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Climate, tectonics or morphology: what signals can we see in drainage basin sediment yields?

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Abstract

Sediment yields from river basins are typically considered to be controlled by tectonic and climatic drivers. However, climate and tectonics can operate simultaneously and the impact of autogenic processes scrambling or shredding these inputs can make it hard to unpick the role of these drivers from the sedimentary record. Thus an understanding of the relative dominance of climate, tectonics or other processes in the output of sediment from a basin is vital. Here, we use a numerical landscape evolution model (CAESAR) to specifically examine the *relative* impact of climate change, tectonic uplift (instantaneous and gradual) and basin morphology on sediment yield. Unexpectedly, this shows how the sediment signal from significant rates of uplift (10 m instant or 25 mm a^{-1}) is lost due to internal storage effects within even a small basin. However, the signal from modest increases in rainfall magnitude (10–20 %) can be seen in increases in sediment yield. In addition, in larger basins, tectonic inputs can be significantly *diluted* by regular delivery from non-uplifted parts of the basin.

1 Introduction

Sediment yields from upland basins are driven by tectonics and climate. The magnitude of sediment delivered by this "erosional engine" (Whittaker et al., 2009) is a major control on the size and location of sediment facies found in depositional basins, and thus creates an opportunity to invert sedimentary records to establish climate and tectonic histories of the source basin.

However, the presence of two major external forcings (climate and tectonics) as well as the internal autogenic processing of these signals (e.g. Jerolmack and Paola, 2010; Van De Wiel and Coulthard, 2010) leads to a plurality of possible interpretations for each sedimentary record (Leeder, 2011). The difficulty of inverting this plurality to establish whether individual or identifiable combinations of forcings can be determined is a fundamental limitation to our present capability to determine past climates and landscape histories from sedimentary records.

At its simplest, the sedimentary system can be split into three components, an upland production "erosional engine" (Whittaker et al., 2009), transport of sediment, and deposition in a basin or store (e.g Schumm, 1979). Historically, research has focused on controls in the depositional setting; only more recently have researchers examined how tectonic and climatic changes can alter sediment production. For example, Willgoose et al. (1991), Whipple and Tucker (2002), Tucker and Whipple (2002), and others have demonstrated with numerical models how post uplift there is an increase in basin sediment discharge associated with a "wave" of incision that migrates upwards through a basin. More recently, Densmore et al. (2007) showed that for small fans the timing and amplitude of sediment flux to basins is controlled by changes in fault slip rates. Some have shown how climate changes can also change or increase sediment delivery (Tucker and Slingerland, 1997; Coulthard et al., 2002) through mechanisms such as the extension of the stream network and increased stream powers. However, there has been little work quantifying the relative impacts of climate and tectonics on sediment delivery and how these may manifest themselves in the sedimentary record.

In addition, comparatively little research has examined the transport of sediment from uplands to basin, with many theoretical and modelling studies assuming a direct link between the two. Yet in numerous natural settings there is a considerable length and width of alluvial "conduit" between areas of sediment erosion and deposition. Geomorphological research indicates that this "conduit" operates in a non-linear way as part of a complex response (e.g. Schumm, 1979; Coulthard et al., 2005), and more recent research has suggested that (geologically) short term storage in floodplains may "shred" any upstream signals of forcings (Jerolmack and Paola, 2010).

In this paper we apply a numerical landscape evolution model to demonstrate that there are unexpected and major differences between the relative impacts of climate and tectonics on sediment delivery, and illustrate how the shape of the basin and length of conduit imparts an important control on this relationship.

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2 Model description and simulation set up

The simulations were carried out with the CAESAR landscape evolution model (Coulthard et al., 2002; Van de Wiel et al., 2007). The main features of CAESAR are a combined hydrological and hydraulic flow model that operates on a sub-event time step, with multi-grainsize erosion and deposition as well as slope processes (diffusive creep and landslides). The hydrological model is based on Topmodel (Beven and Kirkby, 1979) and the hydraulic model is two dimensional steady state, using a flow sweeping algorithm (Coulthard et al., 2002; Van de Wiel et al., 2007). Bedload sediment transport is calculated using Einstein's equation for bedload transport allowing for the transport of separate size fractions (Einstein, 1950). CAESAR was initially developed to examine the relative roles of climate and land cover change on geomorphology and sediment yield and has been applied to a range of real drainage basins with outputs successfully compared to independent field data. These examples include patterns of sedimentation in Alpine Environments (Welsh et al., 2009) sediment yields and longer term lowering rates from Northern Australia (Hancock et al., 2010), comparisons to field plot experiments (Coulthard et al., 2012), predicting patterns of contaminated sediment dispersal (Coulthard and Macklin, 2003) and simulating 9000 yr of drainage basin evolution in the UK (Coulthard and Macklin, 2001).

