence of research on systems dominated by megaclasts (that is, particles coarser than −11 phi units (2.048 m) in diameter (Blott and Pye, 2012)). This is understandable. Such particles tend to be located in the hard-to-reach headwaters of river systems and are not easily amenable to measurement (see, for example, Chatanantavet et al. (2010, pp. 8–9)). Yet fluvial megaclasts are probably more common than the literature would suggest. Aside from those reported in

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this study, we have recorded megaclasts with *b*-axes in excess of 4 m in the remote upstream reaches of Nabukavesi Creek in southern Viti Levu in Fiji and have observed imbricated megaclasts with *b*-axes > 2 m in the upstream parts of the Houai Xai river in the mountains of Phou Khao Khouay in central northern Laos. Kehew et al. (2010) recorded stream-entrained boulders and megaclasts reaching sizes of 5 m within and downstream of the bedrock canyon of the Wadi Isla in the mountains of the Sinai Massif, whilst stream-transported clasts of up to 3.6 × 3.7 × 7.0 m were carried by the 1976 flood along the Big Thompson River in the foothills of the Front Range in Colorado, USA (Shroba et al., 1979, p. 113).

One consequence of this neglect is that we have little understanding of the role of megaclasts in contributing sediment to the lower parts of the river system and in determining flow behaviour in boulder-bed channels. Large, relatively immobile grains possess roughness values that are comparable with flow depth. They cause increased turbulence, local flow acceleration, large spatial variations in velocity and stress, hydraulic jumps and fluid aeration (Yager et al., 2007). The largest grains bear a significant portion of the total shear stress in coarse bedload streams. As a result, the stress available to move the finer sediment is reduced and conventional bedload transport equations typically overpredict sediment flux by several orders of magnitude (Yager et al., 2007; Ghilardi, 2014).

The geometry of the macro-roughness elements in megaclast channels and the resultant flow complexity mean that classical flow resistance equations cannot be used to predict flow velocity and bed shear stress (Canovaro et al., 2007). The conditions under which coarse sediment is entrained are also poorly understood (see, for example, Buffington and Montgomery (1997), Gazendam (2005) and Alexander and Cooker (2016)). One of the consequences of this is that it is difficult to interpret the depositional products of ancient and modern megafloods, limiting our capacity to reconstruct extreme flow conditions.

The aim of this project was to add to the limited amount of information on rivers characterised by very coarse bed sediments. In particular, we sought to establish the nature of downstream change in sediment size in rivers dominated by megaclasts and to place this information in the context of the well-established patterns recognised for finer gravels.

2. Downstream fining

Classically, the downstream decrease in the size of river bed sediments has been attributed to abrasion. Originally this referred to the effects of grinding and abrasion during transport (Sternberg, 1875, pp. 483, 486–487). Over time, however, processes such as splitting, crushing, chipping, cracking, sandblasting, vibratory abrasion, chemical processes and intermittent weathering (Kuenen, 1956a, 1956b; Bradley, 1970; Schumm and Stevens, 1973) have also been subsumed under this heading. That abrasion (in its broader sense) plays a role in size reduction is clear from downstream changes in gravel lithology in which the less durable components of the bedload are systematically depleted (see, for example, Abbott and Peterson (1978), Shaw and Kellerhals (1982) and Kodama (1994a)). Despite this, the rates of fining observed in rivers are generally orders of magnitude higher than those obtained from experimental studies of abrasion in tumbling mills (see, for example, Adams (1978), Kukal (1990, pp. 87–90), Ferguson et al. (1996) and Rice (1999, p. 35)). It is possible that laboratory simulations underestimate abrasion because they neglect to consider the intermittent weathering and weakening of particles exposed between flood events and the vibratory abrasion of stationary particles (Schumm and Stevens, 1973), and because they fail to replicate the effects of the removal of the weathered outer layer of particles (Bradley, 1970; Jones and Humphrey, 1997; Heller et al., 2001). It is also conceivable that conventional tumbling mills poorly replicate the processes of abrasion. Thus, Kuenen (1956a), using a revolving current device that carried particles over a bed of coarse sediment, measured rates of abrasion many times those obtained when particles were transported in standard comminution mills, whilst Kodama (1994b) was able to replicate fining rates in rivers by using equipment that simulated the vigorous collision of particles that occurs in natural systems.

Despite these findings, the consensus has been that abrasion provides only a partial explanation of the rate of downstream fining in natural rivers and that selective sorting, by which smaller particles are preferentially transported further and faster downstream and larger particles preferentially deposited, must play a dominant role. Support for this belief comes from studies of systems in which significant downstream fining occurs, but in which abrasion can play only a minimal part (Paola et al., 1992; Seal and Paola, 1995, pp. 1416–1417; Ferguson et al., 1996; Seal et al., 1997).

Although downstream fining has been identified in gravel-bed rivers in a range of environmental contexts, the pattern is frequently disrupted. Tributaries may introduce finer or coarser sediment into the main channel, regolith may be moved down hillslopes into the stream, and the river may entrain material eroded from its banks or from subjacent stores of alluvial sediment (for example, Miller (1958, pp. 23–27) and Rice (1998)). As the river crosses individual rock units or fracture zones, particles of particular size may be added to the stream load, disordering the fining pattern (Miller, 1958, p. 27). Clasts of different lithologies may fine at different rates downstream, complicating the generally straightforward pattern of size reduction (Werritty, 1992). Downstream fining may also be disrupted by changes in base-level and sediment supply (Hoey and Bluck, 1999) and as a result of the absence from the fluvial system of particles of a particular size-class (Yatsu, 1954, 1955).

Although most attention is focussed on the behaviour of natural systems, human action may also disturb the pattern of downstream fining. Sediment supply may be reduced by the construction of impoundments across the channel (Surian, 2002) and by the extraction of gravel from river beds. Or the provision of sediment may be increased, as a result, for example, of vegetation clearance, landscape disturbance and changes to the sediment delivery system (Gomez et al., 2001, p. 1814). Human changes to river geomorphology may alter the dynamics of sediment movement and affect the supply of sediment from a stream's bed and banks. And water regulation and abstraction may alter flow regimes, changing the incidence of low flows and reducing mean flows, with significant consequences for sedimentary behaviour.

3. The study area

This work was undertaken in the basin of the Sabeto River of western Viti Levu, Fiji (Fig. 1). The river's catchment is narrow and elongate. It is underlain by sedimentary, intrusive, volcanic and volcaniclastic rocks of Late Oligocene–Early Pliocene age (Rao, 1983; Hathway, 1993; Rodda, in press) (Fig. 2). The catchment extends over 137 km^2 and reaches an altitude of 1195 m asl on its northeastern rim. The trunk stream is 34.8 km long. It rises at an altitude of just over 1000 m on the northern rim of the great amphitheatre within which lies the village of Navilawa. The river leaves the amphitheatre at its southwestern corner and flows west to reach the ocean at Nadi Bay, midway between Nadi and Lautoka. The river's long profile displays a relatively smooth, exponentially declining form (Fig. 3).

The river possesses few significant tributaries capable of introducing coarse sediment into the main channel (Fig. 1). Above between 15 and 18 km downstream, the river flows in a relatively confined valley and the hillslope and channel systems are closely linked, although we have no information on the efficiency of sediment influx into the channel. Beyond that point, the valley widens and the presence of a floodplain means that the channel is decoupled from the surrounding hillsides.

