We would like to thank the reviewers for their thorough and thoughtful comments on our manuscript. We have addressed their comments in the in the document below. We were unable to include a model diagram as suggested due to the abstract nature of the model, however we have improved our description of the model in the text including rearranging our methodology section, adding new equations describing the model space and highlighting the cartoon diagrams we have included in our figure 3.

We also would like to thank the handling editor, Susan Conway, for their time finding reviewers for the manuscript and their initial copy editing on the previous draft of the manuscript

Prof. Densmore Comments

1. While I agree that landslides convert bedrock into mobile regolith, they also transport that regolith, so I think this should be 'erosion' rather than 'weathering' which implies in situ development. We deliberately describe the generation of regolith as weathering in our model due to our lack of sediment transport. We define our use of the terms regolith and weathering later in the paper. No change (line 14)
2. You could simplify this sentence, as it's repetitive (it basically says 'we examine how earthquakes influence exhumation by exploring how earthquakes affect exhumation') Replaced with “We examine how earthquakes and landslides influence exhumation and surface uplift rates with a zero-dimensional numerical model, supported by observations from the 2008 Mw7.9 Wenchuan earthquake.” (Line 16)
3. Can you state more clearly what you are relating? This sounds like you're using seismic scaling laws and weathering scaling laws - is that right? Changed to “Our model uses empirically constrained relationships between seismic energy release, weathering, and landsliding volumes to show that large earthquakes generate the most surface uplift, despite causing exhumation of the bedrock surface.” (Line 20)
4. I don't really understand this sentence - it might become clear from the manuscript but it's not very easy to follow. Changed to “Our model suggests that when earthquakes are the dominant uplifting process in an orogen, rapid surface uplift can occur when regolith, which limits bedrock weathering, is preserved on the mountain range.” (Line 21)
5. This seems like a pretty important contribution of this work, so I wonder if it's worth stating up front that this is something that you're going to look at - rather than leaving it for midway through the abstract Done included in line 16
6. The wording here is not clear - are you referring to concentrations in landslide material, or in sediment derived from landsliding, or in the intact bedrock below the landslide excavation depth, or...? Changed to “After the earthquake there is a lowering in concentrations of ^{10}Be in regolith leaving the orogen but, the concentrations return to the long-term average within 10^3 years” (Line 23)
7. Can you be more clear about what you mean? What signal, and how is it shredded? I know this is an evocative phrase but it's usage here doesn't really explain what you're talking about Deleted this sentence

8. By 'long-term' do you mean 'measurable with common thermochronometers' or 'measurable by thermochron and CRNs' or something else? Deleted this sentence and included “$>10^3$ years” when discussing thermochronometers. (line 26)
9. Rock Done (line 31)
10. You could perhaps specify isostatic rock uplift here as an alternative Done (line 38)
11. You could insert 'any net' here, as it makes it clear that changes in mass balance don't necessarily equate to positive or negative surface uplift Done (line 39)
12. I agree about erosion - how does weathering affect the mass balance, other than producing erodible materials? Removed the word ‘weathering’
13. This seems like a good sentence to put earlier in the paragraph, before you get to the factors that can control that mass balance (which you mention above) We have rearranged the paragraph as suggested (line 30)
14. I'm not sure what you mean here - how does exhumation occur 'towards' a surface? Replaced with ‘exhumation of the bedrock surface’ (line 33)
15. Unless I misunderstand what you mean here, you seem to be using weathering and erosion interchangably. They are not the same thing! Replaced with erosion and ensured consistency in our usage of these terms (line 42)
16. You could also mention the fact that sediment stores tend to be limited, although not many have tried to quantify this; work by Will Ouimet and the Bloethe and Korup stuff in the Himalaya might be worth citing We are grateful to be pointed to additional relevant literature and have added references to the work described. “However, observations collected after earthquakes suggests that regolith remains in low-order catchments (Pearce et al., 1986), single large landslide deposits (Korup and Clague, 2009; Stolle et al., 2017), landslide dams (Ouimet et al., 2007) and valley fills (Blöthe and Korup, 2013) for up to 104 years. An estimated 44% of the sediment produced in the Himalaya is stored in the long term in some form before it exits the mountain range, demonstrating the importance of storage and sediment recycling to orogen scale sediment fluxes (Blöthe and Korup, 2013).” (Lines 48 - 52)
17. This is an important part of your argument and I think it's worth a bit more precision here. Yes, regolith remains in low-order catchments, but the issue is more around the residence time of earthquake-derived sediment (from coseismic or post-seismic landslides), and how that compares with the residence time during interseismic periods. I'd also be careful of citing a single number ('hundreds of years') - for example, Wang et al. showed a number of different residence times (using a very restrictive and approximate definition of residence time). It's also worth citing here the work on proportions of earthquake-derived landslide volume that are exported vs remaining in the catchments. Basically, while I agree with your point, I think it would be good to be as careful as you can in how you express it. We are happy to clarify and add precision to our discussion of sediment residence time and earthquake sediment fluxes. We have added “An estimated 44% of the sediment produced in the Himalaya is stored in the long term in some form before it exits the mountain range, demonstrating the importance of storage

and sediment recycling to orogen scale sediment fluxes (Blöthe and Korup, 2013). Similar findings are found in studies on post-earthquake sediment fluxes, in New Zealand up to 75% of the sediment produced by the 1929 Murchison earthquake remained in catchments 50 years after the earthquake (Pearce et al., 1986). While in Taiwan between 99 and 92% of the sediment produced by the Chi-Chi earthquake remained in catchments 8 years after the earthquake (Hovius et al., 2011). The slow removal time of earthquake derived sediment suggests residence times could exceed recurrence times of earthquakes in tectonically active mountain ranges. If significant volumes of sediment remain in the landscape for times longer than the recurrence period of earthquakes then large earthquakes could contribute significantly more to surface uplift than currently assumed (Li et al., 2014; Marc et al., 2016b; Parker et al., 2011).” (Lines 52 – 60)

18. What is non-linear about debris flows and flooding? We have clarified the language used to describe the remobilisation of landslide deposits, see next comment for changes.
19. Does that remobilisation need to be stochastic? What do you mean by this? We have changed this sentence to; The low connectivity between landslide deposits and channels and the low transport capacity of many small mountain channels highlights the stochastic nature of post-earthquake sediment transport as debris flows and floods are the primary sediment transport process. The timing of debris flow triggering is related to the interaction of storms and slope hydrology, which cannot be easily predicted, while the volume remobilised by debris flows is primarily controlled by the non-linear process of sediment entrainment during run out (lines 77 – 81)
20. Two points here. First, as mentioned in the abstract, be careful of a phrase like 'signal shredding' - it only makes sense if it's clear what signal you're referring to, and at this stage of the manuscript you haven't yet explained that. Second, what kind of record are you envisioning? A single earthquake that displaces a Gilbert delta up or down, or buries a wave-cut coastal notch, will almost certainly be recorded. A scarp cutting an alluvial deposit will also record a past earthquake - all of these are sedimentary records. You also need to consider the fidelity of the tools with which we can look at records of sedimentation or exhumation - whether or not a single earthquake is recorded in the time-temperature trajectory of a rock is immaterial if we don't have the thermochronometers to reproduce that trajectory with sufficient resolution. So I think you need to be a little more specific about what kind of records you are focused on before you can speculate on why those records might be imperfect, as the reasons will depend on the record. We agree our useage of the term signal shredding could be more precise. We have changed this sentence to; “This slow and stochastic removal of sediment from the orogen could be one reason why, despite the large volumes of sediment produced by an earthquake, single earthquakes are rarely recorded in erosional or stratigraphic records. Rather than a sink receiving a large impulse of sediment, which can be easily recorded via a change in average grain size or sedimentation rate, the rate change is instead smeared or shredded across the residence time of the sediment resulting in significantly less change which is far harder to measure (Jerolmack and Paola, 2010).” (lines 81 – 85)
21. 'have' done

22. This reads backward to me - I think it makes more sense to say that the differences in erosion rates have been linked to this difference in time scales. The counter-example to this is the work of Li et al. in Wenchuan, or Wittmann et al. in the Alps, showing similar erosion rates over different time scales... Erosion rates do change with the time scale used to measure the erosion, Ouimet 2010 propose that the recording time of cosmogenic radionuclides could be close to the return period of the large earthquakes. If this is true any variation of the cosmogenic nuclide derived erosion rate from the long term thermochronometric erosion rate could be due to earthquakes. We have clarified this further below.
23. T done
24. Again this seems like a key sentence, but I'm not sure what you mean. What methodology? How does this follow on from the previous sentences? What is 'coseismic material within landscapes'? At this point in the introduction, it should be really clear to the reader what the problem is that you're going to tackle, and I'm still not really sure what that is. We have clarified these sentences and added the research problem to the paragraph. "The averaging time for different measures of erosion rate (e.g. cosmogenic vs. thermochronometric) may strongly affect the probability of measuring a single earthquake. If the recording time of erosion, (103 years for cosmogenic radio nuclides or 104-5 years for thermochronometry methods) is similar to or less than the return period of large earthquakes, then any difference between short and long term erosion rates could be due to the influence of earthquakes (Kirchner et al., 2001; Ouimet, 2010). By investigating the variation of erosion rates with varying time scales, or with coseismic landslide density (Niemi et al., 2005; West et al., 2014), we may be able to identify the long-term impact of earthquakes on orogen scale erosion rates." (Lines 85 – 91)
25. entirely? We agree and have removed the word mostly to reflect this
26. In the opening sections of the introduction, you mentioned that coseismic defm is just one source of rock uplift; having given that idea such importance, it now seems odd to simply look at coseismic rock uplift. I'd suggest downplaying that earlier text as it seems to indicate that this is something that you're going to investigate - i.e. that it's part of the problem that you're going to tackle. This comes back to the importance of using the introduction to set up and motivate that problem. We have added a paragraph explicitly stating our research questions and aims. "In this paper we use a zero-dimensional volume balance model to explicitly track earthquake generated sediment through time in a hypothetical orogen based upon the Longmen Shan. We use the tracked sediment thickness into order to understand how earthquake-triggered landslides (EQTLs) affect exhumation and surface uplift at orogenic scales. Our model co-varies the amount of aseismic uplift in the orogen, imposed earthquake magnitude-frequency relationships, and both the timing and maximum magnitude of earthquakes, under multiple possible uplift regimes, in order to fully investigate the role of earthquakes in orogen scale volume budgets. We then use these scenarios to investigate whether earthquakes can be identified from erosion or exhumation records using different timescales and by modelling cosmogenic radionuclide concentrations of sediment leaving the orogen. Finally, we test our