Here, CAESAR was applied to the River Swale located in the North of England (Fig. 1). The section of the Swale modelled in this study lies upstream of Catterick Bridge, consisting of a total basin area of 490 km^2. The average elevation within the basin is 357 m, the altitudinal range is 68–712 m and the average river gradient is 0.0064. At the headwaters the landscape is characterized by steep valleys and the geology is Carboniferous limestone and millstone grit (Bowes et al., 2003). Further downstream, valleys become less pronounced and the underlying geology becomes Triassic mudstone and sandstone (Bowes et al., 2003). For the numerical experiments, three different size sub-basins of the Swale were used (Fig. 1), herein termed small, medium and large, and located upstream of points S1, S2 and S3, respectively. For all

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uplift simulations only the area to the west of point S1 was uplifted (Fig. 1). CAESAR required modification to simulate uplift and this was simply carried out by raising the elevations of the appropriate cells. The climatic inputs into the hydrological component were derived from a 10 yr hourly rainfall data set for the area, repeated for the length of the simulations. Basin hydrology parameters were held constant during all simulated periods. There is no bedrock representation in these simulations, so all incision is into multi-grainsized material.

3 Results

3.1 Impacts of climate and tectonics on sediment totals

To investigate the role of tectonics we conducted a series of experiments on the medium basin by instantaneously uplifting the upper section (i.e. the area west of S1; Figs. 1 and 2) after 50 yr of simulation, and then continuing the simulation for a further 50 yr. This was to establish whether there was any transient response to the uplift event, as well as to examine longer term changes. The simulations were repeated several times with differing amounts of uplift (1 m, 2.5 m, 5 m, 10 m, 25 m, 50 m, 100 m, 250 m). Figure 2a shows cumulative sediment yields from the basin measured at point S2 and Table 1 contains total and percentage increases in sediment yield. The dashed lines are from simulations with different instantaneous uplift amounts and generally show an increase in sediment yield following the uplift events. However, uplift of 10 m or more is required to create a noticeable shift in the cumulative line. Using same basin but disabling the uplift, we then investigated the role of climate by increasing the magnitude of the rainfall input to the hydrological model after 50 yr. The simulations were repeated with rainfall rates increasing by 10 to 100 %, in 10 % intervals. The cumulative sediment yields from these simulations are plotted as solid lines on Fig. 2. Increasing rainfall magnitude creates a very similar effect as tectonic uplift, though with a small but identifiable transient response (a vertical increase in the cumulative). Comparatively small

increases in rainfall magnitude result in relatively large increases in sediment yield (e.g. 20 % increase in rainfall increases sediment yield by 53 %; Fig. 1). To achieve a similar increase of sediment yield, a large amount of instantaneous uplift is needed (e.g. 25 m of uplift results in 64 % increase in yield). In Fig. 3, we compare the sediment yield totals after 100 yr from all of these tectonic and climate simulations. Relatively modest rises in rainfall magnitudes (+20 %, +30 %) result in 50 to 100 % sediment yield increase, which is matched only by large levels of instantaneous uplift (i.e. 25 m or more). At larger rainfall increases, the difference gets even starker. For example, approximately 90 m of uplift is required to achieve the cumulative sediment output from a 50 % increase in rainfall (5.6×10^6 m^3).

These simulations, however, are only over short 100 yr time scales. To investigate longer term trends we extended a select number of these runs to continue for 900 yr. Cumulative sediment yields show a very similar response to the shorter term simulations (Fig. 2b). There is a slight decay in the rate of increase in sediment yields after ca. 200 yr from both uplift and climate change – which is in response to locally increased gradients (tectonics) and expanding drainage areas (climate) leading to an initial surge from readily available sediment. Clearly, the trends observed in Fig. 2a are not transient conditions and persist over longer time periods. We also investigated how gradual uplift (uplift rates of 5, 10, 25 and 50 mm per year) compared to changes in climate. As per previous results we can see that even large rates of gradual uplift are superseded by modest increases in climate (Fig. 2c).

To establish how basin shape and the length of channel between zones of uplift and deposition (the conduit) alter sediment delivery, simulations were carried out uplifting the same upper section of the basin, but increasing the distance between uplift and basin outlet. Three size basins were used, with outlets at S1, S2 and S3, respectively 500 m, 10 km and 30 km downstream of the uplifted area (Fig. 1). As per the previous experiments, uplift was instantaneous and added after 50 yr of simulation. As the temporal response was similar as previous simulations, only the impacts on total sediment yields are shown (Fig. 4). These data demonstrate that the percentage increase in

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sediment yield due to uplift is highest in the small basin, and progressively smaller in the medium and large basins (Fig. 4c).

