Title
A Field Test Of The Influence Of Grain Size In Determining Bedrock River Channel Slope

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A FIELD TEST OF THE INFLUENCE OF GRAIN SIZE IN DETERMINING BEDROCK RIVER CHANNEL SLOPE

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in

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by

Rachael Klier

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approved:

Professor Noah Finnegan, Chair

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Vice Provost and Dean of Graduate Studies

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Abstract
Rachael Klier

A Field Test of the Influence of Grain Size in Determing Bedrock River Channel Slope

Interpreting spatial patterns in rates of fluvial incision from river channel elevation long profile data requires an assumption that tectonic uplift rate governs river channel slope. However, application of the most mechanistically explicit description of river incision [Sklar and Dietrich,2004] suggests that sediment flux and sediment grain size, not rock uplift rate, control river channel slopes in many settings. Because it is usually difficult to independently constrain sediment supply, tectonic interpretations of river elevation long profiles are necessarily uncertain. Here we exploit a natural experiment in Boulder Creek, a ~ 30 km^2 drainage in the Santa Cruz Mountains, CA USA in order isolate the affect of grain size and relative sediment supply on river channel slope in an actively uplifting landscape along a restraining bend in the San Andreas Fault.

A single prominent knickpoint exists near the midpoint of Boulder Creek, separating a 6.8 km long region of low slope(~0.8%) from a steeper(~2.6%) 4.8 km reach along the lower portion of the channel . Mapping and field observations reveal that this knickpoint does not coincide with any lithologic or tectonic boundaries; the channel cuts weak sedimentary rock for it length. In addition, longer wavelength changes in rates of rock uplift due to the bend in the San Andreas fault near Boulder Creek are negligible over the relative small size of Boulder Creek's catchment. Instead the knickpoint coincides with the location of the first tributary that taps a source of resistant, granitic sediment that is not found in the upstream reaches of Boulder Creek. Field observations indicate that coarse granitic bedload is sourced by debris flows and introduced by a series of tributaries draining into the steep lower reaches of Boulder Creek. The knickpoint marks a transition in median grain size from ~2cm upstream of the knickpoint compared to an average of ~18cm downstream of the knickpoint. Additionally, upstream of the knickpoint , Boulder Creek is characterized by potholes and sculpted bedrock, consistent with sediment-starved conditions.

The observation that bedrock channel slope changes are not well correlated with patterns in rock uplift supports Sklar and Dietrich's (2006) theoretical result that modest rates of rock

uplift do not significantly influence river profile slopes. Based on this result and the clear correlation of channel slope and sediment supply along Boulder Creek, we chose to ignore rock uplift rate and instead explore the relative roles of grain size and sediment flux in influencing profile slopes along Boulder Creek. Using field surveys of grain size and high flow depth, we calculate that ~10% of the slope above the knickpoint and ~30% of the slope below the knickpoint is related to maintenance of the channel at the threshold for sediment motion. This implies that ~90% of the slope above the knickpoint and ~70% of the slope below the knickpoint is due to the excess stress that is required to move the coarse sediment load. This would imply that other factors including sediment supply and bed roughness can be significantly more important than thresholds of coarse sediment motion for setting channel slope in mixed bedrock-alluvial systems.

Acknowledgements:

I would like to thank the UCSC Department of Earth and Planetary Sciences for the opportunity to pursue this degree. In particular, I want to thank my advisor, Noah Finnegan, for all of his guidance throughout the degree process. My passion for geomorphology is owed to instruction, encouragement and wisdom that you have shared with me.

Introduction & Setting

The ability of a river to incise into bedrock and transport sediment depends on channel gradient [*Howard et al.*, 1994; *Sklar and Dietrich*, 2004]. The potential for rivers to grow steeper with higher rates of tectonic uplift therefore implies that rates of river incision should evolve to match rates of rock uplift in actively uplifting ranges [*Whipple et al.*, 2004; *Burbank et al.*,1996;*Pazzaglia and Brandon*,2001]. This realization forms the basis for using patterns of river steepness (typically normalized for drainage area) to infer patterns in rates of rock uplift [e.g.,*Wobus et al.*, 2006].

Most commonly, the stream-power incision model is used to model river incision in tectonic geomorphology applications. The stream power model is an empirical erosion rule used to model fluvial erosion rates from two measurable topographic parameters, drainage area and channel slope [*Howard and Kerby*,1983; *Howard et al.*, 1994; *Whipple and Tucker*,1999;*Stock and Montgomery*,1999]. Via an assumption of steady-state between rock uplift and river incision, this approach is used extensively in identifying erosional patterns in tectonically active landscapes [e.g., *Dibiase et al.*,2010]. However, the most mechanistically explicit description of river incision [*Sklar and Dietrich*,2004] suggests that sediment flux and grain size, in addition to rock uplift rate, control river slopes in many settings, thereby complicating tectonically based interpretations of river profiles.

The role of sediment supply in controlling rates of river incision has been demonstrated using physical experiments [e.g.,*Sklar and Dietrich*,2001; *Johnson and Whipple*, 2010; *Finnegan et al.*,2007;*Chantanantavet and Parker*,2008] and theoretical arguments [*Sklar and Dietrich*, 2004]. However, field-based tests are more challenging to accomplish because of the difficulty in isolating the various factors influencing channel incision. *Cook et al.* [2013] used a field study to test controls on long profile evolution and knickpoint behavior after a coseismic event produced a prominent knickpoint on the Da'an River during the 1999 Chi-Chi earthquake in Taiwan. The uplift event provided a unique opportunity to isolate the effect of coarse sediment supply on channel incision because a portion of the river had coarse sediment delivery temporarily shut off. This was the first study to demonstrate in the field the necessity of coarse bedload for sustaining bedrock incision. In addition, *Cowie et al.* [2008] conducted a study showing that variations in sediment supplied to a channel can significantly alter the relationship between channel slope and relative base-level fall rate (equivalent to rock uplift rate at steady-state). *Johnson et al.* [2009] used field and DEM observations from the Henry Mountains of Utah to evaluate various models used to quantify the effect of sediment size and flux on bedrock channel slope. In this study, channels with abundant coarse sediment supply were systemically steeper than channels that were starved of significant coarse sediment. Additionally, the sediment-starved channels had incised more deeply and to shallower gradients than the channels containing coarse bedload, consistent with the theoretical predictions of the saltation abrasion model of *Sklar and Dietrich* [2004].

Collectively, these studies provide evidence that coarse sediment supply has a fundamental impact on the process of river incision into bedrock and thus on the morphology of river elevation long profiles. However, all of these field studies were conducted in landscapes affected (to some degree) by transient signals related to changes in base-level or uplift over time. Transient effects can be difficult to constrain, especially when studying sediment controls across multiple channels, due to the variability in the rate of response between different channels. In particular, the effects of changing base-level can be challenging to account for due to the unpredictability of knickpoint retreat in small bedrock channels [*Crosby and Whipple*, 2006]. The optimum setting to study the role of sediment supply in influencing bedrock channel profiles would be in a landscape at steady-state where river incision rates closely balance rock uplift rates.