In the upstream reaches of the river, the bedload particles reach *b*-axis sizes in excess of 4 m. Bed-sediment size decreases downstream

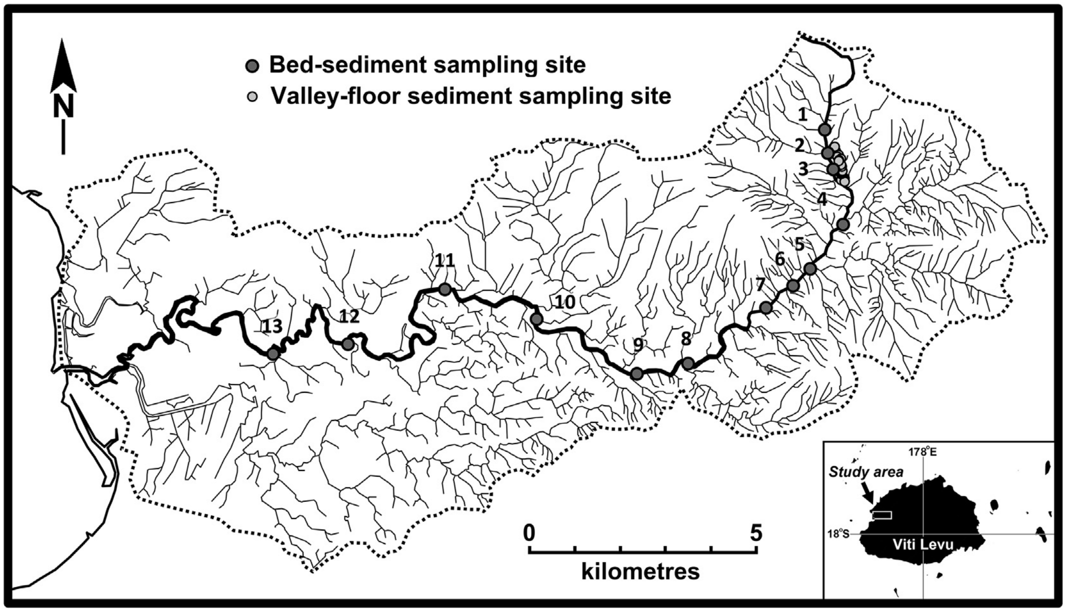

Fig. 1. The drainage and catchment of the Sabeto River of western Viti Levu, Fiji, showing the location of the sampling sites along the trunk stream and the location of the sites where valley-floor sediments were sampled. Source of data: Fiji map series 31 1:50 000 topographic maps, Lands and Survey Department, Suva.

and beyond ~19 km the river flows on a sandy bed. The lithology of the gravels reflects the make-up of the rocks exposed in the catchment. The clasts include granitic rocks of the Navilawa Monzonite and conglomerates of the Nadele Breccia, the Koroyanitu Breccia and the Sabeto Volcanics. For most of its course, the river flows on bedrock, which is intermittently buried by thin deposits of coarse alluvium.

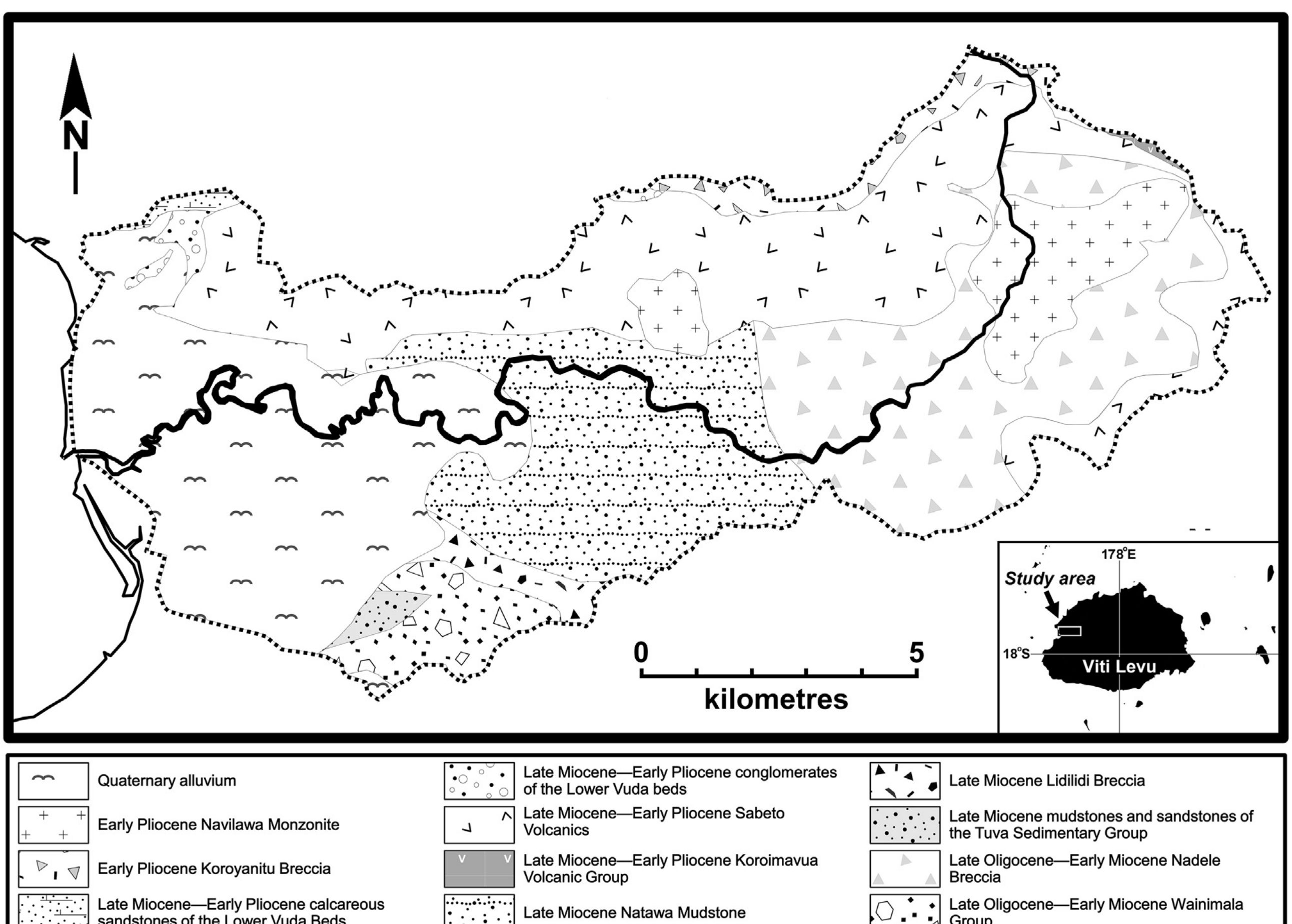

Fig. 2. The geology of the catchment of the Sabeto River of western Viti Levu, Fiji. Source of data: Rao, 1983; Hathway, 1993; Rodda, in press.