In absolute values, sediment yield increases linearly with uplift (Fig. 4b). In the larger basins a noticeable increase in sediment yield only occurs after 25 m of uplift, and is driven by the relatively substantial changes uplift causes in basin relief (without uplift basin relief is 500 m). That aside, however, there are two other processes in operation. Firstly, adding a downstream section of valley floor to accommodate storage of sediment, as is the case in the medium and large basins, removes or "shreds" the part of the signal from the uplift events (Fig. 4b). The physical mechanism for this is evident studying the surface morphology of the simulations, where an alluvial fan forms immediately downstream of the uplift locus (Fig. 5). However, the larger basin does not seem to be more "effective" at shredding this signal than the medium basin, as the curves rise at very similar rates, albeit offset (Fig. 4b). Yet for the larger basin, the percentage change in sediment yield is far less (Fig. 4c). This demonstrates the second process, where the uplift signal is simply *diluted* by sediment being added from the non-uplifted parts of the larger basin as the ratio of uplifted area to total basin area decreases.

Next we compared increases in sediment yield from uplift to those from rainfall in different size basins (Fig. 4a). Unlike the uplift scenarios, where only part of the basin is uplifted, increases in rainfall affect the whole basin, giving 2 to 3 times larger sediment yields for the larger basin, reflecting its larger area (Fig. 4a).

Figure 5 shows the impacts of 50 m of uplift on the geomorphology of the simulations around the area uplifted. This shows the before, and at four time points after uplift. Here there are clear changes in the nature of the channel both upstream and downstream. Upstream there is an entrenching of the main stream with a nick point migrating upstream ultimately leaving a river terrace behind. Downstream there is an immediate change in the channel pattern from single thread to braided (indicative of increased sediment yields) and the development of a small alluvial fan.

3.2 Impacts of climate and tectonics on sediment grainsize

As well as providing information on sediment yields, the multiple grainsizes incorporated within CAESAR allow changes in grainsize to be simulated in response to climate and tectonic forcings. Here we focus our discussion on the median grainsize, D50, for the 100 yr simulations with uplift, for the S1, S2 and S3 basins (Fig. 6). These results show the annual mean D50 for all events within a year, and they thus increase and decrease with years that have more and less large flood events. When viewed as daily data similar patterns were observed, but are omitted here as the yearly totals present a clearer picture. Results for D84 show similar trends and are not discussed.

For S1, the 5 m uplift initially leads to a 20 yr increase in the D50 for the 5 m uplift event (Fig. 6a). The initial coarsening agrees with field observations (e.g. Whittaker et al., 2009) associated with higher stream powers due to increased channel gradients (Whittaker et al., 2009). However, this effect begins to attenuate after 20 yr with the D50 diminishing to slightly less than that prior to uplift. For 10 m and 25 m of uplift there is a very different reaction with both a reduction in D50 and a smoothing of the signal from different annual events. For 10 m uplift there is a partial recovery in this signal after 30 yr and possibly beginning at 50 yr for 25 m uplift. The simulated fining associated with uplift is clearly different from expected results of coarsening (Whittaker et al., 2009) and we offer two explanations for this. Firstly, the 10 and 25 m uplift events we have simulated are very unusual in the field – and therefore it is quite possible we are simulating an effect not observed in the field. Secondly, our model has a high level of connectivity between channel, floodplain and hillslopes. Within our high uplift scenarios significant fluvial incision occurs (see Fig. 5) leading to the immediate introduction of fresh sediment from the collapse of river banks that will be sustained as a wave of incision passes up through the valley floor (as indicated in Fig. 5). The bank and slope material has a relatively higher concentration of fines than sediments in the river bed. In addition, this effect will also translate into tributary streams leading to a sustained input of finer sediment. The reduction in the annual variation in D50 in the 10 m and

25 m uplift simulations is a different example of signal shredding. Here the system has been overloaded with finer sediment creating a situation where climatic variations are no longer observed in the D50 (although they are in the total sediment yield).

With S2 all simulations show a fining of the sediment post uplift, with the effect becoming more amplified with greater amounts of uplift (Fig. 6). This shows that some of the finer sediment released from S1 after uplift is being transported through the reach – though, since the grainsize reduction is reduced from S1 to S2, a substantial volume and proportionaltely more of the coarser material is being stored between S1 and S2. The reduction in inter-annual variability of the D50 that was observed at S1 is less noticeable at S2, although there still is some reduction in the variability as the amount of uplift increases.

For S3 there is little or no variation in D50 pattern in the 5 m and 10 m uplift scenarios. Only in the 25 m uplift scenario is there an observable impact on the D50, namely that the variability decreases. Location S3 is thus sufficiently far downstream of the fault-line for grainsize not be affected by the uplift of 5 and 10 m with only a small impact from the 25 m uplift. In other words, the valley between S1 and S3 absorbs the effects of the uplift on transported sediment sizes.