Here, we exploit such a setting along Boulder Creek in the Santa Cruz Mountains, CA. This natural experiment permits isolation of the effect of sediment grain size on river channel slope in an actively uplifting landscape along a restraining bend in the San Andreas Fault. Boulder Creek is a 30 km^2 tributary of the San Lorenzo river in the Santa Cruz Mountains, CA. The tectonically active Santa Cruz Mountains are developed along a restraining bend in the San Andreas Fault [*Anderson*, 1990] where rock uplift associated with the bend has likely occurred for at least the last ~5 million years [*Burgmann et al*., 1994]. Boulder Creek incises units composed of mudstone and sandstone including; Santa Cruz Mudstone, Santa Margarita Sandstone, Lompico Sandstone, Butano Sanstone and Vaqueros Sandstone ranging from Oligocene to Miocene [*Brabb et al*.,1997](Figure 1a). However, the headwaters of the lower tributaries of Boulder Creek all drain the much more resistant Cretaceous quartz diorite that represents the exposed crystalline basement within the Santa Cruz Mountains. Sediment shed from the crystalline portions of the landscape in the Santa Cruz Mountains is typically much coarser than the sediment supplied by overlying sedimentary rocks [*Donaldson et al*., 2009]. It is this transition in bedload supply to Boulder Creek that we exploit as a natural experiment in order to quantify the effect of sediment size on bedrock channel slopes.

By studying the variations in grain size along a single channel, we aim to better control for variations in base-level forcing that might otherwise complicate comparisons between catchments. In addition, we use a tectonically active setting with a several million-year history of active rock uplift [*Burgmann et al*., 1994] where a steady-state between rates of rock uplift and rates of erosion has been argued [*Gudmundsdottir et al.,* 2013]. We therefore have confidence that channel slopes in our study area are adjusted to move sediment through the landscape and incise bedrock at rates that balance tectonic uplift.

Sklar and Dietrich [2006] present an expression for the bed slope of an incising bedrock channel as a sum of three separate components:

$$S_T = S_D + \Delta S_{qs} + \Delta S_E \quad (1)$$ [*Sklar and Dietrich*,2008]

where S_D is the slope necessary to exceed the threshold of sediment motion, ΔS_{qs} represents excess slope above S_D needed to transport the bedload flux at the rate supplied from upstream and ΔS_E represents the slope needed to erode bedrock at the rate of rock uplift [*Sklar and Dietrich*,2006]. Following the prediction of this model that grain size and sediment supply are the dominant slope components for all but the highest plausible rates of rock uplift, we focus on variations in the threshold of motion (S_D). In addition, we examine patterns in excess stress to constrain ΔS_{qs} as well as channel roughness. Although roughness is not explicitly incorporated in the *Sklar and Dietrich* [2006] framework, roughness, by exerting drag on the flow, may also contribute to the maintenance of slopes in excess of what is required to simply initiate motion. Below we use field and DEM measurements to test the model summarized by equation 1.

Methods

We extracted elevation longitudinal profiles and drainage areas of both Boulder Creek and its tributaries_from a USGS 10 m DEM (Figure 2). Channel slopes were computed for 100m sections of the channel. We measured characteristic high flow depths from high flow indicators at 8 locations along Boulder Creek (Figure1a). Uncertainties in defining bankfull depth varied with local reach morphology and likely ranged up to ±25% of individual measured values. The intermediate diameters of 100 clasts were measured at eight locations along Boulder Creek using the Wolman pebble count method [*Wolman*,1954]. Pebble count locations were chosen from locations both above and below where Boulder Creek first receives crystalline sediment. In order to minimize sampling error, all pebble counts/measurements were conducted by R. Klier. Particles smaller than 2mm were categorized as ‘sand’. We made field observations at numerous tributary junctions along Boulder Creek in order to constrain the mechanism of sediment delivery to Boulder Creek.

To compare channel slopes for reaches that carry coarse crystalline sediment to those that do not, we use a Chi transformation of the long profile data to remove the effect of drainage area on channel slope [*Perron and Royden*, 2013](Figure 3a,3b,3c). For the chi transformation, we use a reference concavity of 0.5 and a reference drainage area of 1 km^2. In order to isolate the effects of bedload sediment supply on channel slope, we analyze only channels that are developed on the weak sedimentary rock within the Boulder Creek catchment. Hence, the lower tributaries with diorite in their headwaters were clipped so as only to include the portions of these tributaries with diorite bedload but weak sedimentary bedrock (Figure 2, Figure 3a). The distribution of diorite within the Boulder Creek catchment is based on interpretations of previous geologic mapping of Santa Cruz County [*Blissenbach et al.*,1997].

We use field measurements of slope, grain size and bankfull depth for 8 locations along the length of Boulder Creek to determine the relative importance of the threshold of motion in setting the slope of Boulder Creek and, by inference, its tributaries. Specifically, shear stress for each location, τ is calculated using steady uniform flow:

$$\tau= \rho_w ghs \quad (2)$$

where s represents channel gradient,g is gravitational acceleration, h is high flow channel depth, and ρ_w is the density of water. The shields stress, τ^*, is a non-dimensionalization of τ by the submerged sediment grain weight:

$$\tau^* = \frac{\tau}{(\rho_s - \rho_w) g D_{50}} \quad (3)$$

where ρ_s represents sediment density and D_{50} is the median grain size. The critical shields stress (τ^*_c) has a range of 0.03 to 0.08 [*Buffington and Montgomery*, 2008]. Here, critical shield's stress is calculated using the slope-dependent critical shields stress equation [*Lamb et al.*,2008]. Using field measurements of slope, median grain size, bankfull depth and rearranging equation 1., we directly calculate both total shear stress (τ_T) and the threshold of motion stress(τ_D) [*Sklar and Dietrich*, 2008](Table 1).

$$\tau_T=\tau_D+\Delta\tau_{qs}+\Delta\tau_E \quad (4) \quad \text{[Sklar and Dietrich,2008]}$$

Based on theoretical predictions from the saltation abrasion model that rock erodibility contributes only a small amount to the total slope of most bedrock river channels, we ignore this component in our calculations [*Sklar and Dietrich*,2006;*Johnson et al.*,2009]. We then calculate the excess stress ($\Delta \tau_{ex}$) above the threshold of motion for each of the 8 field locations by computing the difference between the total bankfull stress and the incipient motion stress(Table 1).The excess shear stress ($\Delta \tau_{qs}$) can be interpreted within the framework established in equation 4 as reflecting the stress required to move the sediment supply (i.e., $\Delta \tau_{qs}$). Alternatively, excess stress above the stress required to initiate motion may also reflect channel roughness, which partitions stress between the grains on the bed and other roughness elements in the channel such as woody debris, boulders and bedforms [e.g., *Manga and Kirchner*, 2000; *Yager et al.*, 2007].