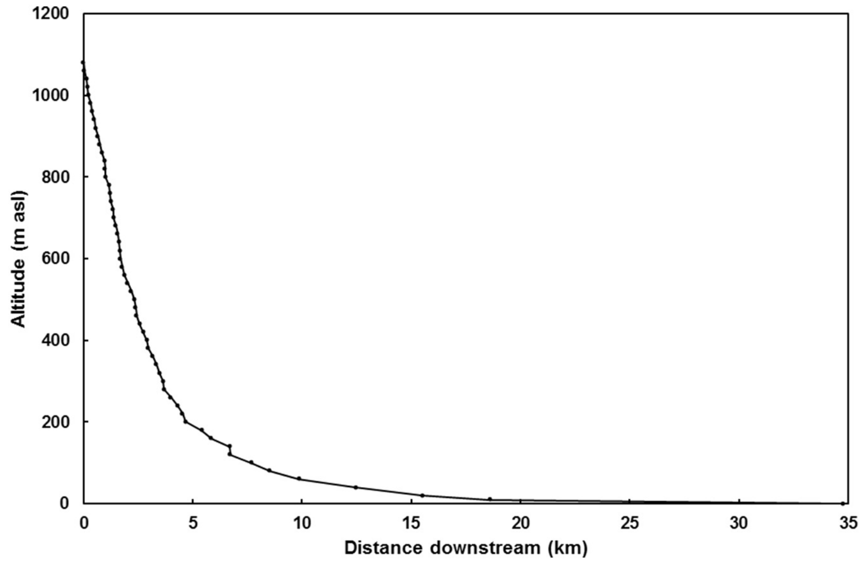

Fig. 3. The long profile of the Sabeto River of western Viti Levu, Fiji. Source of data: Fiji map series 31 1:50 000 topographic maps, Lands and Survey Department, Suva.

Below ~19 km, however, the river is alluvial, flowing on deposits consisting largely of silty sands containing thin and laterally discontinuous interbeds of gravel.

The megaclasts appear to be of fluvial origin. The strongest evidence of this comes from their systematic downstream decrease in size. Debris flows and hyperconcentrated flows are characterised by sediment-rich, high viscosity fluids. These possess shear strength and are capable of supporting coarse particles within the flow. Under these conditions, abrasion is relatively ineffective, large grains tend to accumulate at the flow front and particles tend not to fine in a downstream direction (Suwa, 1988; Brummer and Montgomery, 2003; Gómez-Villar et al., 2014, pp. 204–206; Pradhan, 2017).

Additional clues to the environment of deposition come from the fabric of the megaclasts. At several sites along the river, the clasts display the upstream-dipping *b*-axis orientation characteristic of fluvially transported bedload sediments (Rust, 1972; Harms et al., 1982) (Fig. 4). This is quite unlike the *a*-axis alignment that is typical of hyperconcentrated flow deposits (Gale and Rao, 2015, pp. 1016–1017) and common in debris flow deposits (Lindsay, 1968; Houmark-Nielsen, 1983).

Fig. 4. Imbricated megaclasts immediately downstream of Site 6, Sabeto River, western Viti Levu, Fiji. Flow direction is from left to right. The megaclasts display clast support and upstream, *b*-axis dip. The vertical scale is 1 m long.

Table 1
Rainfall at Nadi Airport, western Viti Levu, Fiji, 1942–2003 (mm). Source of data: Fiji Meteorological Service.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Mean	312	290	346	176	88	66	49	62	75	91	129	180	1864
Highest recorded	981	788	918	580	332	266	190	286	279	342	461	562	
Lowest recorded	13	46	76	22	1	0	0	0	0	2	4	22	
Highest daily	356	340	301	190	141	120	122	170	125	269	119	271	

In its lower reaches, the bed of the river has been modified by sand and gravel extraction. This is unlikely to have had any impact on our measurements, however, as the very coarse gravels that are the focus of this work are of no value for construction and it is improbable that particles of this size would have been removed from the stream bed.

The closest meteorological records are from Nadi Airport, 4 km southeast of the mouth of the river. Temperatures vary little. Mean daily minima range from 18.5 °C in July to 22.8 °C in January, whilst mean daily maxima vary from 28.5 °C in July to 31.5 °C in January (1942–2003 records; source of data: Fiji Meteorological Service). The mean annual rainfall is 1864 mm, with a drier winter (the mean precipitation in July is 49 mm) and a wet summer (the mean precipitation in January is 312 mm), although high daily falls may be expected at any time of the year (Table 1). The climate lies within the Aw (tropical monsoon) category of Köppen's (1936) climatic classification.

The catchment lies within the south Pacific tropical cyclone belt and the river experiences frequent floods associated with cyclonic rainfall. Records are poor, but there were major cyclone-related floods in October 1972, February 1974 and February–March 2001 (McGree et al., 2010). Although there is no record of its magnitude, the 1972 event, associated with Tropical Cyclone Bebe, appears to have been particularly severe. The village of Nadele in the valley bottom was so badly affected that the entire settlement was abandoned and its occupants moved to a new site (named Korobebe after the cyclone).

Limited river flow data are available for the catchment. The estimated 6 h extreme rainfall at Nadi Airport was used to model the 10 and 50 year floods at the catchment outlet (Tonkin & Taylor, 2007, pp. 18–19). Values of 79.3 and 292.3 $m^3\ s^{-1}$ respectively were obtained.

4. Sampling

Probably the best index of downstream fining comes from the pattern of the coarsest active material along the length of the channel. By contrast, measures of 'average' particle size may be skewed by the fine tails of the grain-size distribution, whilst the downstream pattern of fine material is largely influenced by local factors, such as the availability of depositional sites in which sediments may be protected from entrainment.

Coarse sediments have an importance far beyond this, however. They provide a measure of the operation of hydraulic mechanisms such as flow competence and abrasion. They play a significant role in determining boundary roughness. And it has been suggested that the coarsest exposed material in the channel provides the dominant grain-size control on channel behaviour (Church and Kellerhals, 1978, p. 1153).

In determining the size of the coarsest component of fluvial bed sediments, most workers have either employed coarse percentiles of overall samples of the bed sediment or have used an average of a number of the largest clasts present at a site. Given the maximum size of the bed sediments in the upstream reaches of the Sabeto, any attempt to obtain representative samples of the entire bed-sediment distribution would have been impractical (Gale and Hoare, 1992, 1994). We therefore adopted the second approach, that of sampling the largest particles on the stream bed. To ensure that the coarsest material at a site was sampled correctly, our tactic was to collect well in excess of the number of particles necessary to determine the coarsest clast size. We therefore measured the size of the coarsest 25 particles at a sampling location and then employed either the coarsest clast (D_{max}) or the mean of the coarsest two (D_{1-2}), five (D_{1-5}), 10 (D_{1-10}) or 15 (D_{1-15}) clasts in our analyses. The intermediate or *b*-axis was employed as a measure of particle size. Note that our measurement of *b*-axis length followed the protocol of Krumbein (1941a, pp. 65–66), in which the *b*-axis represents the longest axis orthogonal to the longest (*a*-) axis, rather than the approach implicitly used by certain recent workers (see, for example, Domokos et al. (2014)) in which the *b*-axis is taken as the distance between sub-parallel planar faces of the particle.

5. Results

An important constraint on the pattern of fining in the upstream reaches of coarse bedload systems such as that of the Sabeto is the availability of very coarse material to be reworked into the channel and made available for transport. Without this, the upper part of the grain-size–distance plot is likely to be subject to source limitation and to display a flat or positive relationship between particle size and distance downstream. Measurements of particles on the valley floor adjacent to Sites 2–3 (Fig. 1), however, reveal that clasts significantly larger than any of those found in the river are available for entrainment by high-magnitude events (Fig. 5). This suggests that the size of particles liberated from the bedrock is well in excess of the entrainment capacity of the current stream, that the system is unlikely to experience supply limitation and that source control is unlikely to play a role in the observed pattern of downstream variation of particle size.