Figure 7 describes the impacts of climate on grainsize for basins S1, S2 and S3. Unlike uplift overall there is a far weaker response in the grainsize signal to increased wetness. For S1, S2 and S3 there is negligible change in grainsize after the 10 % increase in wetness, with any variations indiscernable from variations prior to the increase. However, for larger increases in wetness drops or dips in grainsize are amplified. These drops in grainsize correspond to wetter years indicating that these correspond to the increased delivery of fine sediments during wetter periods.

3.3 The role of autogenic processes

Within our results, we believe we can see evidence of autogenic, or internal processes that are creating signals within the basin outputs. In Fig. 8, we have plotted the annual

and decadal sediment outputs from the 900 yr simulations with actual and relative values (relative values are normalised to the mean sediment output).

Signals generated in post uplift sediment curve of S2 and to a lesser extent S3 are of similar (10 m) and greater (5 m) magnitude than peaks immediately following the uplift itself. Therefore, at both annual and decadal timescales the S2 and S3 basins are capable of generating sediment yield peaks equivalent to or greater than those seen immediately after uplift. There is also evidence that uplift changes the nature of sediment outputs from the system. For example, for S3 there is a post-uplift reduction in annual variability of absolute sediment yield, while for S2 there is a post-uplift increase in variabilty for releative sediment yield (Fig. 8).

Finally, in terms of the relative sediment yield, the impact of uplift is barely visible for S3 – at least with 5, 10 and 25 m uplift settings. The relative changes (right side graphs in Fig. 8) also show there is both a greater indication of the uplift signal in S2 than S3 (supporting earlier findings).

4 Discussion

These results provide is with considerable insight into how a drainage basin processes different external forcings. In these experiments climate changes clearly generate greater increases in sediment yield than uplift. In this study we have deliberately explored extreme values of climate and uplift, but if we restrict the results to more reasonable values (e.g. instantaneous uplift up to 10 m and rainfall/climate increases of 30 %) then in systems where the sedimentary deposits are *not* proximal to the sediment source, climate changes clearly have a far greater impact on sediment delivery. In our simulations elevated sediment yields from 10m of uplift are equivalent to a 10 % increase in rainfall magnitude. Even looking at longer time scales and continual uplift rates of 25 mm yr equate to a 10 % increase in rainfall.

However, the converse is apparent when examining grainsize. Here (especially in S1 and S2) there is a mixed reaction to uplift that generates an increase or decrease in D50 according to the magnitude of the change. As previous studies have studied uplift/grainsize interactions on uplift levels equivalent to our smaller values we may have discovered a different effect. This would suggest a switch in sediment response above certain levels of uplift. Alterations in climate have a less apparent impact on D50 with the exception of the largest increases in rainfall magnitude (30 % and 50 %) leading to an increased drop in grainsize during wetter years.

The role of the sedimentary system "shredding" input signals (Jerolmack and Paola, 2010) is also apparent – with the addition of less than 10 km of non-uplifted floodplain removing much of the uplift signal from both sediment volume and grainsize. Interestingly, as basin size increases the impact of "shredding" does not increase, thus indicating that only a short area of accommodation for storage and re-working of sediment is required. Furthermore, the larger the area of basin relative to the size of the area uplifted the relative importance of shredding decreases as the signal is diluted by sediment from tributaries and other parts of the basin. Our findings support previous work indicating long lag times from tectonic changes that are "buffered" by the drainage basin (Allen, 2008; Metevier and Gaudemer, 1999), in particular with areas of valley floor and floodplain (Castelltort and Van Den Driessche, 2003; Metevier and Gaudemer, 1999) as found in our expaning catchment settings. It is worth noting that increases in sediment delivery are generated by *all* uplift and climate scenarios – but as catchment area and valley floor length grow, peaks in sediment will be smoothed, or lost within the noise of the autogenic signals.

There may be important implications from this reseach for the interpretation of stratigraphy. Firstly, our results only generate sediment yields at the edge of our simulated drainage bains. We, therefore, do not account for any depositional settings or changes in accommodation space that may occur subsequently downstream. However, we suggest that the thickness of a facies found in such sedimentary records is more likely to represent changes in climate rather than any uplift history, except for where there is a direct and high level of connectivity between source and deposit. Closer to the point of uplift, coarsening in grainsize is likely to be indicative of small/moderate uplift but a

fining in grainsize indicates either large amounts of tectonic uplift or major increases in rainfall magnitude. In short, changes in the volume of sediment exported from a basin is more contingent on climate than tectonics, yet changes in grainsize in this sediment are more likely to represent tectonic changes rather than climate.