hypothesis that the variation in erosion rates can be an indicator of seismic activity using a global database of cosmogenic radionuclide derived erosion rates." (lines 92 – 100)

27. In real terms, does this mean 'out of the catchment' or 'out of the mountain belt' or 'into the first geologically-relevant long-term store', or something else? Added in our model this means removal of sediment from the entire mountain range. (line 106)
28. Should this be 'exhumation relative to the bedrock surface'? You're not exhuming the bedrock surface, you're moving the rock relative to that surface This is correct and we have corrected the manuscript with your suggestion. (line 123)
29. S Done
30. Be careful - U has to be thickness per unit time We have clarified the units "where U (units of Length/Time) is the thickness of rock entering the orogen during a time step" (line 135)
31. rock uplift? We have included the word rock to clarify (line 135)
32. The text above states that you are only looking at coseismic rock uplift, but here you are including aseismic mechanisms. This needs to be consistent Within our introduction we have added a paragraph to explicitly state we are looking at a-seismic and coseismic uplift. (line 95)
33. I don't quite understand this sentence - first of all, if it's local compensation then you're not considering flexure, and what is the cause of the flexural-isostatic deformation? You haven't mentioned erosion yet. We have clarified our language and the calculations we have used. "The addition of mass to a column of crust by thickening will produce an isostatic compensation which will reduce the overall surface uplift response to rock uplift. In our model we apply a simple compensation based upon the relative densities of the crust and mantle to account for the isostatic response (Densmore et al., 2012; Molnar, 2012; Turcotte and Schubert, 2002). The calculated response is applied immediately to the volume balance and the surface uplift." (lines 142 – 146)
34. Missing word here, making this a run-on sentence We have separated this sentence into two for clarity. "There is ongoing debate to how much of a mountains surface uplift can be attributed to aseismic vs coseismic sources and how they interact (Hubbard and Shaw, 2009; Royden et al., 1997). Acknowledging the complexity of the debate we simplify the aseismic component of uplift and generalise it as the proportion of uplift that cannot be accounted for by Uco. Hence, topographic surface uplift can be represented as" (lines 147 – 151)
35. This is a bit clunky as you're using both words and symbols. We have added definitions of our symbols in the text to help readability and increase clarity. "Where the ratio between aseismic uplift (Uas) and coseismic uplift (Uco) is defined by the term α which represents the proportion of the total uplift rate that is caused by aseismic uplift, such that $(1 – \alpha) U = U_{co}$ and $\alpha U = U_{as}$" (Lines 153 – 154)
36. Discharge Done
37. The units don't make sense here, as each of the terms in equation 3 has units of L/T. So it's really confusing to refer to tihs as a 'volume'. And why is the third term in terms of an instantaneous rate of change (dR/dt) while the first

and second are finite totals over a time interval dt? We agree and have changed the word “volume” to “thickness”. To clarify the units and equations used in the model we have removed this equation and rearranged the order in which we define them. (Lines 156)

38. Why is this clause needed? Why is this not simply the rate of lowering of the bedrock surface (by conversion of rock to regolith) by all processes other than landsliding? I don't understand why this only applies when there is no regolith - weathering still happens under a regolith layer (in fact it may happen more rapidly if the production function is humped). Or am I misunderstanding this? Regolith production by earthquakes does not produce enough regolith to keep the model in steady state, therefore non seismic production of regolith must be a significant process in the mountain range. We have decided to model weathering only occurring during times when no regolith is present due to the weathering rate of the Longmen Shan being unknown. This may produce an underestimation of non-seismic regolith production which can be investigated when the true weathering rate of the Longmen Shan is known. We have included this discussion in our methods section and added further discussion in the discussion section. “W (m) is the thickness of rock weathering caused by all other mechanisms (simply the thickness of material removed from the bedrock when there is no regolith cover), this is included to ensure erosion can continue even when regolith is not present. In our model weathering does not occur when there is a covering of regolith as the weathering rate for the Longmen Shan, our study site is unknown. This way of including weathering in our model allows it to be an emerging property rather than a fixed rate.” (Lines 159 – 163)
39. Define S_T in the same way that you define S_B in the next equation We have removed this equation and added a new equation 5 to simplify our description of our model. $\frac{dS_T}{dt} = \frac{dS_B}{dt} + \frac{dR}{dt}$ (5) (line 167)
40. elevation? We prefer the term topographic surface to remain consistent with our discussion of surface uplift.
41. Isn't this redundant when combined with equation 3? How do you know E, if not from the combination of the three terms in eqn 3? I guess I'm not sure why this needs to be restated in another eqn. We have removed equation 3 and replaced it with this equation to prevent confusion of units and to simplify our explanation of our methodology (Line 157)
42. Missing word this has been corrected
43. I'm not sure what this means - do you mean the area that undergoes coseismic rock uplift above some threshold? Or a subset of that area? Our model uses the assumption of a zero-strain line to estimate the area which will feel some uplift from the largest earthquake on the modelled fault. We have also added an equation to define the model area “The model represents the average topographic surface uplift, regolith generation, and bedrock surface lowering for the area of coseismic displacement of the largest possible earthquake for the modelled fault. The length of the modelled area is set by the length of the surface rupture on the modelled fault while the width is the distance to the estimated line of zero strain based upon the dip of the modelled fault.” (lines 168 – 171)

44. I don't understand from this how coseismic rock uplift and coseismic uplift volume are related - these are definitely not the same thing! To help clarify the relationship between coseismic uplift volume we have changed the language to reflect we are calculating the rock uplift volume, We have also added an equation to define the model area and clarify this is used to convert the volume into a thickness. (equation6, line 173)
45. What do you mean? I don't follow this sentence. The rest of this paragraph is also hard to follow - perhaps a cartoon would help? Why does aseismic rock uplift affect the amount of coseismic rock uplift in large earthquakes, which seems to depend only on M_w by equation 7? We have rephrased the paragraph to help clarify and because this is also a result we will elaborate later in the manuscript. "We use an optimising algorithm to fit the uplift produced by equation 7 to ensure the model remains in a flux steady state. The use of the α aseismic uplift scaling parameter has the effect of increasing the time averaged rock uplift of time steps of small earthquakes and decreasing the rock uplift of large earthquakes." (Lines 181 – 185)
46. This is the first mention of a model area A - seems like this is needed for converting volume to rock uplift as well? And do you use the same area for all earthquakes (which seems to disagree with line 135)? If so, then your average depth is going to be really small for smaller EQs, because they will trigger a smaller volume of landsliding (eqn 8) but you're averaging over an unreasonably large area. I think this needs to be clarified, and again a cartoon might help to explain what you're doing. We have added an equation and text to define the model area earlier as suggested and have designed a figure to help further clarify the model design. We have also clarified the line specified. (lines 169 – 173)
47. And Done
48. OK, but how is the material removed from the mountain belt estimated? Is that the material that has to be removed to maintain steady state? This seems like a pretty restrictive assumption because it implies an instantaneous adjustment to the conditions imposed by any sized earthquake - meaning, I think, that there is no way of recording the longer-term impacts of an earthquake. Isn't that what you are looking for? We have deleted this sentence as it was repetition of a previous point. The removal of regolith from the orogen is controlled by the long-term erosion rate of the orogen modelled, in this case the Longmen Shan. We track the instantaneous addition of regolith by earthquakes and its slow removal by the sediment discharge E.
49. What do you mean by the minimal parameters? Changed to "for the small number of parameters" (line 203)
50. Possible. Added (line 209)
51. Relationship between what and what? What is N? And this should probably be broken out as a separate equation for consistency. We have separated the equation out from the text and added some language for clarity. "N is the number of earthquakes that occur above a certain magnitude in a year. The smallest earthquake we model is a Mw5 which occur on average every 5 years." (lines 215 – 216)
52. I don't think you have previously defined Nmin We have removed reference to N_{min}