Irrespective of the size measure chosen, the coarsest particles at each sampling site display a strong negative relationship with distance downstream (Fig. 6). Although most previous attempts to quantify relationships of this type have favoured exponential models, several alternative fining patterns have been identified (for example, Adams

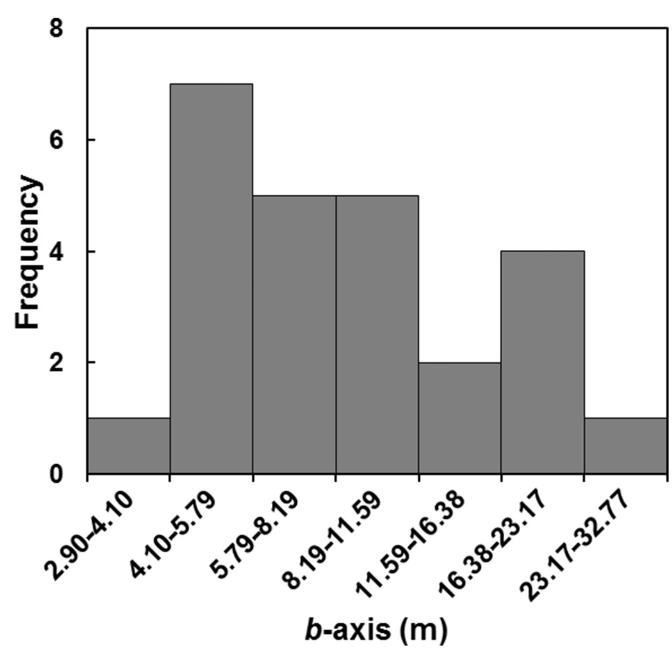

Fig. 5. The size distribution of the coarsest 25 particles on the valley floor adjacent to and upstream of Sites 2 and 3, Sabeto River, western Viti Levu, Fiji. Particle size is represented by the length of the particle's *b*-axis. The distribution is plotted using a bin width of 0.5 phi-units.

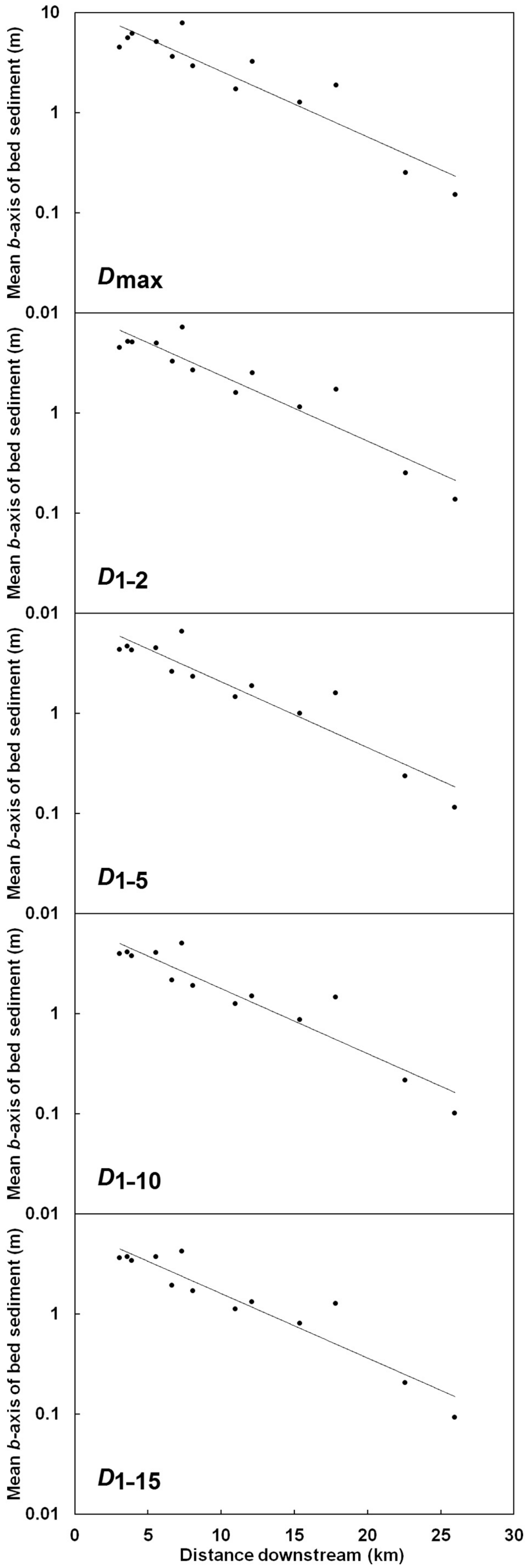

Table 2
Linear, logarithmic, power and exponential models were applied to the relationship between the coarsest particles at each site (determined from D_{max}, D_{1-2}, D_{1-5}, D_{1-10} and D_{1-15}) and distance downstream along the Sabeto River of western Viti Levu, Fiji using least-squares regression. The table lists the coefficient of determination (r^2) associated with each model and each measure of particle size.

Measure of coarsest component	Linear	Logarithmic	Power	Exponential
D_{max}	0.688	0.660	0.698	0.867
D_{1-2}	0.698	0.680	0.715	0.879
D_{1-5}	0.675	0.674	0.725	0.879
D_{1-10}	0.722	0.752	0.742	0.883
D_{1-15}	0.744	0.787	0.753	0.891

(1979), Brierley and Hickin (1985) and Rice (1999, pp. 33–34)). Linear, logarithmic, power and exponential models were therefore applied to the D_{max}, D_{1-2}, D_{1-5}, D_{1-10} and D_{1-15} data sets using least-squares regression. In all cases the exponential model provided the best explanation of the relationship (Table 2).

In the following discussion, therefore, we employ the exponential model as the best description of the downstream pattern of fining in the Sabeto River. Thus:

$$D_x = D_0\, e^{-ax}$$

where x = distance downstream (km)
D_0 = initial particle diameter (mm)
D_x = particle diameter at distance x downstream (mm)
a = size-fining coefficient (km^{-1})

The exponent a in this model represents the rate of decline of grain size per unit distance downstream. Values of the size-fining coefficient obtained in earlier studies vary over five orders of magnitude (see, for example, Shaw and Kellerhals (1982, pp. 47, 148–151) and Moussavi-Harami et al. (2004, p. 150)). Several factors may affect the diminution rate. These include the rate of change of channel slope (Rice, 1999, p. 36), the lithology of the particles (Adams, 1978) (but see Rice (1999, pp. 34–36)), and whether fining is largely a result of abrasion (≤0.1 km^{-1}) or sorting (≥0.1 km^{-1}) (Rice, 1999, p. 34) (but see Kuenen (1956a) and Kodama (1994b)). Seal et al.'s (1997) experiments suggest that, where fining is the result of selective deposition, the fining rate is inversely related to the length of the depositional system, perhaps explaining the high rates of fining observed on alluvial fans. Bluck (1987, pp. 173–174) investigated alluvial fans where clast weathering and particle recycling from the underlying deposits were thought to be unimportant and where minimal down-fan rounding suggested a minor role for abrasion. Fining rates were inversely related to fan radius, offering support for Seal et al.'s (1997) experimental work. Hoey and Bluck (1999) identified a similar inverse relationship between basin area and diminution rate in gravel-bed rivers. The rate of fining appears to be additionally related to the rate of deposition, with the highest fining rates observed in rapidly aggrading alluvial fans (Shaw and Kellerhals, 1982, pp. 47, 149–151; Seal et al., 1997, p. 874). Under these conditions, coarse particles, which are moved only during rare, high-magnitude events, are progressively buried before having the opportunity to catch up those finer particles that are entrained by relatively low magnitude flows. Finally, Adams (1979) observed high rates of fining of 'unsound' (fractured, weathered and angular) clasts in the upstream reaches of rivers. As the clasts become 'sound' downstream (that is, once splitting and the removal of angular protuberances and weathering rinds has taken place), their rate of fining decreases.