These results also indicate that a short term peaks in sediment volume are more likely to be generated by increases in rainfall than uplift events. Therefore, marked increases in the thickness of facies – if representing increases in sediment supply – are more likely to indicate climatic changes rather than tectonic. It is important to note that this "short term" sediment peak equates to a year or more of increased sediment delivery, rather than that from individual flood events, which may be very difficult to identify (Van de Wiel and Coulthard, 2010). Furthermore, for moderate levels of uplift, the autogenic factors generate annual and even decedal peaks in sediment of equivalent or greater magnitude than uplift. In other words, the noise generated within the system is greater than the signal from the input.

There are obvious limitations in our approach, mainly in the model set up and the location. The Swale is not a tectonically active basin, but was chosen as CAESAR has been extensively evaluated and validated on the Swale over decedal to centennial time scales. For determining how the distance from uplift affected any tectonic or climatic change signal the Swale has a relatively straightforward valley floor and is typical of many upland basins. Importantly, we chose a natural basin over an artificial landscape (e.g. Van De Wiel and Coulthard, 2010) as we wanted to include topographic heterogeneity (tributaries, floodplains, alluvial fans) as well as actual rainfall records and grainsizes. In addition, finding a field site with enough available data (in particular initial conditions e.g. topography) and with a tectonic and climatic history was difficult (as discussed later). We deliberately manipulated uplift rates and climate changes in a rather unrealistic manner, but this is to establish the outer limits of the relationships between climate, uplift and morphology on sediment yield. Further modes of uplift were tried (fore tilt, back tilt, sideways tilt, gradual and instant) and all gave similar results.

Compared to alternative landscape evolution models, CAESAR has a high level of process representation. Therefore, some of the phenomena we have simulated here (e.g. different grainsize responses to varying uplift) require such a high level of parameterisation and could be missed by less complex, especially one dimensional network based models. This raises a question as to the level of process detail, spatial and temporal resolution that are required to simulate landscape dynamics. If high levels of detail are required, this may expose a particular problem for long term landscape modelling, as field data to drive simulations (e.g. initial landscapes, grainsizes, climates) and validate model runs (e.g. stratigraphy, topographic data) is especially hard to come by. In addition, a circularity can develop whereby stratigraphy may be used to validate models, as well as generate driving data – yet could be highly variable and not truly reflect drivers or products of the basins dynamics (e.g. Coulthard et al., 2007; Van De Wiel and Coulthard, 2010).

5 Conclusions

A series of numerical experiments were carried out, in which the impacts of climate change and tectonic uplift on catchment sediment yield was evaluated. Our results indicate that both have an impact on the sediment yield, but the nature of that impact is different. Climate changes are more likely to impact the total volume of the sediment yield. Tectonic uplift, on the other hand is more likely to affect the grain size distribution of the sediment yield. In our simulations, the impacts of tectonic uplift on the volume sediment yield are pronounced immediately downstream of the uplift zone, but considerably less notable the further downstream you check. In effect the tectonic signal is diluted by storage of sediment in the floodplain.

In addition, our results also indicate that autogenic variability of sediment yield, due to temporary storage and release of sediment within the basin, can be of the same or of magnitude than the spikes in sediment yield associated with the external disturbance, i.e. climate change or tectonic uplift.

All of these findings have implications for the reliability and meaning of inverting sedimentary records for determining past environmental and tectonic conditions.

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Table 1. Sediment yields in uplift scenarios for 100 yr simulations.

scenario	S1		S2		S3	
	cum. yield (10^6 m^3)	rel. change (%)	cum. yield (10^6 m^3)	rel. change (%)	cum. yield (10^6 m^3)	rel. change (%)
base	2.18	0.0	1.63	0.0	16.16	0.0
1 m uplift	2.23	2.5	1.65	1.2	16.24	0.5
2.5 m uplift	2.46	13.0	1.68	3.1	16.23	0.4
5 m uplift	2.98	36.9	1.71	4.8	16.41	1.5
10 m uplift	3.96	81.8	2.02	24.1	16.58	2.6
25 m uplift	6.74	209	2.67	63.7	17.78	10.0
50 m uplift	11.82	442	3.75	130	19.90	23.1
100 m uplift	21.03	865	6.12	275	23.76	47.0
250 m uplift	40.67	1767	12.78	684	30.64	89.6

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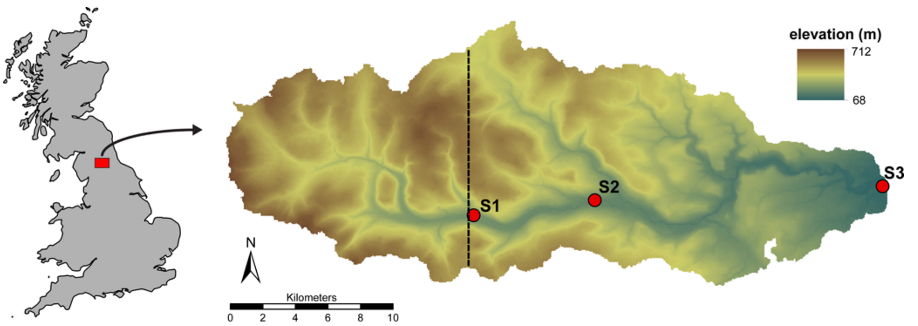