53. It would be useful to specify what those uncertainties are We agree and have clarified the uncertainty in the equation. “This relationship gives a return time of 1816 years for earthquakes of the same magnitude of the Wenchuan earthquake. Other studies (Densmore et al., 2007; Li et al., 2014, 2017a), have proposed a return time anywhere between 500 – 4000 years for a Mw7.9 earthquake. We use the uncertainty in the frequency of Wenchuan sized earthquakes to vary equation 9 to test the impact of earthquake frequency on exhumation and surface uplift.” (lines 216 – 219)
54. I know that you're treating these as equivalent, but I'd encourage you to cut this clause and to keep your terms more rigorously defined - an erosion rate is not the same as a flux We have removed the reference to erosion rate.
55. Which fault? And what value does this take? In the text above, you have specified the model domain area, so stay consistent in how you refer to that here. We have added reference to our new equation 6, which defines the model area and rewritten this section to clarify. “The model area is set by equation 6, using parameters derived from the Wenchuan earthquake, the length (L) is the surface rupture of the Wenchuan earthquake (240km), the focal depth (D) was between 14 and 18km deep and the dip angle ranged between 40 and 90° (Li et al., 2014). We use the average area provided by these parameters of 2600Km2 for our model.” (lines 221-223)
56. Again - stay consistent in how you refer to model parameters. As written, this sentence makes it sound like the width is 2600 km2, whereas you've chosen some values of length and width (unspecified) to give a domain area of 2600 km2 We agree and have rewritten the section, see above
57. I'm not sure what this means - historical record of what? We have removed this reference as we have rewritten the section, see above
58. Again - which fault? The Wenchuan earthquake ruptured 3 separate faults, and there are several other active faults in the Longmen Shan that did not rupture. The Beichuan fault also extends beyond the limits of the 2008 rupture. We have removed reference to a fault and clarified that the length of the model is the surface rupture of the Wenchuan Earthquake, see above
59. ...given our assumed value of E Added (line 227)
60. This might be more clear if you wrote 'from each 25 Myr model run', if that's what you mean This is correct and we have changed our wording to your suggestion. (line 229)
61. 'two further' - you haven't described any previous experiments, unless you mean varying alpha between 0 and 1 (which you mention in the previous para, but which seems to correspond to the first experiment here). I think it would be useful to have a single statement of the experiments that you are doing and the specific things that you are testing; right now, it feels like you scatter that information across different parts of this section. We have added a paragraph detailing our research questions and aims in our introduction (lines 92 – 100) and clarified this section here. “We investigate the change in exhumation rates due to different proportions of coseismic and aseismic rock uplift and varying earthquake frequency and maximum earthquake magnitudes.” (lines 230 – 231)

62. I think it would be useful to specify the production function that you used. Presumably you apply this function to the model column, irrespective of whether it is regolith or bedrock in the upper few metres? Do you track concentrations in depth bins and then average the values in the bins containing regolith, or is there another approach? We have added a new equation (10) to clarify the production function used and have added further text to discuss the modelling approach. “The production rate (P) of 10Be decreases exponentially with depth, z, based upon the density of the bedrock (ρ) and the attenuation length (Λ). The production rates (atoms per gram per year) and attenuation lengths (grams per centimetre squared) depend on the radiation being modelled, in our model we simulate spallation (production rate, 5.784 atg-1y-1, attenuation length, 160 gcm-2), fast muons (production rate, 0.0418 atg-1y-1, attenuation length, 4320 gcm-2) and slow muons (production rate, 0.014 atg-1y-1, attenuation length, 1500 gcm-2) and combine them to give a total concentration at depth intervals set by the long term erosion rate (Braucher et al., 2011; Granger and Muzikar, 2001). When an earthquake generates regolith the top depth intervals are mixed, and the constant erosion rate is applied to remove regolith from the surface. After a spin up time of 10 kyr, the model tracks concentration of 10Be in the sediment leaving the model. The spin up time is the time required for the concentrations to reach a stable concentration which is perturbed by earthquakes. As erosion in the model is constant, and set to the long-term exhumation rate, any change in concentration represents the effect of stochastic magnitudes of EQTL on exhumation.” (Lines 238 – 249)
63. erosion rate? Changed 9line 245)
64. exhumation rate, not exhumational flux changed to erosion rate (line 245)
65. Again, I'm not sure why this is stochastic. What do you mean? Changed to “stochastic magnitudes of EQTL on exhumation” (line 248)
66. The Added
67. Magnitude of what? Area, volume, length? We have changed the sentence for clarity “In mountain range there are significantly more small landslide deposits than large ones, such that the magnitude and frequency of these volumes follows a power law” (lines 63 – 64)
68. Are This sentence has been reworded
69. While I don't disagree with anything you've written in this paragraph, it feels odd in a section entitled 'results'. This is essentially a summary of what we think we know about the connectivity and residence time of landslide material after a large earthquake. It would make more sense to me if it were integrated into the introduction material, so that here you can get straight to the point of your analyses. I'm still not fully clear at this stage of the ms about what you are trying to look at, so having this section here doesn't help We have reworked this paragraph to be part of the introduction as suggested. (lines 61 – 69)
70. of new regolith Added (line 253)
71. This might be more clear as 'distribution of earthquake magnitudes', which is a frequency Changed to the suggested language (line 261)

72. I don't think this is necessarily true - maybe better to say 'for soil-mantled hillslopes' or 'soil-mantled landscapes', because they are still subject to mass wasting processes We have changed the language as suggested. (line 264)
73. I'm not a big fan of acronyms unless they can't be avoided, so I'd encourage you to to consider whether you need this. I don't see it used further down in the text We use both acronyms in figures 2 and 3 and in the discussion of the results so we will keep them.
74. This is a nice result, and shows the power of this modelling approach
75. This is an interesting result, and makes sense in the context of your 0-d model. It would be worth annotating Fig 2C to show where this happens, as it's important enough for you to draw attention to it in the text.

    I do wonder, however, about application in 2-d space across a whole mtn belt. Typical mean landslide densities are only 1-10% even in large EQs, and the work that Parker et al. (2015) did in New Zealand shows only a weak correlation in ls locations between successive EQs. So the caveat on this sentence might be '...when those successive earthquakes cause failures in similar places on the hillslopes'. I'm not suggesting that the authors change anything here, but this might be a point for the discussion... We have attempted to point out where this effect occurs on figure 2c and added some discussion to our result, “Where large earthquakes are closely spaced in time (and space), pre-existing regolith can limit weathering of the bedrock surface, encouraging uplift of the topographic surface in areas. In catchments close to active faults the bedrock is likely to be heavily fractured and the shaking is more intense, producing larger landslides with greater densities (Marc et al., 2016a; Meunier et al., 2013; Valagussa et al., 2019). If the regolith is not fully removed from these catchments in between earthquakes it is possible that the CLRPF may encourage greater surface uplift. In our model the regolith produced by earthquakes is spread evenly across the landscape, which does not occur in reality. Even in the most impacted catchments landslide density is rarely above 10% per Km2, suggesting that remobilisation of landslide regolith on the hillslope may be rare unless the regolith can remain in the catchment for multiple earthquake cycles (Dai et al., 2011; Marc et al., 2015; Parker et al., 2011, 2015). CLRPF is therefore, likely to be a local effect mainly impacting catchments close to active fault belts. (lines 282 – 290)
76. Perhaps refer to this as 'zone 1' and use the same terminology in the figure and caption, because otherwise the reader might not know what 3A.1 or 3A. (2) means Added (line 301)
77. The Added
78. ...and so the regolith thickness is expected to increase Added (line 304)
79. Conversely, Added (line 304)
80. On line 248 you say that net bedrock surface uplift occurs for 5.6<Mw<6.4 - can you not combine these statements, since you're saying nearly the same thing twice? Removed the line and combined with line 248 as suggested.
81. M<sub>w > 7.6 Done

82. You have already explained this in section 2 - no need to repeat it here. This underscores the importance of laying out your experimental design and being very clear about what things you are going to test - if that is obvious to the reader at the start of section 3, then there's no need to repeat this Removed and laid out experiment in the introduction (lines 91 – 100)
83. This sentence is not needed, because you say the same thing on lines 263-265 Removed
84. This is the first mention of how you have changed the recurrence intervals; it would be good to have this information in section 2. But as you make large EQs more frequent, have you adjusted the entire EQ sequence to keep the same long-term coseismic rock uplift rate? If so, how does that affect the b-value of the EQ mag-freq distribution? It's hard to follow what you've done, although again it could just be my misunderstanding of the text. We have added clearer information on how we do this with our new equation 9 and better described our experiments in our introduction and methods. (lines 91 – 100 and lines 216 – 220)
85. Where does this come from? Changed to 14% as this is just a repetition of the earlier results in the paragraph. (line 321)
86. – Done
87. You haven't yet cited Fig 5A, unless I missed it Reference to 5A was missed and has now been added to the previous paragraph. “However, this variation may only be seen in exhumation or surface uplift records with recording times of less than 1000 years (Figure 5A).” (line 324)
88. What's the concentration immediately before the EQ? Would be worth annotating the figure with that. There are no ticks on the x-axis (plus it's logarithmic so you can't show t=0) We have added ticks and annotations to figure 5b.
89. Suggest expanding on this point to relate the text more closely to the figure: ', giving rise to a post-earthquake spike in concentrations in sediment leaving the model space. With our parameter values, this spike occurs c. 200-300 years after the EQ and persists for a few hundred years...'