Fig. 6. The variation in D_{max}, D_{1-2}, D_{1-5}, D_{1-10} and D_{1-15} with distance along the Sabeto River of western Viti Levu, Fiji. The best-fit lines represent the application of exponential models to each data set.

Table 3
The size-fining coefficient (a) associated with fitting an exponential model to the relationship between measures of particle size and distance downstream along the Sabeto River of western Viti Levu, Fiji using least-squares regression.

Measure of coarsest component	Exponent (km^{-1})
D_{max}	0.1509
D_{1-2}	0.1508
D_{1-5}	0.1513
D_{1-10}	0.1496
D_{1-15}	0.1483
Other measures of particle size	
D_{11-20}	0.1441
D_{16-25}	0.1427

Although the relationship has rarely been assessed explicitly, there is some evidence that, within an individual system, the size-fining coefficient increases with increasing grain size (see, for example, Church and Kellerhals (1978, p. 1156), Shaw and Kellerhals (1982, p. 31), Paola et al. (1992, p. 1759), Seal and Paola (1995, p. 1416), Gomez et al. (2001, p. 1818) and Moussavi-Harami et al. (2004, pp. 149–150)) (see also Paola and Seal (1995, p. 1403)). Our data confirm that a similar pattern can be observed along the Sabeto River (Table 3).

The size-fining coefficients determined in this study (Table 3) lie towards the high end of the total array of values obtained in earlier investigations, but well within the range observed in conventional gravel-bed rivers (~0.001–1.0) (Shaw and Kellerhals, 1982, pp. 47, 148–151; Moussavi-Harami et al., 2004, p. 150).

Plotting the Sabeto River data reveals that a number of data points lie some distance from the best-fit regression line and are not well explained by the exponential model (Fig. 6). Those points lying more than one standard error from the best-fit line are highlighted in bold in Table 4. At Sites 1, 5 and 9, of the five size fractions determined only one lies beyond ±1 SEy, and this by only a small amount. We suggest that the departures from the model at these locations are therefore not significant. At Site 13, particle size is somewhat lower than would be predicted by the exponential model. This may in part reflect the insensitivity of the low-order exponential model to shifts in particle size at the far end of the system. At the remaining two sites (6 and 11), however, the pattern of departure is consistent for all five of the size measures employed. Although the outliers are only statistically significant at conventional 0.05 probability levels in the case of site 11, we suggest that these data reflect real differences in the particle-size distributions at these sites.

Support for this thesis comes from the pattern of particle sizes obtained from each of the sites. Sampling the coarsest individual clasts of a fluvial gravel would be expected to yield a unimodal, coarse-skewed distribution.[1] In general, this is the pattern displayed by the samples taken from the Sabeto River (Fig. 8). However, two of the samples, those from Sites 6 and 11, possess anomalous coarse components. These give rise to distinctive bimodal distributions made up of a discrete coarse peak adjoining a conventional coarse-skewed fluvial distribution. These are the sites that, on every measure of maximum particle size, plot as outliers on the regression models.

The unusual nature of the coarse component at Site 6 is reinforced by the distinctive morphology of the megaclasts at this site. These have been entrenched by fluvial channels to close to normal river levels (Fig. 9). The presence of these channels indicates that the boulders must have remained in their current positions for at least the time necessary for their entrenchment to have taken place. Rates of fluvial

[1] Each fraction of the coarser tail of the distribution will consist of the entire population of gravels of that size at a site, with the number in each fraction of the coarser tail increasing exponentially as particle size decreases. The finest fraction in the distribution, however, will consist of the remainder of the particles collected: this will represent only a sample of the population in the next finest size fraction. Support for this model comes from counts made on representative samples of the entire size-distribution of fluvial gravels (Fig. 7).

Table 4
The departure of each sampling site from the best-fit line associated with the exponential model relating particle size and distance downstream along the Sabeto River of western Viti Levu, Fiji. The table lists SEy (the standard error of the estimate, which describes the variation of the residuals about the regression line) for each site for each of the five measures of the coarsest component of the sediments (D_{max}, D_{1-2}, D_{1-5}, D_{1-10} and D_{1-15}). The bold font denotes values of SEy > 1 and SEy < 1.

Sampling site	D_{max} SEy	D_{1-2} SEy	D_{1-5} SEy	D_{1-10} SEy	D_{1-15} SEy
1	**−1.084**	−0.940	−0.720	−0.561	−0.532
2	−0.441	−0.425	−0.362	−0.299	−0.556
3	−0.110	−0.339	−0.449	−0.396	−0.675
4	0.029	0.167	0.247	0.380	0.186
5	−0.376	−0.413	−0.644	−0.723	**−1.035**
6	**1.528**	**1.638**	**1.715**	**1.490**	**1.126**
7	−0.375	−0.395	−0.393	−0.527	−0.848
8	−0.578	−0.557	−0.472	−0.486	−0.782
9	**1.176**	0.880	0.508	0.321	0.030
10	0.217	0.206	0.176	0.194	0.008
11	**1.872**	**1.993**	**2.114**	**2.296**	**2.065**
12	−0.938	−0.789	−0.627	−0.545	−0.697
13	−0.923	**−1.030**	**−1.097**	**−1.151**	**−1.419**

incision into bedrock vary widely, with measured values ranging from 0.02 to 14 mm a^{-1} (Lague, 2014, p. 40). Even with the most extreme of these rates, however, the channel shown in Fig. 9 cannot have been formed in less than a century. Since the boulder must have remained stable during this period, it is highly unlikely that the clast could have been entrained by the largest event known in the Sabeto record, that associated with Tropical Cyclone Bebe in 1972. We suggest that the boulder was likely to have been emplaced well before this time and that it and the other anomalous clasts at the site represent the products of extremely high-magnitude flows along the river, far greater than those of the 1972 flood. The sediments at Site 6 thus appear to consist