Fig. 1. Location map (left) and elevation map (right) of the Swale basin. The area to the west of the fault line (dashed black line) was uplifted in the uplift simulations. Points S1, S2 and S3 indicate three locations where simulated sediment yields were recorded, respectively corresponding to a small, medium and large upstream sub-basin. Point S1 is located immediately downstream of the fault line. Points S2 and S3 are 10 and 30 km downstream from the fault line.

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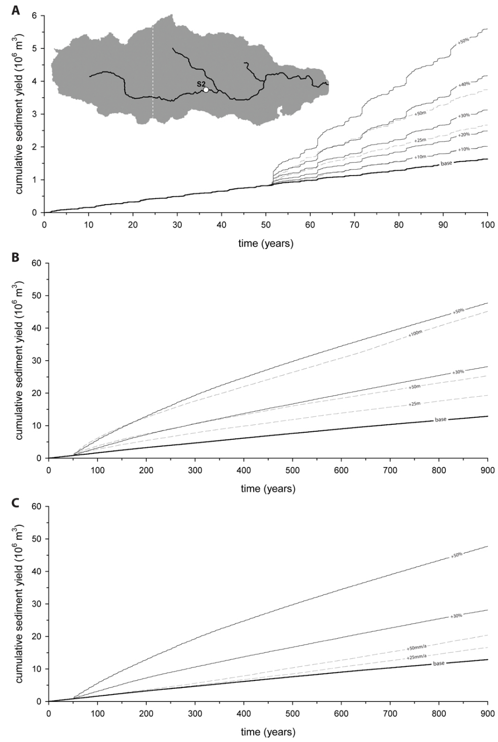

Fig. 2. Simulated cumulative sediment yields at point S2 for a range of different scenarios. **(A)** 100 yr scenarios for rainfall increase and instantaneous uplift. **(B)** 900 yr scenarios for rainfall increase and instantaneous uplift. **(C)** 900 yr scenarios for rainfall increase and gradual uplift. The uplift or increase in rainfall occurred at 50 yr. The base scenario (no uplift, no rainfall increase) is shown as a thick solid line, rainfall scenarios are shown as thin solid lines, and tectonic scenarios are shown as thin dashed lines. Inset shows location of fault line and measurement point S2.

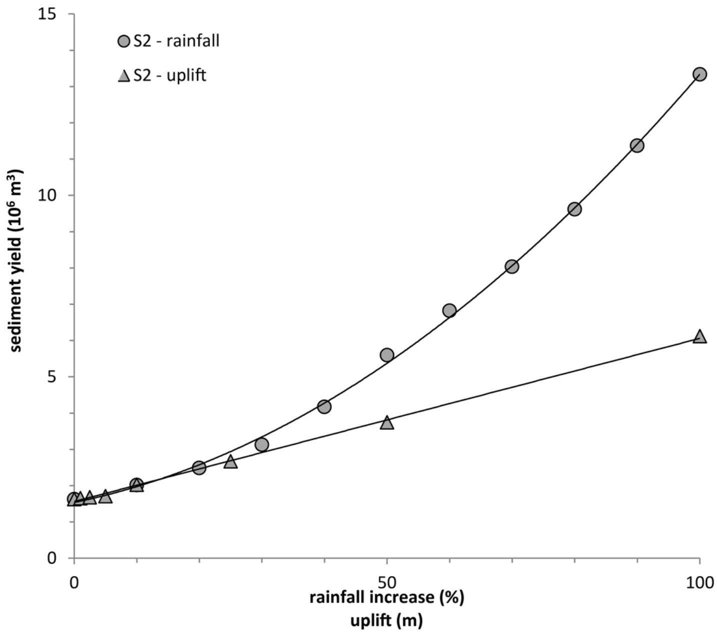

Fig. 3. Impact of rainfall increase and tectonic uplift on sediment yield after 100 yr, at point S2 (see Fig. 1 for location).