Results

A single prominent knickpoint exists near the midpoint of Boulder Creek, separating a 6.8 km long region of low slope (~0.8%) from a steeper (~2.6%) 4.8 km reach along the lower portion of the channel (Figure 1b,Figure 2). Geologic mapping reveals that this knickpoint does not coincide with a lithologic or tectonic boundary. The channel only cuts weak sedimentary rock along its entire course. Instead, the knickpoint coincides with the location of the first tributary that taps the resistant diorite that is not found in the upstream reaches of Boulder Creek (Figure 1a,1b). Our grain size measurements reveal that the knickpoint along Boulder Creek also marks an order magnitude downstream jump in median grain size. Grain size measurements collected from eight different locations along Boulder Creek show that the average D_{50} upstream of the knickpoint is 2 cm compared to an average D_{50} of 18 cm downstream of the knickpoint (Table 1). Upstream of the knickpoint, Boulder Creek is characterized by potholes and sculpted bedrock, consistent with sediment-starved conditions (Figure 5a,5b). Downstream of the knickpoint, bedrock exposure on the bed is far less common and the bed is typically blanketed in coarse diorite sediment (Figure 5c). Field observations indicate that the coarse bedload is sourced by debris flows and introduced by a series of tributaries draining into the steep lower reaches of Boulder Creek. In addition, in the field we observe a narrow ~ 9 m deep bedrock gorge along ~1.5 km of Boulder Creek downstream of the first tributary, Jamison Creek, that deposits diorite in Boulder Creek (Figure 5d).

DEM analysis reveals that the tributaries containing diorite have significantly more relief because the diorite source is almost exclusively outcropping near the channel heads. The tributaries without diorite bedload are upstream of the knickpoint on the main stem and have much shallower slopes than the tributaries downstream of the knickpoint sourcing diorite (Figure 2). Figure(3b-c) shows chi plots upsteam and downstream of the knickpoint along Boulder Creek that marks the transition between diorite bedload and non-diorite bedload containing tributary channels. Averaging the normalized channel steepness ($dz/d\chi$) upstream of the knickpoint yields an average value of 0.03, compared to 0.1 downstream of the knickpoint (Figure 4). In other words,for a given drainage area, channels with diorite bedload are ~3 times steeper than the channels without.

The 8-fold change in median grain size across the knickpoint along Boulder Creek coincides spatially with an approximately 2.5 fold increase in the bankfull shear stress on Boulder Creek (Table 1). Excess stress ($\Delta\tau_{ex}$) increases across the knickpoint by less than a factor of 2. This implies that as a percentage of the total bankfull stress, the stress needed to exceed the threshold for motion is increasing downstream. Specifically, upstream of the knickpoint, the stress needed to exceed the threshold of motion represents ~10% of the total stress. Alternatively, downstream of the knickpoint, the threshold of motion stress makes up ~30% of the total shear stress. This result also implies that as a percentage of the total stress, the excess stress is decreasing downstream.

Discussion

Our results illustrate that along Boulder Creek changes in channel gradient are spatially coincident with the location of the first tributary that introduces coarse diorite into Boulder Creek (Figure 1a,1b). Specifically, the mean high flow stress jumps from ~ 170 Pa to ~ 490 Pa across the knickpoint, apparently in response to a change in the stress needed to initiate motion from ~ 15 Pa upstream of the knickpoint to ~ 155 Pa downstream (Figure 7). In addition, we observe a systematic 3-fold increase in the gradient of tributary channels that enter Boulder Creek carrying coarse diorite bedload relative to those tributaries that carry only weak sedimentary bedload (Table 1). Taken together, these patterns of channel steepness and their strong correlation with bedload lithology in the Boulder Creek catchment supports *Sklar and Dietrich's* (2008) model that bedrock channels evolve in response to grain size. We emphasize that all of the channels examined flow across weak sedimentary bedrock, so we are able to isolate the effect of bedload grain size alone on channel steepness.

That said, along Boulder Creek high flow stress, which jumps by about a factor of 3 downstream, does not increase in proportion to grain size, which increases approximately 8-fold. If we take the measured D_{50} upstream and downstream of the knickpoint on Boulder Creek as representative of diorite-rich and diorite-absent streams in this area, then the tributary channels exhibit a similar discrepancy as they also only increase in slope by a factor of ~ 3 between the two populations.

There are two end-member scenarios that may be invoked to help explain why there is not a simple linear relationship between grain size and channel slope, as would be expected if channels were adjusting only in response to the requirement to move the coarse sediment load. As discussed earlier, both bed roughness and coarse sediment transport require that bankfull stresses be maintained above the threshold for motion. Along Boulder Creek, where we have detailed measurements of hydraulic geometry, the fraction of the total stress used to initiate motion is lower above the knickpoint than below it (~30% less).

For rock uplift rates in the Santa Cruz Mountains [*Burgmann et al*,1994;*Gudmundsdottir et al.*,2013], *Sklar and Dietrich* (2008) suggest 50-80% of the total bed slope should be accounted for by the need to initiate grain motion. Because the slope needed to erode bedrock is negligible, 20-50% of the slope then should go towards transport of the coarse load. The observation that the stress (which is linearly related to slope) needed to initiate motion above the knickpoint along Boulder Creek is only 10% of the total channel stress at high flow therefore implies that something in addition to sediment load must be invoked to close the stress budget here. This point is further underscored by field observations of potholes and fluted abrasional morphologies, suggesting sediment starved conditions on the upstream portion of Boulder Creek and hence relatively modest coarse sediment transport rates.

We speculate that the tortuous bed morphology observed in the field upstream of the knickpoint along Boulder Creek (Figure 5a) accounts for the additional drag implied by our field measurements of grain size and hydraulic geometry. It's worth emphasizing that experiments of bedrock abrasion [*Johnson and Whipple*,2010; *Finnegan et al.*, 2007] reveal that the growth of bed roughness during incision under sediment starved conditions exerts a first order control on sediment transport efficiency. This, in turn, implies that the growth of abrasional bed morphologies, such as potholes, can exert a large drag on the fluid conveyed through an open channel.

Downstream of the knickpoint on Boulder Creek, with the exception of the bedrock gorge, which we discuss below, the bed morphology changes dramatically so that it is almost completely covered with coarse diorite sediment (Figure 5c). Because bed sediment cover and sediment supply are typically strongly correlated in flume experiments of bedrock incision [*Chantanantavet and Parker*, 2008], the observed change in bed morphology is consistent with a downstream increase in coarse sediment load. Given the proximity of the diorite source to lower Boulder Creek (Figure1a) and the relative resistance of diorite to downstream abrasional breakdown compared to sedimentary bedrock [*Sklar and Dietrich*,2001], it is not surprising that lower Boulder Creek experiences a much higher coarse sediment supply relative to upper Boulder Creek.