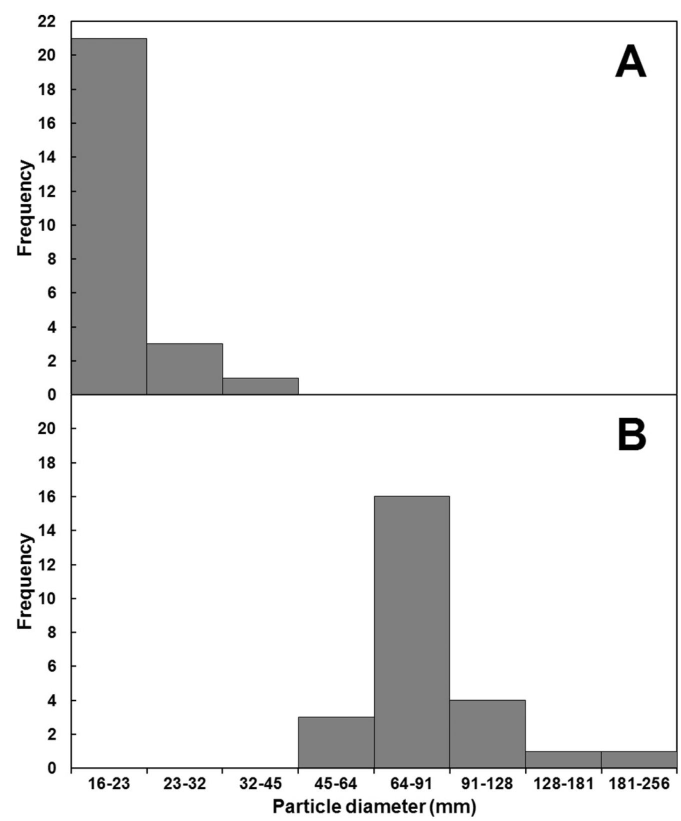

Fig. 7. The sampling distributions obtained by measuring the coarsest 25 clasts of representative samples of fluvial gravel. The distributions are plotted using a bin width of 0.5 phi-units. (A) Glaciofluvial gravel, Warborough Hill, central north Norfolk, UK (Gale and Hoare, unpublished data). (B) Fluvial gravel, Squaw Creek, Montana, USA (Bunte and Abt, 2001, p. 39).

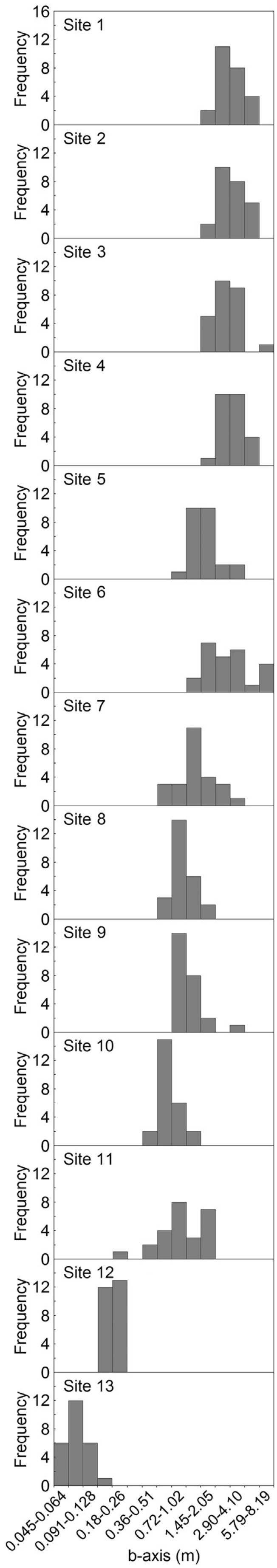

Fig. 8. The size distribution of the gravels collected at Sites 1–13, Sabeto River, western Viti Levu, Fiji, arranged in downstream order. Particle size is represented by the length of the particle's *b*-axis. The distributions are plotted using a bin width of 0.5 phi-units.

of two components, an ancient, very coarse element and a finer constituent displaying the characteristics of a normal bedload deposit.

Although not as spectacular, the situation at Site 11 is similar to that at Site 6. Here the river flows on and within an older alluvial deposit that forms a broad floodplain. As the modern river undercuts the banks and scours the stream bed it exposes large clasts from the older deposits. These are immobile under normal flow conditions and remain as a distinctive lag on the stream bed. Like those at Site 6, the sediments at Site 11 thus appear to consist of two components, an older, very coarse element and a finer constituent displaying the characteristics of a normal bedload deposit.

6. Discussion

Megaclast-dominated fluvial systems have been largely ignored by researchers, whilst their particular hydraulic, sedimentological and geomorphological characteristics have gone generally unrecognised. Probably the sole aspect of such systems that has drawn the attention of scholars is the role of megaclasts in the recognition of ancient cataclysmic floods and in the reconstruction of palaeoflood magnitudes. Indeed, workers in this field have explicitly identified megaclasts as the products of extraordinary flows that lie outside the sphere of those rare, but repeatable events that are simply extreme-magnitude examples of more common phenomena (Baker, 2007, p. 65).

The particles examined in this study are up to four times the linear dimension and up to 60 times the mass of the largest particles studied in earlier investigations of downstream fining (such as those of Brierley and Hickin (1985) and Chatanantavet et al. (2010, pp. 8–9)). Despite this, the pattern of fining (as represented by the size-fining coefficient (Table 3)) is very similar to that observed in other gravel-bed rivers (Moussavi-Harami et al., 2004, p. 150). Should we therefore interpret the pattern of downstream fining in the Sabeto as a product of normal, albeit high-magnitude, stream flows or can we follow Baker in attributing all deposits of this sort to extraordinary events?

Individual cataclysmic floods are known to have carried megaclasts many tens of kilometres downstream (see, for example, Malde (1968, pp. 8, 13–17) and Kochel et al. (2009, p. 92)), whilst Elfström (1987, p. 113) and Fenton et al. (2002, pp. 195, 203) have observed a systematic downstream decrease in the size of megaclasts deposited by catastrophic flows. There are therefore close similarities between the Sabeto deposits and those produced by certain cataclysmic floods. On the other hand, cataclysmic floods occur under a limited set of conditions, the consequence of very large, high-energy catastrophic outbursts of water from natural and artificial reservoirs (Arzhannikov et al., 2016, p. 1691). They may be caused by the collapse of natural dams, subglacial volcanic eruptions, the discharge of subglacial meltwaters, the breaching of lake basins or the rapid introduction into large waterbodies of substantial quantities of rocks and/or ice (O'Connor and Costa, 2004; Arzhannikov et al., 2016, p. 1691). In the case of the Sabeto, a glacially related cause of flooding may be discounted immediately. No evidence exists of glacial or periglacial conditions in the tropical Pacific over at least the last 12 Ma (Zhang et al., 2014), a period that extends to well before the formation of the rocks over which the river flows. Nor is there geomorphological or sedimentological evidence that a body of water that might have provided a source for outburst flooding has ever existed in the headwaters of the Sabeto (Rao, 1983). Rather than being the result of individual cataclysmic events, therefore, we conclude that the coarse bed deposits of the Sabeto are the products of rare but repeatable flows. This being the case, our results suggest that the downstream-fining behaviour recorded in the Sabeto is consistent with that of other gravel-bed systems and that there is no disjunction between the