    What is the significance of the flat-line long-term average that the values return to? Is that the same as the pre-EQ value? If so then it's worth pointing that out We agree with this suggestion and have added a few lines to describe the figure. “Regolith exiting the mountain range has a lower cosmogenic nuclide concentration for 200-300 years after the earthquake, after this period of low concentrations there is a peak of concentration higher than the long term average (500 years after the earthquake) before a rapid return to the long term average concentration (Figure 5B).” (lines 334 – 337)
90. I'm not sure what this clause means - poor recording in what sense, and by major events do you mean large EQs? Wouldn't a highly variable CRN concentration be a way of identifying the past occurrence of those large EQs? We have clarified the sentence to discuss a hypothetical landscape which has earthquakes but a worker maybe unaware of them. “Therefore, in landscapes with frequent Mw>7 earthquakes and regular long-term storage of regolith, but without a detailed historical record of major earthquakes, it is possible to record more variable cosmogenic

concentrations than might be expected, including positive as well as negative excursions from the long-term mean.” (lines 340 – 343)

91. A added
92. as represented by Added (line 351)
93. Hmmm... I have my doubts about the utility of this, especially given the fairly dodgy assumptions that went into that 1999 map. How large are the 59 areas? How have you derived a single value of PGA for each of those areas from the map, and how meaningful is that single value? How did you divide the areas into 'active' and 'inactive'? These choices matter because they determine your specific results. It's worth putting these data into a table as well as Fig 6, so that there's more clarity about how you've derived them We have added to this paragraph to clarify how we define our coseismic and aseismic landscapes and recognise the uncertainties inherent in using a single number to characterise a large area. “ Due to the size of the geographical areas there may be multiple seismic hazard levels recorded; we simply use the mean value to classify the area. The use of a single number to characterise a large area can underestimate the potential PGA. While a single number may not accurately describe the entire area, it does allow us to compare the variability of denudation rates with seismic hazard. We then crudely classify the regions as dominantly coseismic or dominantly aseismic: regions with thrust faults and erosion rates greater than the median are deemed coseismic, while slowly eroding regions with no thrust faults are aseismic. “Mixed” regions are those that do not fall under either of these classifications” (Lines 352 – 358)
94. That may be, but that's not what Fig 6C shows! Panels B and C both show variation in denudation rates against variation in steepness or PGA, not against the values themselves. Can you write this more carefully? We have rewritten this sentence and the caption of the figure to better describe our findings. “We find that while areas with higher seismicities have more variable erosion rates, the variation in erosion rates correlates much closer with the variation in steepness index (Figures 6B&C).” (lines 369 – 371)
95. Relevance? And you haven't said anything about how relief or steepness are measured, or what those numbers mean when averaged (presumably?) over areas of >10^5 km2. How did you do the averaging? Again, the details matter because they determine your specific results We have added an equation defining the steepness index and an introductory sentence describing why we are looking at steepness. “). Relief is a major control on erosion rates, with steeper catchments having higher erosion rates than shallower ones (Montgomery and Brandon, 2002). The most seismically active mountain ranges are also among the most varied in relief as they have some of the steepest catchments in the world. Therefore, we need to test whether variability in erosion rates is more closely related to variation in catchment steepness or the seismicity of the area. Within the database compiled by Harel et al., 2016 they include a normalised channel steepness index which we use to compare the impact of catchment steepness on erosion rate. The channel steepness index equation is derived from the stream power equation, $M_x = (\frac{E}{K{A_0}^m})^{\frac{1}{n}}$ (11)

96. Where Mx is the steepness index, E is the erosion rate, K is the erodibility coefficient, A0 is a reference area of $1m^2$ and m and n are empirical relations. The index is normalised by assuming fixed values for m and n (Harel et al., 2016). We would expect that in areas with highly variable steepness indexes the erosion rates are also more variable. However, the most seismically active mountain ranges are also among the most varied in relief with some of the steepest catchments in the world. Therefore, we need to test whether variability in erosion rates is more closely related to variation in catchment steepness or the seismicity of the area (Figures 6B&C). We find that while areas with higher seismicities have more variable erosion rates, the variation in erosion rates correlates much closer with the variation in steepness index (Figures 6B&C). (lines 360 – 371)

97. I agree with the first clause... but I'm not sure about the second, and I don't think your results can speak to this point, because you've assumed a single long-term value of E. The key relationship here is between the rate of regolith production by landsliding, and the rate of evacuation by all other processes. Steeper hillslopes and river networks will be more efficient at removing landslide-derived regolith by a whole host of processes. Can that keep pace with the increased rate of regolith production that comes from higher rock uplift rates in steeper landscapes? I don't know, and it's a really interesting question - but I don't think your results address this. Am I misunderstanding what you're saying? Sounds like this could be a follow-up analysis, but unless you can provide more information here, I'm not convinced that it fits in this manuscript We have removed the 2nd clause discussing residence time as our model does not investigate residence time directly as correctly pointed out. The sentence now reads "Steeper basins in tectonically active mountain ranges are more susceptible to coseismic landsliding so will have more variable denudation rates through time, depending on the residence time of the landslide regolith and the frequency of earthquakes, than shallower basins." (lines 371 – 373)

98. recurrence times? Otherwise I'm not sure what you mean by this This correction is correct and we have changed the wording. (line 389)

99. In terms of what - cosmogenic concentrations in sediment samples, or some other measure? We have clarified this sentence "have been shown to be large enough to average out the perturbations in cosmogenic radionuclide concentrations caused by large landsliding events" (lines 403 – 404)

100. from what? Changed to "While these basins will offer reliable estimates of long-term erosion rates, the aim in this exercise is to identify variations away from the long-term rate, thus smaller basins could be suitable targets to recognise variations due to earthquakes." (lines 405 – 408)

101. that, while Added

102. I'm not sure what this last clause means or how it relates to the first part of the sentence - can you reword this for clarity? We have reworded the sentence "Our simulations show that the regolith generated by large earthquakes can reduce the rate of weathering and exhumation due to their potentially long residence time on hillslopes. Reducing exhumation rates also increases the uplift of the bedrock surface however, these effects are small when compared to the impact of the varying the magnitude and frequency of earthquakes" (lines 413 – 415)

103. Again I'm not sure what this means - what does it mean that 'large earthquakes are unaccounted for'? We have clarified this to "Small earthquakes contribute very little to both uplift and weathering resulting in below average exhumation being recorded if a large earthquake does not occur during the averaging time of the exhumation record" (lines 417 – 419)
104. What is stochastic about this removal in your model? You've assumed a steady long-term value of E We have removed the word stochastic (line 420)
105. orogen-scale variation in what? Added "in exhumation" (line 421)
106. While I agree with this statement, it is the first place anywhere in the manuscript that you've mentioned sediment cascades, so it really doesn't fit here as one of your conclusions. I think if you want to raise this point, it would be better to mention it in the discussion as an avenue for further research (i.e., getting to the heart of sediment residence times and what they are controlled by), which I totally agree is a big gap in our understanding. We have added a brief discussion on sediment cascades and residence times and rephrased the sentence in the conclusion. "Higher resolution exhumation records and the growing recognition of the complex nature of exporting landslide sediment from mountainous catchments will help to explore this problem." (423 – 424)
107. A minor point, but it's not actually clear why this is relevant to your analysis - you are using other results for long-term E, EQ mag-freq distributions, and Malamud et al.'s relationship between Mw and landslide volume. How does a multitemporal ls inventory come into the model? We have removed reference to the landslide inventory as while it was important for initial observations which the model is built upon it is not involved in the model itself. (line 426)
108. What does it mean that OF wrote the model and experiment? We have rephrased the contributions section to provide greater clarity to each authors' role in the manuscript. (line 436)
109. While this is a visually appealing figure, I'm not convinced that it conveys much information. Panel A is cited as showing thick regolith but minimal erosion, but neither of those things are clear from the image (they certainly wouldn't be the things that I would take from the image unless they were mentioned in the caption). Panel B is cited as showing 'huge volumes of regolith' but the extent or thickness of landslide debris is not clear from the image, and there's no scale. Panel C is cited as showing a large range in areas, but that's pretty common knowledge and I'm not sure that it needs a large figure to illustrate it; there's no information in the panel on depth compared to pre-existing regolith thicknesses. So all in all, I'm not sure that this really adds to the manuscript. We have annotated our figure to make it more informative and altered the caption and its reference in the text to highlight why describe landslides as weathering bedrock rather than eroding. (lines 595 – 605)
110. A general comment on the figures - they would benefit from some more care in things like font sizes and labels, which are highly variable between figures. The symbol for moment magnitude should be M<sub>w in panel A; regolith thickness is discussed in metres in the text and inset panel B but given in mm in panel B itself; 'Myr' is

needlessly repeated in the x-axis label of panel C. They are small things but will collectively help with clarity for the reader. We have incorporated the suggestions proposed to help with readability.

111. Replace with 'thickness', to stay consistent with the dimensions of your 0-d model? Done (line 607)
112. Whose average residence time? And it took me a few looks to realise that there was a second y-axis, as the label is jammed against panel B. You could perhaps add the qualifying clause 'assuming a particular long-term value of E = 0.62 mm/yr', or something similar, to avoid confusion We have added the clarifying clause (line 609) and increased the spacing between the axis to read with readability.
113. et al. We have corrected this reference (line 608)
114. Watch your units - volume per area yields a depth (as described in the text), not a production rate We have removed the word ‘rate’
115. Should this be 'within'? This sounds like you're taking EITHER the max or min volume for a given magnitude We have changed the word from to within as suggested. (line 610)
116. Where is the black line representing 100% aseismic rock uplift? We have increased the thickness of the black line to ensure it can be easily seen.