From a stress partitioning perspective, a higher percentage of the total high flow stress is accounted for simply by the need to initiate motion (~30%) along lower Boulder Creek. Therefore, only ~70% of the total stress can go to roughness as well as coarse sediment transport. This observation, combined with the field evidence for higher coarse sediment transport rates along lower Boulder Creek, implies that as a percentage of the total stress there is much less excess stress that needs to be accounted for beyond the need to initiate motion and transport the coarse load along lower Boulder Creek as compared to upper Boulder Creek. Again, for rock uplift rates in the Santa Cruz Mountains [*Burgmann et al.*,1994;*Gudmundsdottir et al.*,2013] as a fraction of the total slope, the slope needed to initiate grain motion should be comparable to the slope needed to move the coarse sediment load. This implies that a much lower fraction of the total high flow stress along lower Boulder Creek must be accounted for by channel roughness. In addition, our observations imply that the plane bed alluvial conditions observed over much of lower Boulder Creek have apparently less roughness than the potholed bedrock channel found upstream.

One notable wrinkle in the overall morphologic patterns described above is the bedrock gorge found at the confluence of Jamison Creek and Boulder Creek. Here the channel cuts a deep slot into sandstone and is littered with sandstone boulders as well as diorite cobbles (Figure 5d). We speculate that this ~ 1.5 km section of gorge is an epigenetic gorge [*Ouimet et al.*, 2008] incised following burial of Boulder Creek by debris flows sourced from Jamison Creek and adjacent tributaries. The evidence that supports this interpretation is that the gorge is restricted to the location where a series of amalgamated debris flow fans impinge on Boulder Creek (Figure 6). Because the epigenetic gorge section is much smaller than the steep section of lower Boulder Creek, we are confident that the overall patterns observed along Boulder Creek are not a simply a transient response to recent debris flow activity. Indeed, if anything, because of the connection between coarse sediment loading and epigenetic gorge formation [*Ouimet et al.*, 2008], this feature supports the relative increase in coarse sediment supply inferred at the transition from upper to lower Boulder Creek.

Conclusions

We studied bedrock channels in the Boulder Creek catchment of the Santa Cruz Mountains, CA. Based on a 'near' steady-state argument [*Gudmundsdottir et al.,2013*] that channel slopes have adjusted to transport sediment and incise bedrock at rates equivalent to rock uplift, we can effectively isolate the effect of grain size on channel slope in a bedrock channel network. We observe that bedrock channels transporting coarse (~ 18 cm D_{50}) diorite are consistently about 3 times steeper than channels transporting relatively finer (2 cm D_{50}) sedimentary bedload. Thus, although there is clear relationship between channel slope and bedload grain size here, there is not a simple linear relationship between grain size and channel slope, as would be expected if channels were adjusting only in response to the requirement to move the coarse sediment load. We speculate that in this landscape, adjustments in roughness and sediment load that accompany grain size complicate the signal between grain size and channel slope. Our analysis exposes the complexity of confidently extracting a tectonic signal in a setting where bedrock and most importantly bedload lithology is diverse.

UPSTREAM							
Slope	D_{50}(m)	Depth (m)	τ(Pa)	τ^*	τ^*_C	Threshold of motion stress(τ_D) (Pa)	Excess Stress(τ_{EX}) (Pa)
0.010	0.02	1.7	167	0.4	0.05	18	148
0.009	0.03	2.1	185	0.4	0.05	22	163
0.008	0.02	2.1	165	0.6	0.05	12	153
0.008	0.02	2.2	173	0.5	0.05	15	158
DOWNSTREAM							
0.025	0.16	2	490	0.2	0.06	154	336
0.031	0.20	2.3	699	0.2	0.06	204	495
0.020	0.19	2.3	451	0.2	0.06	173	278
0.020	0.17	2.3	452	0.2	0.06	155	296

Table 1] Field measurements of slope,median grain size and bankfull depth were used to directly calculate total shear stress, Shields stress,threshold of motion stress and excess stress.The critical Shields stress was calculated using the slope-dependent Shields stress equation[Lamb et al.,2008].

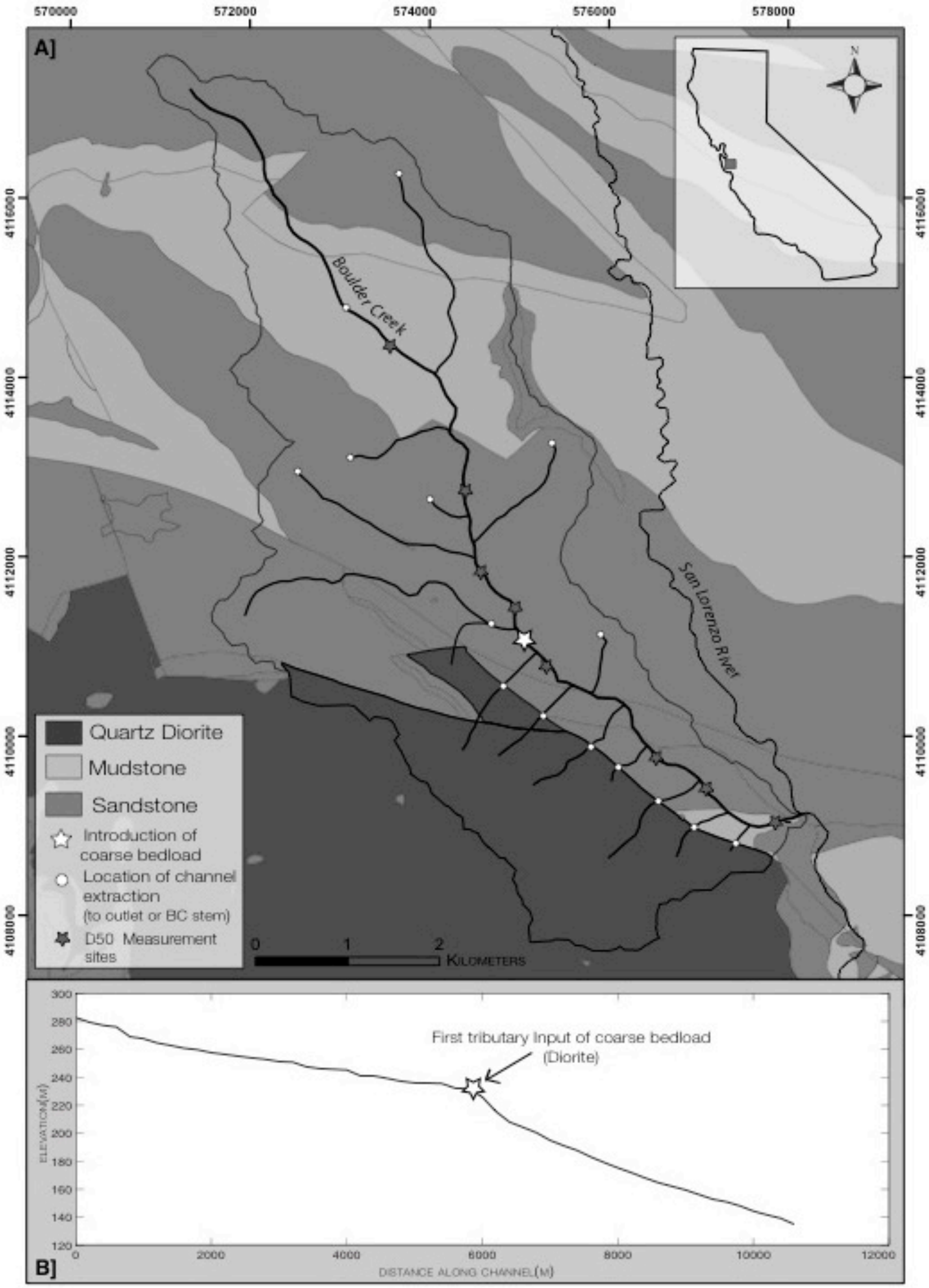
A]
570000
572000
574000
576000
578000
4116000
4114000
4112000
4110000
4108000
N
Boulder Creek
San Lorenzo River
Quartz Diorite
Mudstone
Sandstone
Introduction of coarse bedload
Location of channel extraction (to outlet or BC stem)
D50 Measurement sites
0
1
2
Kilometers
B]
First tributary Input of coarse bedload (Diorite)
ELEVATION(M)
DISTANCE ALONG CHANNEL(M)
300
280
260
240
220
200
180
160
140
120
0
2000
4000
6000
8000
10000
12000