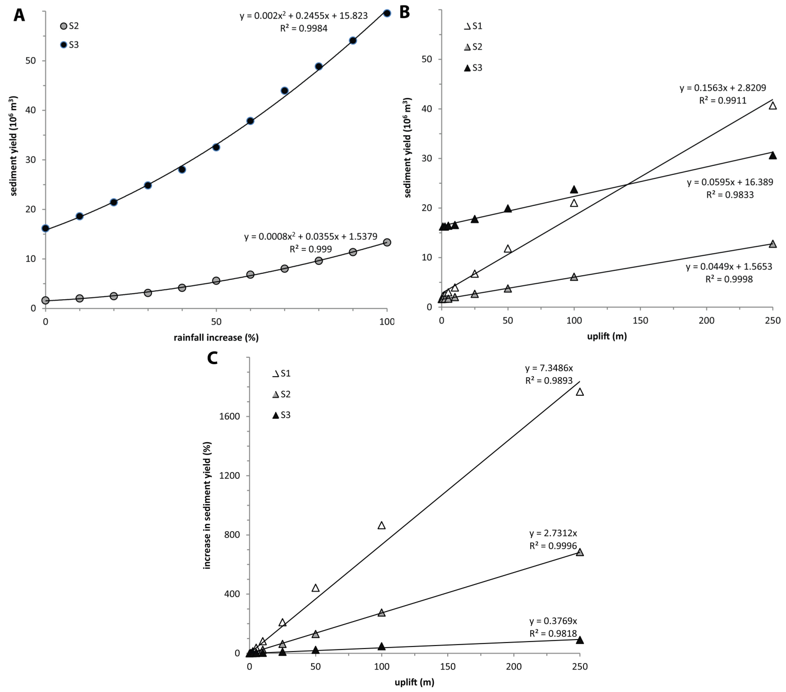

Fig. 4. Impact of rainfall increase or tectonic uplift on simulated sediment yields after 100 yr, at point S1, S2 and S3 (see Fig. 1 for locations). **(A)** Total sediment yield for rainfall scenarios. **(B)** Total sediment yields for instantaneous uplift scenarios. **(C)** Percentage change in sediment yield, relative to the base scenario, for instantaneous uplift scenarios.

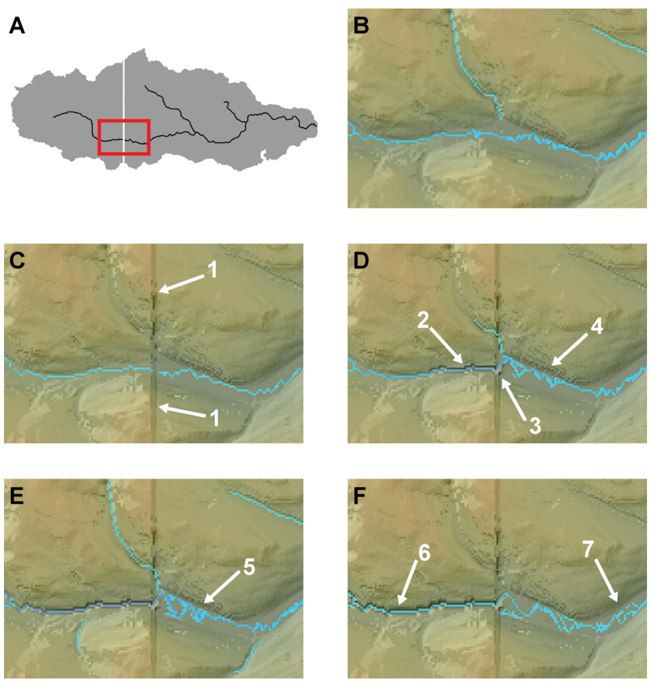

Fig. 5. Geomorphic changes occurring after the 50 m instantaneous uplift scenario. **(A)** location of fault (solid white line) and area selected for elevation maps (red rectangle). **(B–F)** Elevation maps of selected area, respectively after 1750, 1828, 2026, 2319, and 3622 days of simulation. Arrows indicate specific features: 1. Escarpment after uplift; 2. Incision of channel upstream of fault line; 3. Formation of small alluvial fan; 4. Braided river pattern downstream of fault line; 5. Expansion of braiding; 6. Continued incision upstream of fault line; 7. Downstream propagation of braided river pattern.

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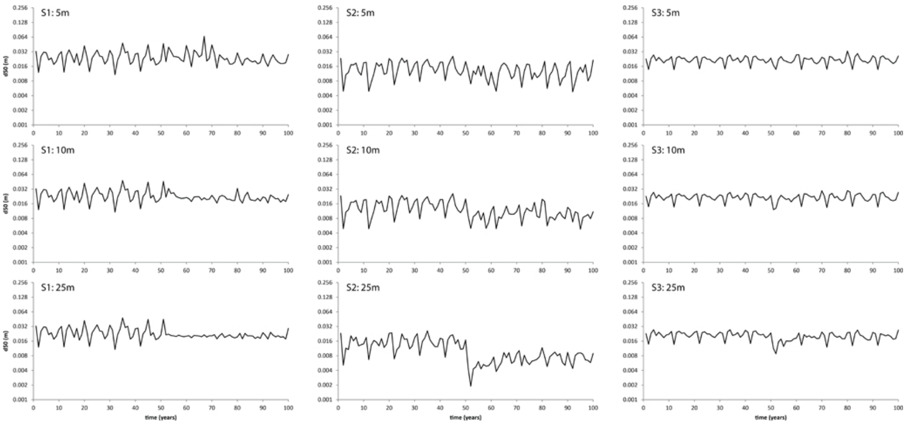