In the text you make a point of mentioning the impact of closely-spaced large earthquakes, but since neither EQ timing or magnitude is shown on this plot, it's not really possible to see this directly. You could consider adding a bar chart along the bottom of EQ timing/magnitude, and then use arrows to point out a closely-spaced set that give rise to surface uplift. Due to the large number of earthquakes represented in the plot it is not possible to represent the sequence of earthquakes in a clear way.

I am a little surprised that the model surface elevation only changes by +/- 20 m in 25 Myr - that is comparable to some of the slowest denudation rates on Earth. How, then, did the Longmen Shan actually form? Sure, they've been around in one form or another since the Triassic... but this result seems to suggest little or no elevation change (at these rates and by these processes) over much of the present collision Our model has very little consistent surface uplift due to the assumption that the orogen is in steady state for the entire model run. For the mountain range to increase permanently in surface uplift the orogen would have to be out of steady state. We have added a line in the caption to help clarify this “The assumption of steady state prevents any long-term permanent uplift, all variations in surface elevation are driven by the sequence of earthquakes and changes in regolith thickness” (lines 618 – 621)

117. This figure is a little hard to interpret - partly because the symbology doesn't seem to match the legend (which shows just two lines rather than 3, none of which is a long-dashed line). Why is the bedrock interface (which presumably has a single elevation in your 0-d model) shown as a colored field of possible values rather than as a line? I'm sure I'm just misunderstanding what's being plotted, but it's not intuitively obvious how to read this We have moved the legend and increased its size to ensure it is more readable and easily seen. We have also increased the visibility of lines on the graph and removed the fills to ensure clarity.
118. Panel Changed

119. Does '5.0' mean that you only apply Mw 5.0 EQs, since that's also the minimum size? Yes that is correct. Added “the run with a maximum magnitude 5 has only earthquakes of a magnitude 5” (line 634)
120. Averaged over what time window? This is correct, added “averaged over the run time” for clarity (line 643)
121. How did you divide the areas into these three categories? And the text mentions only 'active' and 'inactive', which doesn't correspond to the categories used here. We have changed the category names to match the text. We have also added further clarification on how we derive the categories in the text. (lines 355 – 358)
122. How do the symbols relate to the colors used in panel A? Please clarify this - not least because some of your readers might be colorblind! We have increased the size and variety of the symbols used and included them in the legend
123. Median Removed
124. PGA of a 475 year return time earthquake isn't 'seismicity' - just be clear about what you're plotting Added “represented by the 475 year return Peak Ground Acceleration (ms-2)” for clarity (line 650)
125. This needs to be adequately explained in the text - this very brief mention in the caption isn't sufficient to know what this means We have removed the definition from the caption and expanded upon it in the text. (lines 364 – 367)

Reviewer 2.

1. erosion agents – In our manuscript we describe landslides as weathering due their small transport distances. We define our use of terms in the introduction.
2. be more explicit about the types of records...I'm guessing sedimentary records We have clarified this with “whether sedimentary or geochemical” (line 16)
3. what do you mean by stochastic? Removed the word “stochastic”
4. I don't understand what you mean by this. Exhumation of bedrock happens across a surface... To clarify we have replaced the word exhumation with lowering. (line 21)
5. This is not really clear. How would regolith be preserved if landslides remove this? We discuss the role of landslides generating regolith later in the manuscript. This is a key part of our study and we will ensure it is carefully described.
6. This is an interesting result Thank you
7. From yours or other studies? We have removed this sentence to ensure clarity between our and other’s findings.
8. i.e. should produce according to your model? We have added the phrase However, our model suggests… To clarify our statement of findings (line 26)
   You need to distinguish between your model results and results of other studies more in this abstract.
   But, I'm intrigued to read the rest of the paper...
9. new paragraph We have separated this paragraph into two

10. by hillslope processes too Hillslope transport contributes very little to the total transport length of sediment on its journey out of the orogen. We have a new paragraph discussing the relative importance of fluvial and hillslope transport and residence time of landslide regolith. (lines 65 – 69)
11. This perhaps needs more explanation We have removed this sentence and replaced it with a new section on the slow export of sediment following earthquakes to better make our point. (lines 54 – 60)
12. at which would perhaps work better here. This sentence has been replaced
13. can be, or are difficult... Changed to “can be” as suggested (line 45)
14. I think you need to distinguish between regolith which I think of as intact soil mantle with material detached by landslides but not yet completely removed...perhaps this could be termed colluvium or landslide deposits? We have clarified our usage of regolith as “that regolith, transportable sediment produced by landsliding or weathering, remains in low-order catchments” (lines 49 – 50)
15. would this be signal shredding or just a lagged signal in the record? We have reworked this section to make our point clearer. In doing so we have reworded this sentence to “Rather than a sink receiving a large impulse of sediment, which can be easily recorded via a change in average grain size or sedimentation rate, the rate change is instead smeared or shredded across the residence time of the sediment resulting in significantly less change which is far harder to measure (Jerolmack and Paola, 2010).” (lines 83 – 85)
16. I think you need to rephrase to make it clearer that whilst thermochronometric records capture large earthquakes, cosmogenic radionuclides may not. We have rephrased as suggested “. If the recording time of erosion, 103 years for cosmogenic radio nuclides 104-5 years for thermochronometry methods, is similar or less than the return period of large earthquakes then any difference from the long term erosion rates, normally recorded by thermochronometry, could be due to the influence of earthquakes (Kirchner et al., 2001; Ouimet, 2010).” (lines 86-89)
17. This is a bit vague. We agree and clarified the sentence. “By investigating the variation of erosion rates with varying time scales, or with coseismic landslide density (Niemi et al., 2005; West et al., 2014), we may be able to identify the long term impact of earthquakes on orogen scale erosion rates.” (lines 89 – 91)
18. By now I get why you are calling this bedrock weathering - because the sediment doesn't get transported into the fluvial system, but sticks around on the hillslope for a while. However, I think you are still referring to removal of bedrock by landslides so need to find another term or say erosion. Otherwise this could also mean damage to bedrock by earthquakes in the sense of earthquake preconditioning. We understand that our definition of weathering does not include preconditioning of the bedrock by earthquakes and we hope we have been explicit in our definition in the next section. “Weathering is the in-situ conversion of rock into regolith. In our model, rock must be converted to regolith before it can be transported. In our model we explicitly separate the role of EQTLs generating regolith by weathering bedrock from their role as (inefficient) eroders of bedrock and regolith – i.e., we separate their role in producing loose material from their role in transporting that material. EQTLs occur on hillslopes, typically having

transport lengths consistent with hillslope lengths, with only the largest impinging on the fluvial system (Li et al., 2016).” (lines 109 – 112)

19. But this is still transported some distance, i.e. eroded... We have added a line earlier in the text to define our usage of landsliding as weathering “When looking at an orogen as a whole and the transport of sediment within it, landsliding only transports sediment a very small insignificant distance hence, we define landsliding as a weathering process rather than erosional.” (lines 67 – 69)
20. This statement is a bit contradictory...if the transport lengths are consistent with hillslope lengths, this infers that they connect with the fluvial system... Also, don't EQTLs tend to occur on ridges? Observations from the Wenchuan earthquake show that less than 50% of the sediment produced by the earthquake is connected to the channel network. When there the fluvial system is largely unable to mobilise this sediment and so remains reliant on hillslope/fluvial processes, such as debris flows, to move the sediment into the major river system. We have rewritten the introduction to include these observations in the introduction (lines 60 – 69)
21. but they aren't responsible for weathering bedrock, just removing it. Who argues this? Does Larsen et al. 2010 refer to landslides as agents of weathering? We agree that landslides do not weather bedrock in the traditional sense. Our use of weathering is just to describe the short transport distance of the sediment by landsliding and to analyse the common assumption that all sediment produced by the earthquake was bedrock immediately before the earthquake.
22. Actually the size frequency distribution tends to stay relatively constant. It is more the absolute frequency of landslides of all sizes that changes. We agree and have removed reference to the frequency distribution of landslides in our experiment set up to avoid confusion.
23. inter seismic? We do not consider interseismic uplift, other than our use of aseismic uplift. This is clarified in our methods section (lines 146 – 147)
24. I am still not entirely clear on the aims and objectives of the paper. We have rewritten this section to help to clarify our aims and objectives. (lines 92 – 100)
25. repetetive! This has been rewritten
26. but they inevitably transport some of this in the process...therefore I wouldn't say this is purely insitu weathering. In our model there is no transport of sediment, so we define the production of regolith as weathering. In reality only a very small proportion of the sediment produced is evacuated immediately so nearly all sediment produced is only meters away from its initiation point.
27. how do you define each of these and how does rock uplift vary from bedrock surface uplift? We have added definitions for clarity. “Rock uplift is the expected increase in the bedrock surface before considering erosion, it is either produced by coseismic or aseismic means. Bedrock surface uplift is the vertical distance moved by the bedrock surface after erosion. The topographic surface uplift is the total vertical distance moved after considering changes in the bedrock surface and the thickness of the regolith layer.” (lines 116 – 120)