Figure 1a] Simplified geologic map of Boulder Creek watershed showing spatial distribution of diorite,mudstone and sandstone [Brabb et al.,1997]. White star marks the location where diorite is introduced to Boulder Creek. All of the tributaries transporting coarse bedload tap a crystalline source at their headwaters. Channel traces are calculated from USGS 10m elevation model. Map coordinates are given in (UTM)10N,Nad27.1b] Longitudinal profile of Boulder Creek identifying the location where Diorite is introduced from the first tributary sourcing coarse sediment to the main stem.

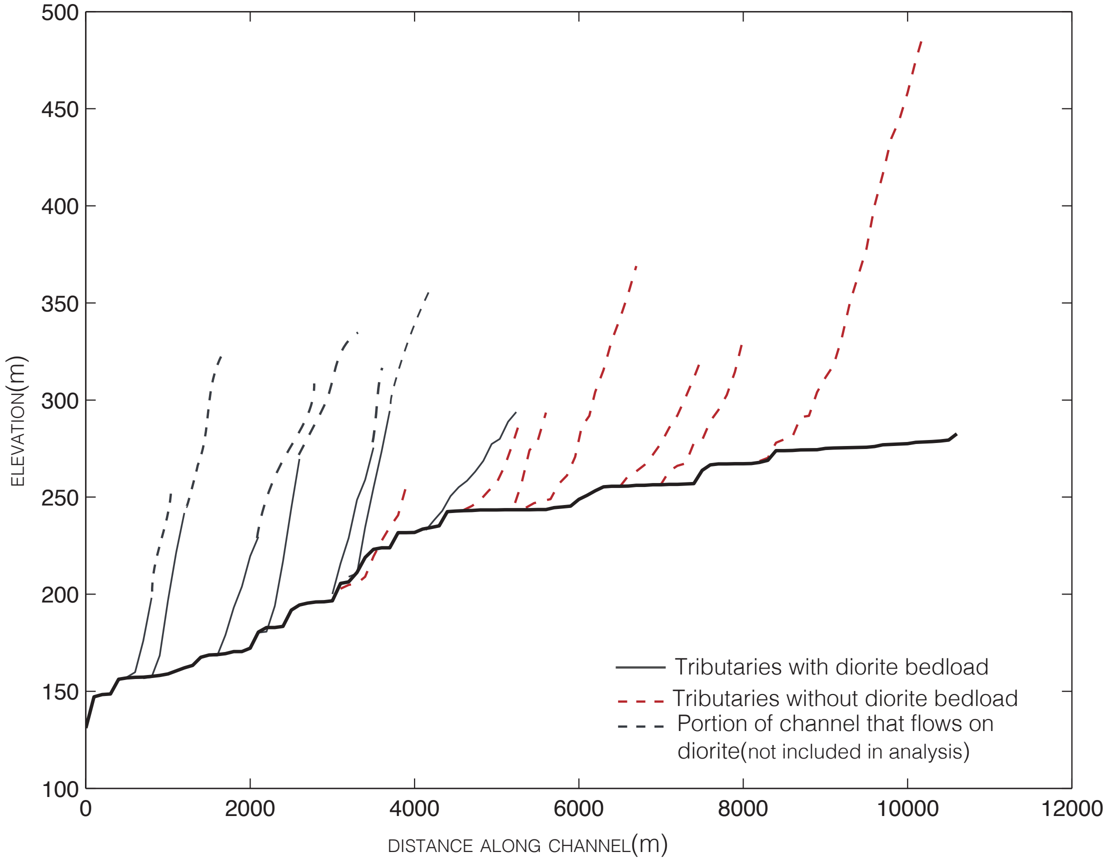

Figure 2] DEM longitudinal profiles for channels in figure 1.Elevation profiles extracted from USGS 10m DEM and subsampled at 100m intervals.