Fig. 6. Median annual grainsizes for S1, S2 and S3 for 5, 10 and 25 m uplift simulations. Values are calculated by summing total daily sediment yields for each of 9 grainsizes output by CAESAR, over a simulated year. This was carried out in preference to calculating daily median grainsizes and then averaging this over a year, which would skew the median grainsize by over-weighting the contribution of days with small daily sediment totals.

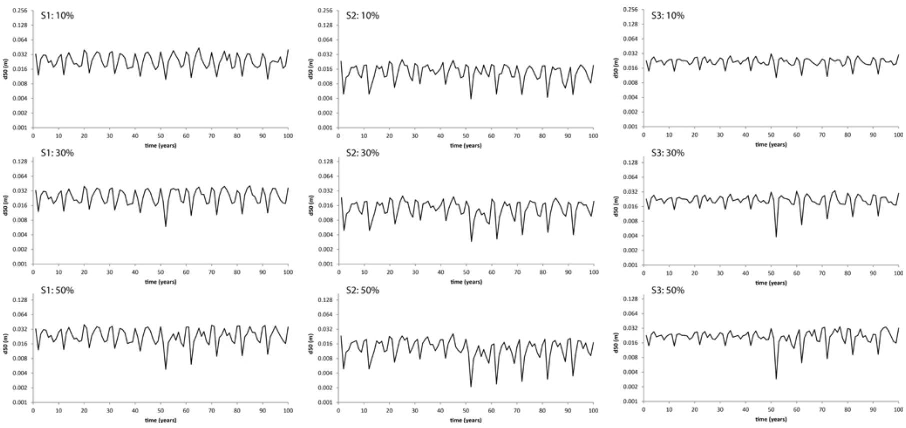

Fig. 7. Grainsize changes after rainfall changes for S1, 2 and 3 with 10, 30 and 50 % increases in precipitiation magnitude after 50 simulated years. Median grainsizes were calculated as per the method outlined in Fig. 6.

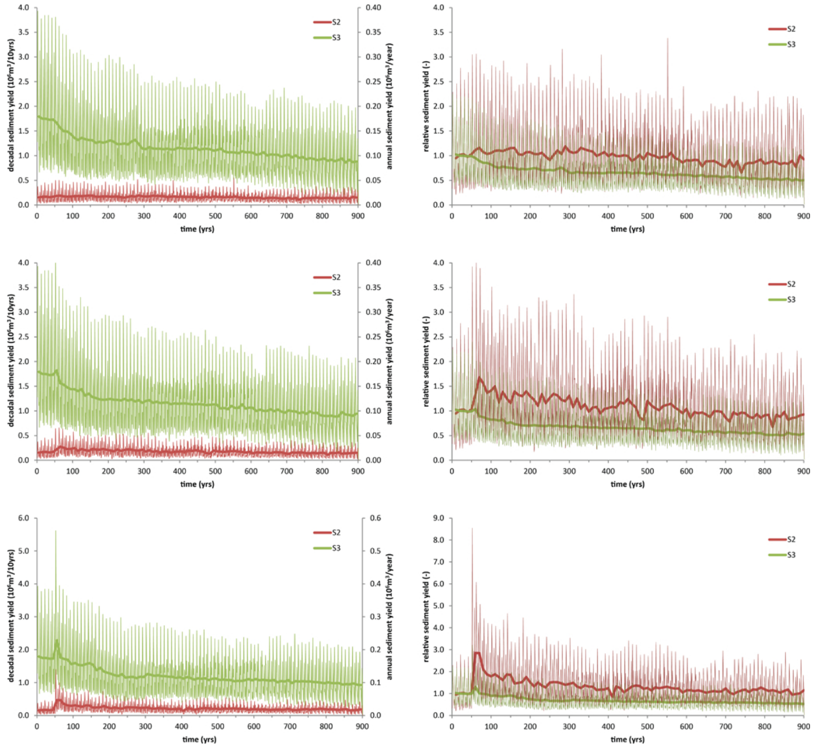

Fig. 8. Anual and decedal sediment yields for S2 and S3 over 900 simulated years for 5, 10 and 25 m of uplift respectively (top to bottom). The left side shows absolute values and the right side relative values (normalised to pre-uplift average).