28. I think you could do with a diagram/schematic visualizing all these boundaries and terms. We have cartoons in our figure 3 which demonstrate the boundaries with some case studies. Due to the abstract nature of the model we were unable to produce a satisfactory figure.
29. per unit time Added (line 136)
30. by what? Added "unmodelled geomorphic processes (including erosion by rivers, landslides, and other hillslope processes)," for clarity (line 137)
31. not removed but converted from bedrock into regolith

    Also can't weathering still occur beneath a regolith cover or even be enhanced by regolith cover depending on the function used? We have clarified the usage of our W term in our manuscript. "W (m) is the thickness of rock weathering caused by all other mechanisms (simply the thickness of material removed from the bedrock when there is no regolith cover), this is included to ensure erosion can continue even when regolith is not present. In our model weathering does not occur when there is a covering of regolith as the weathering rate for the Longmen Shan, our study site is unknown. This way of including weathering in our model allows it to be an emerging property rather than a fixed rate." (line 159 – 163)
32. wording doesn't make sense We have rewritten this section to include a formal definition and equation defining our area. "The model represents the average topographic surface uplift, regolith generation, and bedrock surface lowering for the area of coseismic displacement of the largest possible earthquake for the modelled fault (A). The length of the modelled area (L) is set by the length of the surface rupture on the modelled fault while the width is the distance to the estimated line of zero strain based upon the dip of the modelled fault (θ) and the focus depth (D) (Li et al., 2014)." (lines 169 – 183)
33. uplift volume? We have stated that the volume is divided by the area to make a length in the text. "divided by the model area A to calculate Uco." (line 180)
34. This needs more explanation We have added some further discussion to better explain this methodology. "The shaking produced by an earthquake correlates which the length and width of its surface rupture, however the width (depth) of the rupture is limited by the thickness of elastic crust. At a maximum magnitude (~Mw6.75) the scaling between earthquake magnitude and shaking changes resulting in a curved relationship b etween total landslide volume and earthquake magnitude." (lines 192 – 195)
35. . Added
36. again this is not really clear. Also, you should stick with using the symbols for the parameters you are referring too...so this would be w? We have removed this sentence as it was a repetition of previous discussion and improved our definition of the terms in the methodology.
37. surely this just is a bedrock landscape? Through this manuscript we attempt to argue that landscapes commonly assumed to be bedrock may still have significant sediment stored within them hence we want to reinforce that these

previous studies have assumed that the Longmen Shan is a bedrock landscape. “which are typically associated with a bedrock landscape” (line 205)

38. Why 10Kyrs? The spin up time is just the time required for the concentrations leaving the model to reach a steady state. “The spin up time is the time required for the concentrations to reach a stable concentration which is perturbed by earthquakes.” (lines 246 – 247)
39. give some citations here for this theory. We have rewritten this sentence and provided some references to better describe our thinking. “The primary control on the total landslide volume produced by an earthquake magnitude is the strength of the shaking, with slope and rock strength as secondary factors (Marc et al., 2016a; Valagussa et al., 2019). If shaking can produce similar volumes of landsliding regardless of how much bedrock or regolith is on the hillslopes, landslide deposits in a mountain range with lots of regolith will contain less fresh bedrock as regolith will make up a greater proportion of material mobilised by the earthquake. As regolith makes up a greater volume of the landslide deposits, we assume that less bedrock weathering occurs. This effect will be particularly powerful in areas where large earthquakes occur frequently in similar locations.” (lines 255 – 261)
40. Is there any empirical evidence for this? Theoretically to me it doesn't make sense as landslides and earthquakes probably don't care about the amount of regolith on the slope? Our response to comment 39 also responds to this point. While it is assumed that large scale rock or hillslope strength has an impact on the volume of landsliding produced by an earthquake, and hence the volume of bedrock eroded, it is complex to quantify.
41. is this because these small earthquakes remove regolith? Smaller earthquakes produce small volumes of regolith, less than is removed by the constant flux of sediment, which thins the regolith layer. “. However, because smaller earthquakes occur much more often (which produce little regolith allowing the layer to thin), the average regolith layer is predominantly thin”
42. Do you have a photo of thick regolith cover? How thick is thick enough to affect short term exhumation rates? We have rewritten this sentence to clarify that we believe that it is possible the for the Longmen Shan to have significant volumes of regolith stored within it for short periods of time. “The Longmen Shan is primarily classified as a bedrock landscape with little storage, this result suggests that there can be times after earthquakes where this is not the case (Ouimet, 2010; Parker et al., 2011).”
43. I just can't get my head around this We have rewritten the sections previously highlighted in order to clarify our methodology and results. We also have added some further clarification and put the result in the context of the literature here. “Where large earthquakes are closely spaced in time (and space), pre-existing regolith can limit weathering of the bedrock surface, encouraging uplift of the topographic surface in areas. In catchments close to active faults the bedrock is likely to be heavily fractured and the shaking is more intense, producing larger landslides with greater densities (Marc et al., 2016a; Meunier et al., 2013; Valagussa et al., 2019). If the regolith is not fully removed from these catchments in between earthquakes it is possible that the CLRPF may encourage greater surface uplift. In our model the regolith produced by earthquakes is spread evenly across the landscape,

which does not occur in reality. Even in the most impacted catchments landslide density is rarely above 10% per Km2, suggesting that remobilisation of landslide regolith on the hillslope may be rare unless the regolith can remain in the catchment for multiple earthquake cycles (Dai et al., 2011; Marc et al., 2015; Parker et al., 2011, 2015). CLRPF is therefore, likely to be a local effect mainly impacting catchments close to active fault belts." (lines 282 – 291)

44. this needs a bit of rewording Reworded to "Ultimately, this interaction between surface uplift and regolith depth is controlled by: 1. the time between earthquakes; 2. the magnitude of the previous earthquake; and 3. the rate of regolith removal. The closer together, in both time and space, large earthquakes occur and the slower regolith is removed from hillslopes, the greater the impact of CLRPF will be on the surface uplift of a mountain range." (lines 291 – 294)
45. I guess spell this out here as it is difficult to follow Done
46. This is a bit vague....volume budgets of what? Reworded to "Regolith generation and volume budgets of earthquakes" (line 295)
47. according to your results or those of others too? Added "Our model demonstrates" to the start of sentence to clarify these are our results. (line 296)
48. but what about earthquake preconditioning of aseismic landsliding? The preconditioning of hillslopes by earthquakes is a significant weathering process in tectonically active mountain ranges. However, it is very difficult to identify the long-term impact of earthquakes on hillslope stability. As a result, we have not included it in our model. We have added a brief discussion of preconditioning in our introduction and our section on Coseismic landslide production.
49. Meteorological Changed
50. is this a landscape response style? perhaps label this (1) Added the indicator zone "(Figure 3A. Zone 1)." For greater clarity (line 301)
51. list these here Done "magnitudes (Figure 3A and C zones 1-4)" (line 299)
52. by landslides? Removed the word erosion for clarity "). Here, the flux of regolith out of the model space is greater than the rock uplift produced by the earthquakes" (lines 300 – 301)
53. how do you calculate erosional flux? This is the long term erosion rate which is defined as E in our methodology.
54. i.e. due to uplift and regolith thickening? or just because of regolith thickening? Clarified with "primarily due to thickening of the regolith" (line 307)
55. we assume each earthquake thoroughly mixes the regolith Done
56. be a bit more explicit about what you mean here We have been more specific and changed the wording to "Therefore, in landscapes with frequent Mw>7 earthquakes and regular long-term storage of regolith, but without a detailed historical record of major earthquakes, it is possible to record more variable cosmogenic concentrations

than might be expected, including positive as well as negative excursions from the long-term mean." (lines 340 – 343)

57. could you include a plot showing these diversions? Included reference to figure 5B (line 343)
58. as expected? This is correct and we have added a clause to clarify. (line 358)
59. or do have? We have rewritten this section to strengthen our arguments. " Steeper basins in tectonically active mountain ranges are more susceptible to coseismic landsliding so will have more variable denudation rates through time, depending on the residence time of the landslide regolith and the frequency of earthquakes, than shallower basins." (lines 371 – 373)
60. why? Changed form to relief to link better with previous discussion. (line 374)
61. related to what? I think you also need to provide more links to figures throughout Added "variability in uplift and exhumation representing around 15% of the average exhumation rate" (line 395)
62. Surely this is just a lagged signal rather than completely shredded? It is a shredded signal rather than lagged due to the slow removal of sediment producing a small increase in sedimentation rates or decrease in cosmogenic nuclide concentration over the residence time of the regolith. ". Even when a large earthquake occurs at the edge of a mountain belt, as has occurred in the Wenchuan region, the variable exhumation signal is further shredded by sediment transport, over the residence time of the regolith, by floods and debris flows, such that even sinks that are within 40 km of the epicentre show limited evidence for large earthquakes (Zhang et al., 2019)." (lines 396-399)
63. This is a bit vague Reworded to "While the largest basins are able to offer reliable estimates of long-term erosion rates, the detrital cosmogenic nuclide concentrations smaller basins will be more affected by bedrock landsliding caused by earthquakes. Therefore, smaller basins could be suitable targets to recognise variations in erosion rates due to earthquakes." (lines 405 – 407)
64. Delete Done
65. where is the regolith in this picture? This image has been edited to highlight the regolith produced by the landslide. (figure 1)
66. You can delete the word aseismic and instead just put a heading above the legend with % aseismic Done (figure 2)
67. See earlier comments but I wonder what the reasoning for this is/empirical evidence? We have addressed the previous comments.
68. how do you calculate the residence time? We have clarified in the caption "average residence time in the Longmen Shan based upon an erosion rate of 0.62mm/yr" (caption figure 2 line 609)
69. Although these must be linked to the assumption that the average depth of regolith produced by an earthquake is limited by the volume of regolith on the hillslope? This is correct.