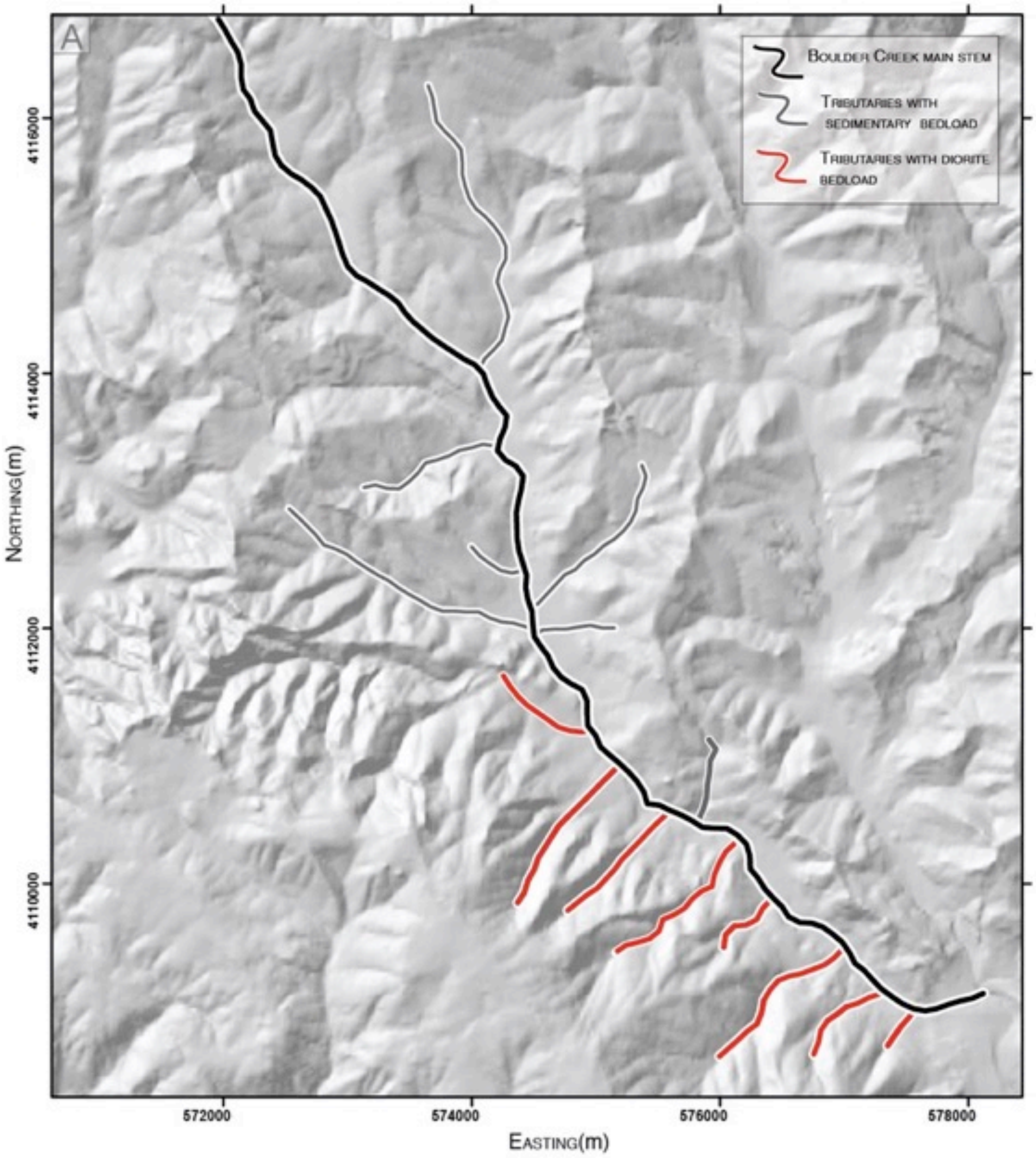

Figure 3a] Location of tributaries used in Chi Analysis (Figure 3b,c). Channels are characterized by the presence or lack of coarse diorite bedload.

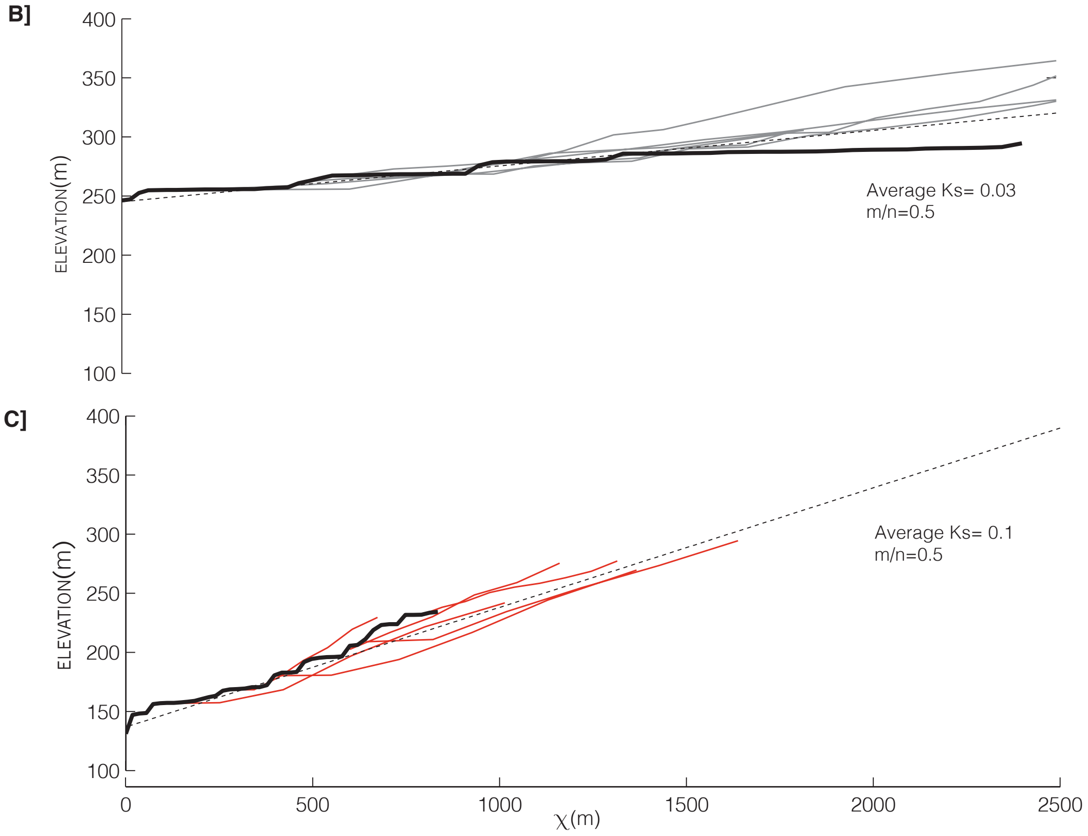

Figure 3] Chi plot of the longitudinal profiles of Boulder Creek and associated tributaries **a]** Channels without coarse diorite bedload **b]** Channels with coarse diorite bedload.Dotted lines represent average channel steepness(K_s).