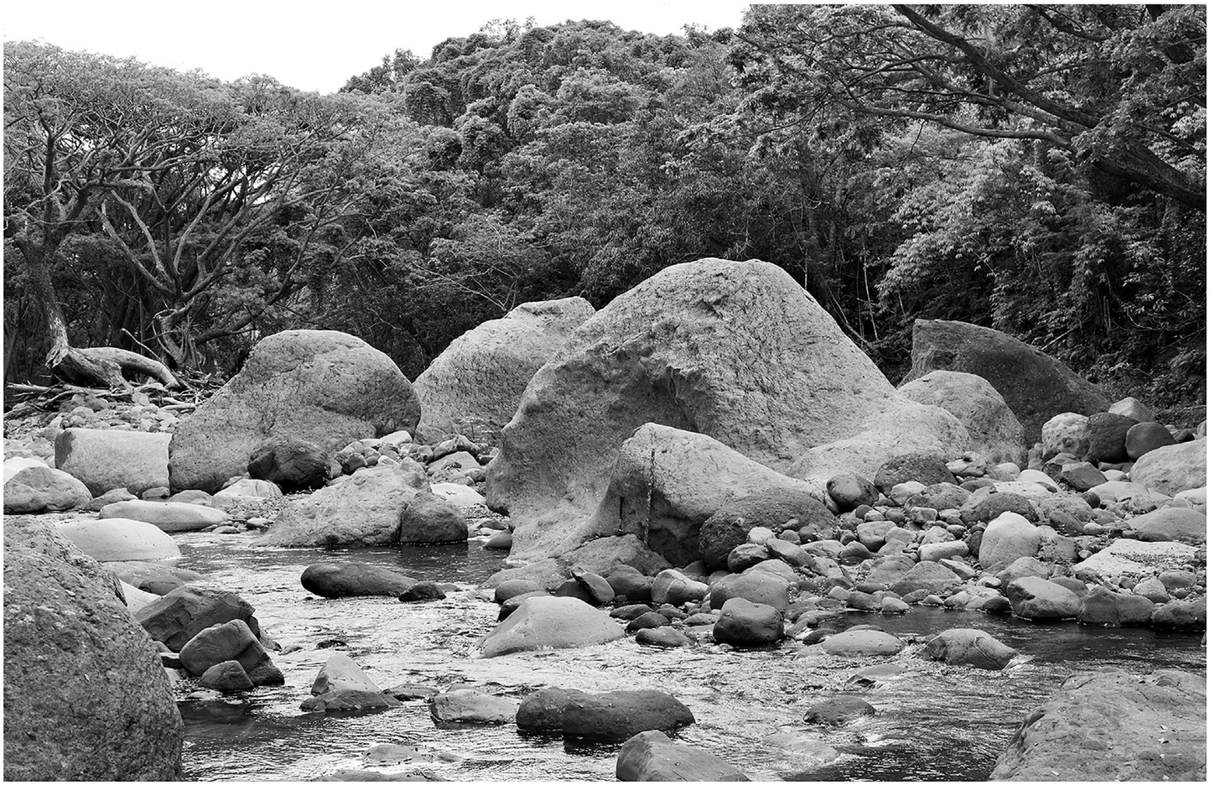

Fig. 9. Site 6, Sabeto River, western Viti Levu, Fiji, showing three of the anomalously large clasts at this location. The example in the middle of the image has been entrenched by a channel incised through the megaclast. The vertical scale is 1 m long.

trends determined on pebbles and cobbles and those observed on the very coarsest fluvial materials.

Somewhat anomalous, however, are the sediments sampled at Sites 6 and 11. These consist of a small number of atypically large particles intermixed with a size-distribution typical of normal fluvial bedload. The two sub-populations at these sites appear to be the products of entrainment events of markedly different magnitudes. The size distributions, the morphology of the coarse boulders and the anomalous position of the sites on the size–distance plot all suggest that the coarse fractions represent the products of an event of even greater magnitude than those responsible for the deposits found along the rest of the system.

By contrast with many other rivers (for example, Church and Kellerhals (1978), Dawson (1988) and Rice (1998)), step-like discontinuities in the fining gradient are absent from the Sabeto. Instead, the relatively consistent pattern of downstream fining is suggestive of a sedimentary system only minimally disrupted by the supply of sediment from tributaries or the reworking of material from sediment

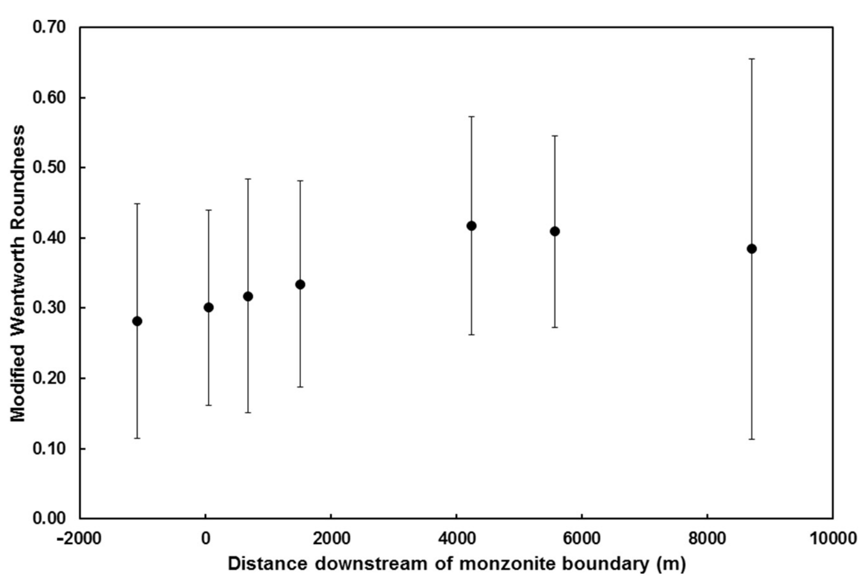

Fig. 10. Changes in the Modified Wentworth Roundness of gravels of Navilawa Monzonite of *b*-axis = 32.0–45.3 mm downstream of the boundary of the monzonite intrusion in the Sabeto River of western Viti Levu, Fiji (Fig. 2). The gravels represent samples of the surface layer of bedload from within the active channel. The data points represent mean values expressed with an uncertainty of ± 1 standard deviation.

sources such as hillslopes and alluvial terraces. Inputs from these sources would appear to be insufficient to redefine sediment throughput along the main channel. Similarly, human intervention in the system, particularly as a result of excavation of the channel bed for sand and gravel, appears to have had little impact on the downstream pattern of clast-size decline.

Several workers have argued that size-fining coefficients of $\geq 0.1\ km^{-1}$ are indicative of fluvial systems in which downstream fining is dominated by sorting (Rice, 1999, p. 34), although it is possible that this belief is an artefact of the inadequacies of experimental methods of measuring abrasion (see, for example, Kuenen (1956a) and Kodama (1994b)). We have no evidence capable of resolving this debate in this specific case. However, we note that our measurements of changes in the shape of gravels of Navilawa Monzonite downstream of the boundary of the intrusion (beyond which point the river can no longer recruit fresh monzonite particles from its bed) (Fig. 2) reveal no significant downstream change in roundness (Fig. 10). It is conceivable that this is because the particles have reached the limiting values of roundness recorded in other studies of fluvial systems. The difference between typical limiting values of 0.55–0.59 (Howard, 1992, p. 474) and those observed here suggests, however, that this is not the case. One interpretation of these results is that beyond some initial smoothing of the particle's outline, abrasion plays little role in downstream fining. We stress, however, that our studies of roundness focussed on the pebble and cobble fraction of the bedload component, considered gravels of only a single lithology and dealt solely with that stretch of river downstream of the monzonite boundary.