The impact of earthquakes on orogen-scale exhumation

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Abstract. Individual, large thrusting earthquakes can cause hundreds to thousands of years of exhumation in a geologically instantaneous moment through landslide generation. The bedrock landslides generated are important weathering agents through the conversion of bedrock into mobile ~~sediment~~regolith. Despite this, orogen scale records of surface uplift and exhumation, whether sedimentary or geochemical, ~~at the orogen scale~~ contain little to no evidence of individual large earthquakes. We examine how earthquakes and landslides influence exhumation and surface uplift rates with a ~~by exploring how stochastic earthquakes and landslides affect surface uplift and exhumation in a~~ zero-dimensional numerical model, supported by observations from the 2008 M$_w$7.9 Wenchuan earthquake~~e~~. We also simulate the concentration of cosmogenic radionuclides within the model domain, so we can examine the timescales over which earthquake-driven changes in exhumation can be measured. Our model uses empirically constrained relationships between ~~–~~seismic energy release, weathering, and landsliding volumes ~~scaling laws~~ to show that large earthquakes generate the most surface uplift, despite causing ~~exhumation~~ lowering of the bedrock surface. Our model suggests that when earthquakes are the dominant uplifting process in an orogen, rapid surface uplift can occur when regolith, which limits bedrock weathering, is preserved on the mountain range. ~~Where earthquakes, rather than aseismic processes predominantly drive rock uplift, rapid surface uplift can occur when regolith is preserved in the orogen, which limits the amount of bedrock weathering. By simulating the concentration of cosmogenic radionuclides within the model domain, we can examine the timescales over which earthquake-driven changes in exhumation can be measured.~~ After a large~~the~~ earthquake there is a~~n initial~~ lowering in concentrations of ^{10}Be in regolith leaving the orogen ~~in well-mixed landslide material~~ but,~~,~~ the concentrations~~ of~~ ~~^{10}Be~~ return~~s~~ to the long-term

average within 10^3 years. The timescale of the seismically induced cosmogenic nuclide concentration signal is ~~We further demonstrate that the variability in exhumation caused by earthquakes occurs at timescales~~ shorter than the averaging time of most~~, >10^3 years,~~ thermochronometers (>10^3 years). ~~When combined with evidence of signal shredding response within recent earthquakes, it seems unlikely for single earthquakes to affect long-term measurements of exhumation rates. Nevertheless,~~However, our model suggests that the ~~short term~~short-term stochastic feedbacks between weathering and exhumation produce measurable increases in cosmogenically measured exhumation rates which can be linked to earthquakes.

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1. Introduction

~~Large, high-relief mountain belts are found along highly active thrust faults, which produce some of the largest and most dangerous earthquakes on the planet (Avouac, 2007; Roback et al., 2018; Stolle et al., 2017).~~Surface uplift of a mountain range is controlled by the ~~through time is set by the~~ balance of additive uplift processes and removal of material by surface, typically fluvial, processes. Earthquakes along thrust belts produce rock uplift and equally importantly generate exhumation via landsliding (Avouac, 2007; Keefer, 1994; Marc et al., 2016a). Landsliding events can scour deeply into bedrock, causing many hundreds or thousands of years of exhumation of the bedrock surface in a geologically instantaneous moment (Figure 1) (Li et al., 2014; Marc et al., 2019; Parker et al., 2011; Stolle et al., 2017)~~ — provided we consider the surface towards which exhumation occurs to be the bedrock surface, rather than the topographic surface. Thrust earthquakes generate uplift by thickening the crust (Avouac, 2007; England and Molnar, 1990), while also producing widespread landsliding (Keefer, 1994; Malamud et al., 2004).~~ Existing mass balances on single (Parker et al., 2011) or sequences (Li et al., 2014, 2019; Marc et al., 2016b) of earthquakes demonstrate that landslide volumes of large thrust earthquakes are comparable to, and may exceed, rock uplift. However, earthquakes are not the only rock uplift process in mountain belts; aseismic mechanisms such as viscous and elastic crustal deformation (Meade, 2010; Simpson, 2015), lithospheric delamination (Hales et al., 2005; Molnar et al., 1993), and ~~others~~ isostatic rock uplift (Molnar, 2012; Molnar et al., 2015) can also contribute. The total time-averaged mass balance, and ~~hence~~ any net surface uplift, is also affected by ~~weathering and~~ erosion between earthquakes (Hovius et al., 2011; Marc et al., 2019; Yanites et al., 2010). Therefore, the contribution of earthquakes to the generation of long-term surface uplift of mountains remains poorly constrained (England and Molnar, 1990; Li et al., 2019).~~ Surface uplift of a mountain range through time is set by the balance of additive uplift processes and removal of material by surface, typically fluvial, processes. Earthquakes along thrust belts produce rock uplift and equally importantly generate exhumation via landsliding. Landsliding events can scour deeply into bedrock, causing many hundreds or thousands of years of exhumation in a geologically instantaneous moment (Li et al., 2014; Marc et al., 2019; Parker et al., 2011; Stolle et al., 2017) — provided we consider the surface towards which exhumation occurs to be the bedrock surface, rather than the topographic surface.~~

Despite the importance of earthquake-triggered landslides in the total erosion~~weathering~~ budget of mountain belts, there is little evidence of large earthquakes in the sedimentary or exhumation records. Increased rates of sedimentation and changes in sedimentary characteristics, linked to the abundance of loose sediment, have been identified in lakes and reservoirs immediately proximal to large faults (Howarth et al., 2012; Zhang et al., 2019). However, these pulses in sedimentation can be~~may be~~ difficult to separate from extreme hydrological events (Zhang et al., 2019). Steep slopes within mountain belts, as well as typical observations of plentiful exposed bedrock on those slopes, have been used to support the idea that earthquake-generated sediment is rapidly removed from orogenic belts (Dingle et al., 2018; Li et al., 2014; Niemi et al., 2005; Parker et al., 2011). However, observations collected after earthquakes suggests that regolith, transportable sediment produced by landsliding or weathering, remains in low-order catchments (Pearce et al., 1986) (Figure 1A), ~~or in~~ single large landslide deposits~~s~~ (Korup and Clague, 2009; Stolle et al., 2017), landslide dams (Ouimet et al., 2007) (Figure 1B) and valley fills (Blöthe and Korup, 2013) for up to 10^4 years ~~for at least hundreds of years~~. An estimated 44% of the sediment produced in the Himalaya is stored in the long term in some form before it exits the mountain range, demonstrating the importance of storage and sediment recycling to orogen scale sediment fluxes (Blöthe and Korup, 2013). Similar findings are found in studies on post-earthquake sediment fluxes:~~,~~ in New Zealand up to 75% of the sediment produced by the 1929 Murchison earthquake remained in catchments 50 years after the earthquake (Pearce et al., 1986). While in Taiwan between 92~~9~~ and 99~~2~~% of the sediment produced by the Chi-Chi earthquake remained in catchments eight~~8~~ years after the earthquake (Hovius et al., 2011). The slow removal time of earthquake derived sediment suggests residence times could exceed recurrence times of earthquakes in tectonically active mountain ranges. If significant volumes of sediment remain in the landscape for times longer than the recurrence period of earthquakes then large earthquakes could contribute significantly more to surface uplift than currently assumed (Li et al., 2014; Marc et al., 2016b; Parker et al., 2011).

Observations of the 2008 Wenchuan earthquake and its aftermath give us insight into the export of landslide generated regolith from mountain belts. Over 60,000 landslides were produced by the earthquake, a total volume of approximately 3 km^3 (Li et al., 2014) (Figure 1C). In mountain ranges there are significantly more small landslide deposits than large ones, such that the magnitude and frequency of these volumes follows a power law (Malamud et al., 2004; Marc et al., 2016a; Stark et al., 2001). Only the largest, or most mobile, landslides can deposit sediment directly into the channel;~~,~~ for the Wenchuan earthquake less than half of the total volume of the regolith produced is connected to the channel network immediately after the earthquake (Li et al., 2016) (Figure 1C). When looking at an orogen as a whole and the transport of sediment within it, landsliding only transports sediment a very small insignificant distance hence, we define landsliding as a weathering ~~process~~ rather than erosional process.

The rate at which landslide deposits can be evacuated from a catchment is typically related to the capacity of the fluvial system to transport the influx of sediment (Croissant et al., 2017; Yanites et al., 2010). If a significant proportion of sediment produced by an earthquake is not influenced by the fluvial system the residence time of the sediment is likely to be increased due to the need for stochastic hillslope processes, such as debris flows to remobilise the sediment into the channel before it can be exported (Bennett et al., 2014; Croissant et al., 2019; Hovius et al., 2011). The rapid stabilisation of the smallest landslides after the Wenchuan earthquake, many without being remobilised, indicates that patchy regolith can remain on hillslopes for much longer than a decade, and likely for centuries to millennia (Fan et al., 2018).