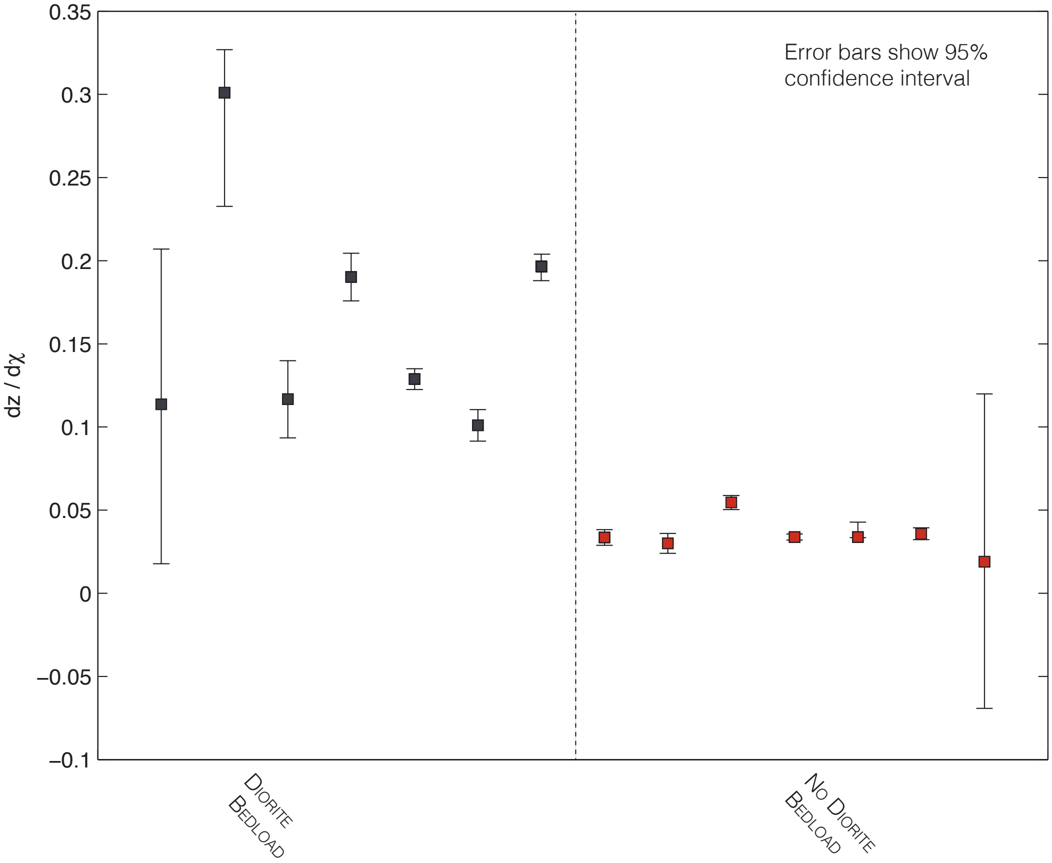

Figure 4] Average dz/dchi of each tributary in figure 3(b,c).The upstream and downstream reaches of the main stem are also plotted (shown far left and far right).

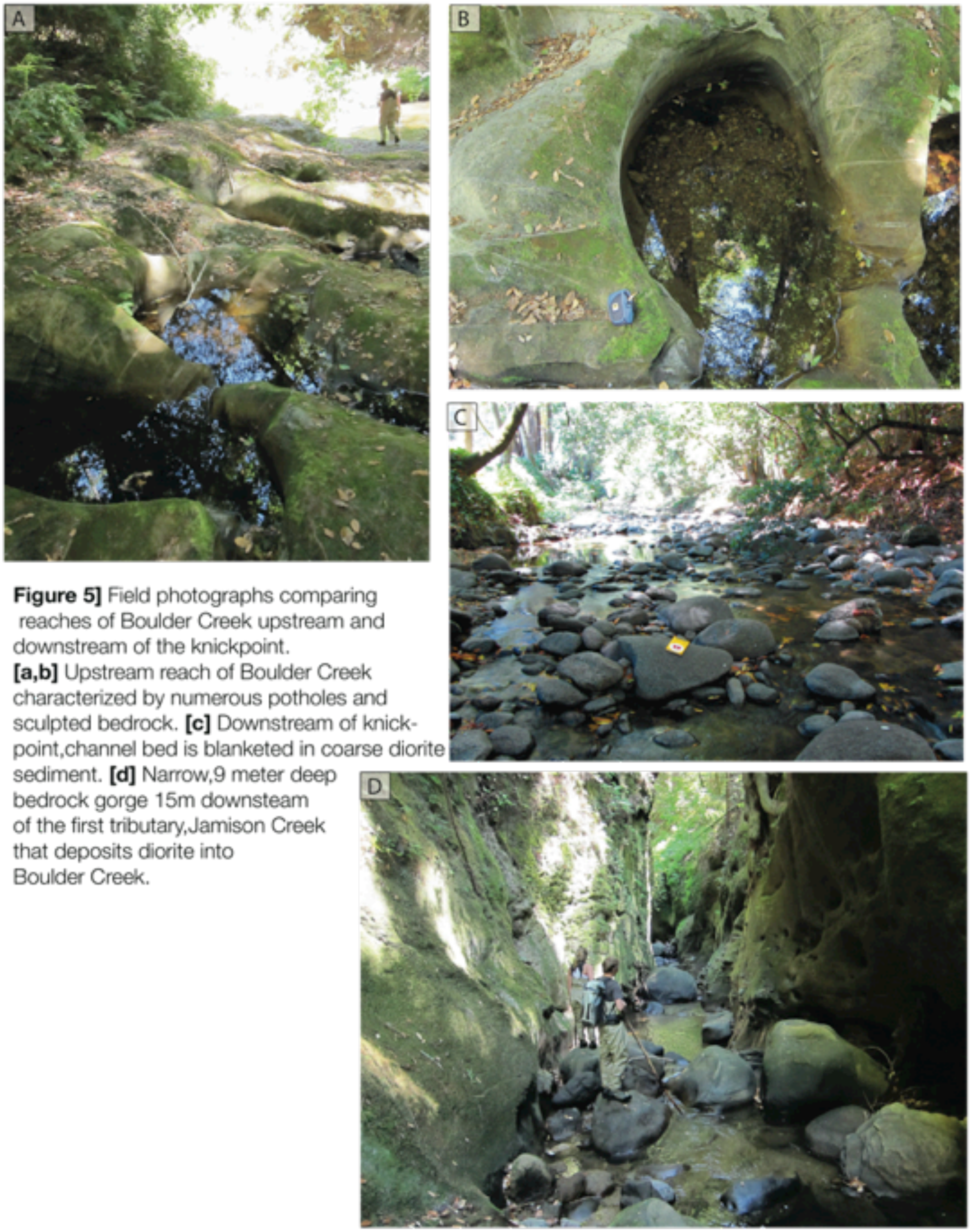

Figure 5] Field photographs comparing reaches of Boulder Creek upstream and downstream of the knickpoint. **[a,b]** Upstream reach of Boulder Creek characterized by numerous potholes and sculpted bedrock. **[c]** Downstream of knickpoint,channel bed is blanketed in coarse diorite sediment. **[d]** Narrow,9 meter deep bedrock gorge 15m downsteam of the first tributary,Jamison Creek that deposits diorite into Boulder Creek.