Our data support the implicit observation of several other studies that the coarser fraction of the bed sediment experiences a more rapid downstream reduction in size than the finer fraction. This may be because the distance over which individual particles are transported is likely to be size dependent. Thus, as transport capacity decreases, the coarsest fraction will tend to be lost by selective deposition. The coarsest particles will therefore tend to be confined to a limited stretch of the channel, resulting in the rapid downstream fining of the coarser fraction (a process observed by Seal et al. (1997, p. 883)). Additionally (and acknowledging the equal mobility concept of Parker et al. (1982)), when particles are entrained, it is possible that coarser material will remain behind as a lag rather than being carried away downstream and deposited over an extensive length of channel.

It is also possible that abrasion (using the term in its broad sense) may be more effective in the case of larger particles than smaller ones, with the result that the coarser fraction of the river's bed sediment fines downstream more rapidly than the finer fraction. At least three factors may contribute to this phenomenon.

(i) If size is defined in terms of an axial dimension, as is the case here, larger particles possess a proportionally greater surface area than smaller. Assuming that abrasion plays a role in size reduction, this is likely to be relatively more significant for large particles than for small, yielding a correspondingly greater rate of size reduction.

(ii) In a typical system, larger particles will be found in the upstream reaches of a river. These particles are likely to have been entrained over shorter distances than smaller grains and to have experienced relatively less rounding from the initial, generally angular condition of particles freshly liberated from the parent rock. The existence of sharp corners and protuberant parts is likely to mean that larger particles experience higher rates of abrasion and thus a more rapid reduction in size. This is confirmed by laboratory studies that show that the protuberant corners of particles are abraded far more rapidly than regions that are flat or display negative curvature (Durian et al., 2006; Roth et al., 2011). Kuenen's (1956a, pp. 346–347) experiments, made in the context of studies of abrasion in the laboratory, show that large particles round more quickly than small ones (see also Daubrée (1879 in Krumbein, 1941b, pp. 483–484), Marshall (1929) and Lewin and Brewer (2002, p. 154)), perhaps because of their greater mass, which would increase the effect of impacts causing chipping and grinding.

(iii) Larger particles are more likely to split than smaller ones. There are at least two reasons for this. First, large particles are more likely than small to intersect structural discontinuities such as joints and bedding planes. Such features represent lines of weakness along which splitting may occur, resulting in a catastrophic reduction in the size of particles. Secondly, the higher mass of larger particles, and thus the momentum with which they collide, may encourage splitting. Kuenen (1956a) and Dobkins and Folk (1970) failed to observe splitting in their studies of, respectively, the experimental abrasion of pebbles and pebble beaches. However, Kuenen's experiments generally involved particles no more than 60 mm in diameter and Dobkins and Folk studied only particles of <256 mm. By contrast, Bluck (1969, p. 3) provided evidence of particle splitting on South Welsh beaches, particularly in the boulder grade (though his published results group together split and chipped gravels, making it difficult to calculate the proportions attributable to each process) and Oak (1984, pp. 77–78) observed widespread and highly visible breakage on the boulder beaches of Australia's New South Wales coast.

Since the coarser fraction of the bed sediment experiences a more rapid downstream reduction in size than the finer fraction and given the very coarse nature of the Sabeto's deposits, we might anticipate that the diminution coefficient for the Sabeto would differ markedly from that of other rivers. Fining rates along the Sabeto clearly lie in the high range of those determined for all laboratory and natural systems (Shaw and Kellerhals, 1982, pp. 47, 148–151). On the other hand, they are very similar to those observed in other gravel-bed rivers worldwide (Moussavi-Harami et al., 2004, p. 150). This, combined with the evidence of the limited shift in values of a as particle size is changed within a single system (Table 3), suggests that size plays only a minor role in determining the rate of downstream fining.

7. Conclusion

Megaclast-dominated fluvial systems have been largely ignored by researchers. This probably reflects the location of megaclasts in the hard-to-reach headwaters of river systems and the challenges involved in measuring coarse particles. Yet such systems are probably far more common than this neglect would suggest and megaclasts are likely to exert an important control on channel geomorphology, flow behaviour and sediment transport. The one aspect of megaclast-dominated systems that has drawn the attention of scholars is the role of megaclasts as indicators of cataclysmic floods and in the reconstruction of their magnitude. Indeed, workers in this area have explicitly identified megaclasts as the products of extraordinary flows that lie outside the sphere of those rare, but repeatable events that are simply extreme-magnitude examples of more common phenomena. Despite this contention, the deposits of the Sabeto cannot be the products of cataclysmic floods and must instead have been laid down by extreme but not otherwise exceptional flows. More broadly, it is clear from observation of modern fluvial systems that megaclasts may be entrained by flows that lie within the existing flow regime. We cannot therefore simply regard such deposits as indicators of extraordinary flows that lie beyond the range of normal conditions.

The specific aim of this work was to establish the nature of downstream change in sediment size in rivers dominated by megaclasts and to place these findings in the context of the well-established patterns established for finer gravels. Our results reveal a strong negative exponential relationship between particle size and distance downstream, a relationship that is maintained irrespective of the measure of particle size used. The rates of downstream fining observed in studies of rivers, river reaches, laboratory flumes and abrasion experiments vary over five orders of magnitude. Although the size-fining coefficients determined for the Sabeto are comparatively high when viewed within this context, they are comparable with those recorded in other gravel-bed rivers (~0.001–1.0) (Shaw and Kellerhals, 1982, pp. 47, 148–151; Moussavi-Harami et al., 2004, p. 150). Despite the great size of the particles found along the Sabeto, therefore, and the possibility that megaclast-transporting systems may behave in ways that differ from the finer-grade systems upon which most work has been undertaken, we see no disjunction between the patterns observed in megaclast systems and those recorded in conventional gravel-bed rivers.

There is a long-standing debate about the relative roles of abrasion and sorting in downstream fining. Although our work did not specifically address this question, our data reveal little evidence for a downstream increase in the roundness of the river's gravels, implying that abrasion is likely to play a minor role in the fining process in this system.

Our work confirms the relationship between particle size and the rate of downstream fining that has been hinted at in other studies. This may be because the distance over which individual particles are transported is likely to be size dependent. Thus, as transport capacity decreases, the coarsest fraction will tend to be lost by selective deposition. The coarsest particles will therefore tend to be confined to a limited stretch of the channel, resulting in the rapid downstream fining of the coarser component. Additionally, when particles are entrained, coarser material may remain behind as a lag rather than being carried away downstream and deposited over an extensive length of channel. It is also possible that abrasion may be more effective in the case of larger particles than smaller ones, with the result that the coarser fraction of the river's bed sediment fines downstream more rapidly than the finer fraction.

The pattern of downstream fining in the Sabeto is straightforward and step-like discontinuities in the fining gradient are absent. This relatively consistent pattern of fining is suggestive of a sedimentary system only minimally disrupted by the supply of sediment from tributaries or the reworking of material from sources such as hillslopes and alluvial terraces. Human intervention in the system, particularly as a result of excavation of the channel bed for sand and gravel, also appears to have had little impact on the downstream pattern of clast-size decline. Despite this, two sites along the river possess anomalously coarse sub-populations. These coarser components must predate the other deposits at the sites. We speculate that they represent the products of earlier and higher-magnitude events along the system. The bed sediments may thus be composite features, each component of which is the product of transport by a specific event of particular magnitude.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2019.01.009.

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