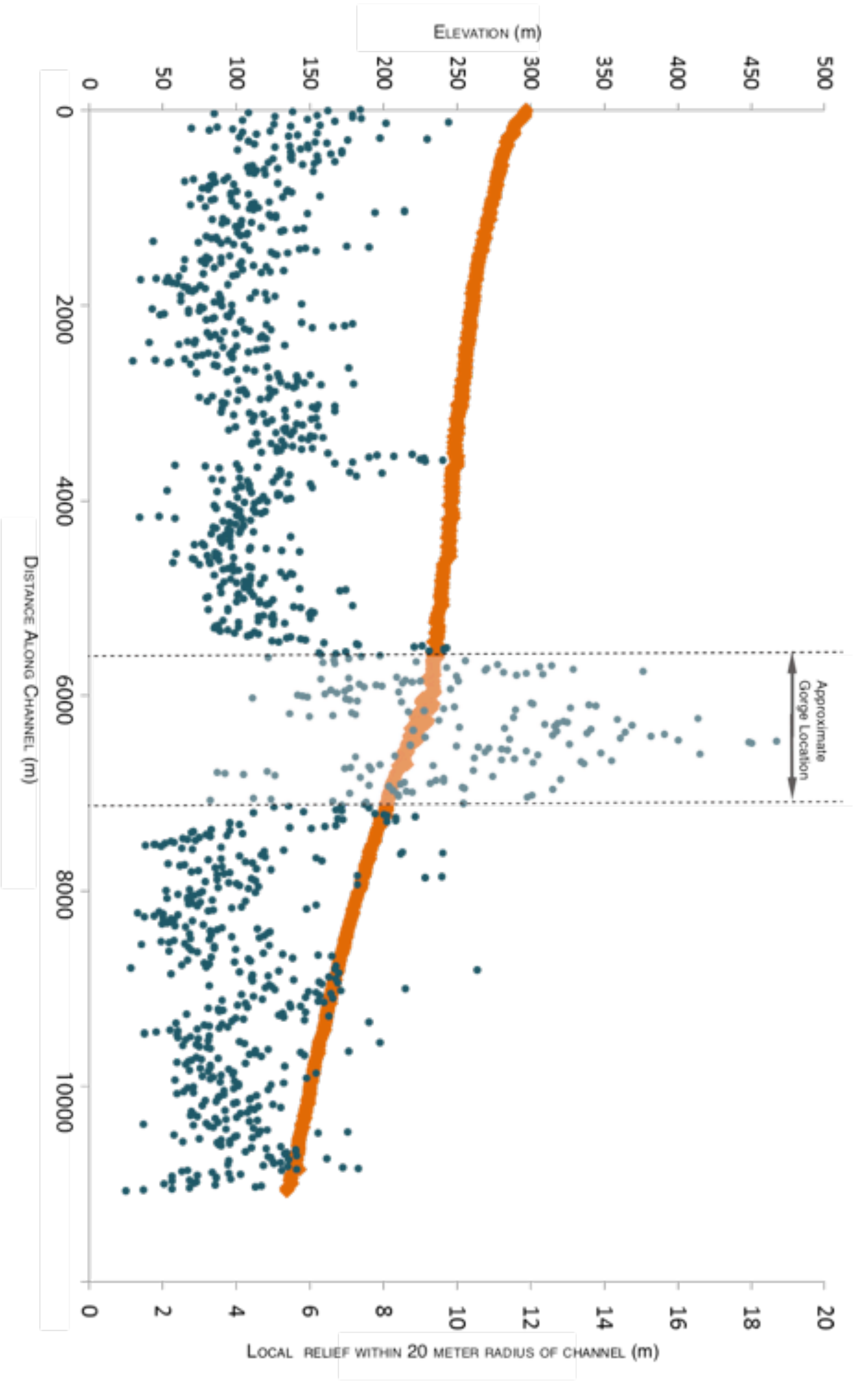
Elevation (m)
0
50
100
150
200
250
300
350
400
450
500
Distance Along Channel (m)
0
2000
4000
6000
8000
10000
Approximate Gorge Location
Local relief within 20 meter radius of channel (m)
0
2
4
6
8
10
12
14
16
18
20

Figure 6] Dotted lines indicate location of gorge determined by extracting elevation values and calculating the local relief within a 20 m radius window.

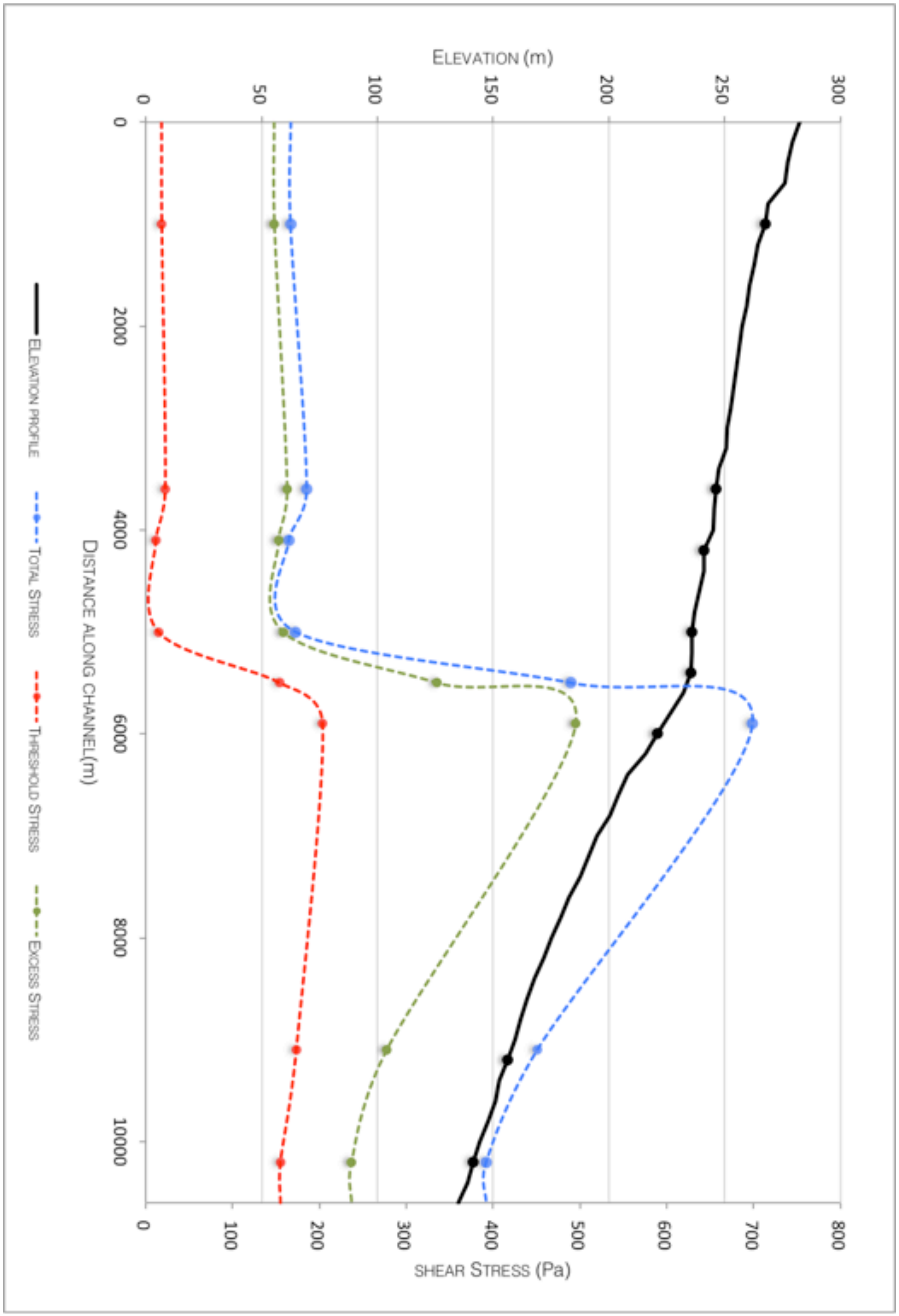
ELEVATION (m)
0
50
100
150
200
250
300
0
2000
4000
6000
8000
10000
DISTANCE ALONG CHANNEL(m)
0
100
200
300
400
500
600
700
800
SHEAR STRESS (Pa)
ELEVATION PROFILE
TOTAL STRESS
THRESHOLD STRESS
EXCESS STRESS

Figure 7] Total shear stress,threshold stress and excess stress values calculated from direct field measurements are shown at each sampling location (Table 1).

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