The low connectivity between landslide deposits and channels and the low transport capacity of many small mountain channels highlights the ~~suggests the export of earthquake generated sediment is~~ stochastic nature of post-earthquake sediment transport as debris flows and floods are the primary sediment transport process. The timing of debris flow triggering is related to the interaction of storms and slope hydrology, which cannot be easily predicted, while the volume remobilised by debris flows is primarily controlled by the non-linear process of sediment entrainment during run out (Horton et al., 2019; Iverson, 2000). The slow and stochastic removal of sediment from the orogen could be one reason why~~,~~ large pulses of sediment associated with single earthquakes are rare or absent from downstream sinks ~~despite the large volumes of sediment produced by an earthquake, single earthquakes are rarely recorded in erosional or stratigraphic records~~. Rather than a sink receiving a large impulse of sediment, which can be easily recorded via a change in average grain size or sedimentation rate, the rate change is instead smeared or shredded by stochastic sediment transport processes like flooding or debris flows~~across the residence time of the sediment resulting in significantly less change~~ ~~The slow stochastic remobilisation of this sediment from mountain belts by belts by non-linear debris flow and flooding processes and the likely signal shredding maybe one reason why single earthquakes are not recorded~~ (Jerolmack and Paola, 2010). The averaging time~~scale~~ for different measures of erosion rate (e.g. cosmogenic vs. thermochronometric) may strongly affect the probability of measuring a single earthquake. ~~that erosion is measured over also affects how any variation in erosion rates is recorded.~~ If the recording time of erosion, (10^3 years for cosmogenic radio nuclides or 10^{4-5} years for thermochronometry methods)~~,~~ is similar to or less than the return period of large earthquakes, then any difference between short and long term erosion rates~~,~~ could be due to the influence of earthquakes (Kirchner et al., 2001; Ouimet, 2010). By investigating the variation of erosion rates with varying time scales, or with coseismic landslide density (Niemi et al., 2005; West et al., 2014), we may be able to identify the ~~long term~~long-term impact of earthquakes on orogen scale erosion rates.

In this paper we use a zero~~0~~-dimensional volume balance model to explicitly track earthquake generated sediment through time in a hypothetical orogen based upon the Longmen Shan. We use the tracked sediment thickness into order to understand how earthquake-triggered landslides (EQTLs) affect ~~The long return times of the largest earthquakes and the short recording time of cosmogenic radionuclides has been linked to the difference of recorded erosion rates between cosmogenic radionuclides and low temperature Thermochronometry (Ouimet, 2010). After the 2008 Wenchuan earthquake detrital cosmogenic nuclide concentrations were lowered, correlating with coseismic landslide density (West et al., 2014). Landslides impacting local apparent erosion rates suggests a methodology for identifying earthquakes and coseismic material within landscapes.~~

~~In this paper we examine how bedrock weathering by stochastic earthquake-triggered landslides (EQTLs) affects~~ exhumation and surface uplift at orogenic scales. ~~We use multiple uplift regimes,~~ Our model co-varies~~ying~~ the amount of aseismic uplift in the orogen, ~~and~~ imposed earthquake magnitude-frequency relationships, and~~changing~~ both the timing and maximum magnitude of earthquakes, under multiple possible uplift regimes, in order to fully investigate the role of earthquakes in orogen scale volume budgets. We then use these scenarios to investigate whether earthquakes can be identified from erosion or exhumation records using different timescales and by modelling cosmogenic radionuclide concentrations of sediment leaving the orogen. Finally we test our hypothesis that the variation in erosion rates can be an indicator of seismic activity using a global database of cosmogenic radionuclide derived erosion rates.~~We explicitly separate the role of EQTLs generating regolith by *weathering* bedrock from their role as (inefficient) *eroders* of bedrock and regolith – i.e., we separate their role in producing loose material from their role in transporting that material. EQTLs occur mostly on hillslopes, typically having transport lengths consistent with hillslope lengths, with only the largest impinging on the fluvial system (Li et al., 2016). EQTLs have been argued to be efficient agents of bedrock weathering due to their propensity to have depths greater than any existing regolith cover (Larsen et al., 2010) (Figure 1). The amount of weathering performed by a particular earthquake depends on the size-frequency distribution of these landslides, reflecting a complex interaction between topography, shaking, and material properties of the bedrock (Keefer, 1994; Malamud et al., 2004; Marc et al., 2016a). We investigate the interaction between coseismic rock uplift, regolith generation, and surface uplift using a volume balance model. By tracking the bedrock surface through time, we can model both exhumation and denudation and how they are affected by varying earthquake distributions. We also model the concentration of cosmogenic radionuclides in sampled regolith in order to compare the modelled results with a global database of cosmogenic nuclide denudation records in order to identify the long- and short-term impacts of earthquakes on mountainous landscapes.~~

1.1 Definitions of terms

This manuscript is precise in its use of terminology around change in elevation of the various surfaces we discuss. These follow standard modern definitions (England and Molnar, 1990; Heimsath et al., 1997), but as we are explicitly measuring the generation of regolith and the movement of two surfaces (the topographic surface and the bedrock surface), the potential for ambiguity requires us to clearly define these terms:

Erosion is the transport away of material, and thus, a change in the topography. In our context, it describes the full evacuation of regolith material from the model domain, i.e. removal of sediment from the entire mountain range.

Weathering is the in-situ conversion of rock into regolith. In our model, rock must be converted to regolith before it can be transported. We explicitly separate the role of EQTLs generating regolith by *weathering* bedrock from their role as (inefficient) *eroders* of bedrock and regolith – i.e., we separate their role in producing loose material from their role in transporting that material. EQTLs on average occur on hillslopes near ridge tops, typically with transport lengths less than hillslope lengths, with only the largest impinging on the fluvial system (Li et al., 2016).

Regolith is the mobile transportable layer of sediment at the surface. In the model, r~~R~~egolith can be created by two distinct weathering mechanisms:~~;~~ landslides cutting into bedrock to create transportable debris, and soil production by physiochemical processes.

Uplift is the increase in elevation of a material or surface in an absolute frame of reference. We distinguish *rock uplift*, *topographic surface uplift*, and *bedrock surface uplift*. Rock uplift is the expected increase in the bedrock surface before considering erosion, it is either produced by coseismic or aseismic means. Bedrock surface uplift is

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the vertical distance moved by the bedrock surface after erosion. The topographic surface uplift is the total vertical distance moved after considering changes in the bedrock surface and the thickness of the regolith layer.

Exhumation is the approach of the rock mass towards the topographic surface and/or the bedrock surface, in the frame of reference of that surface. Our model tracks both surfaces, so therefore it is possible to have a rock uplift event that causes exhumation relative to~~at~~ the bedrock surface without exhumation at the topographic surface, by thickening the regolith.

Denudation is used almost as a synonym for exhumation, but where the frame of reference is the rock mass or the bedrock surface, and the topographic surface moves towards it.

2. Methods

2.1 0-Dimensional Volume Balance Model

Here we present a generalised zero~~0~~-dimensional mountain volume balance model which we use to test the impact of regolith storage on bedrock surface uplift and exhumation. In the absence of sufficient empirical evidence on the long-term spatial distributions of rock uplift, exhumation, and regolith volumes in mountain ranges, we simulate these parameters by treating the evolution of a landscape as a series of dimensionless seismic volume balances.

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In our model w~~W~~e define the change in topographic surface (S_T) with time as

$$\frac{dS_T}{dt} = U - E \quad (1),$$

where U (units of length/~~L/~~t~~T~~ime) is the thickness of rock entering the orogen during a time step and resulting in rock uplift (calculated as the volume entering the orogen across the area of the model per unit time), while E is the rate of regolith removed (l~~L~~ength/~~ per ~~time) from the topographic surface, by unmodelled geomorphic~~fluvial~~ processes (including erosion by rivers, landslides, and other hillslope processes), and thus is the long-term erosion rate of the orogen. Rock can enter the orogen in two ways, either via shortening and thickening of the crust during coseismic thrusting earthquakes (U_{co}) or through one of a number of aseismic uplift mechanisms (U_{as}), such as lower crustal flow (Royden et al., 1997) or lithospheric delamination (Hales et al., 2005). Surface deformation (Bonilla et al., 1984; Wells and Coppersmith, Kevin, 1994), and hence the volume of rock uplifted, scales as a function of earthquake magnitude (Li et al., 2014; Marc et al., 2016b). The addition of mass to a column of crust by thickening will produce an isostatic compensation which will reduce the overall surface uplift response to rock uplift. In our model we apply a simple compensation based upon the relative densities of the crust and mantle to account for the isostatic response (Densmore et al., 2012; Molnar, 2012; Turcotte and Schubert, 2002). The calculated response is applied immediately to the volume balance and the surface uplift.~~, which is adjusted for isostatic compensation based on local flexural isostatic calculations (Densmore et al., 2012; Molnar, 2012; Turcotte and Schubert, 2002). ~~We do not consider interseismic strain as an uplifting mechanism in this model due its limited contribution to permanent surface deformation (Avouac, 2007). There is ongoing debate to how much of a mountains surface uplift can be attributed to aseismic versus ~~vs~~ coseismic sources and how they interact~~.~~ ~~There is ongoing debate as to the specific mechanisms of aseismic uplift that occur in mountains~~ (Hubbard and Shaw, 2009; Royden et al., 1997). Acknowledging the complexity of the debate ~~, and aseismic uplift can occur both through changes in crustal thickness or changes in the density distribution in the lithosphere, w~~we simplify the aseismic component of uplift and generalise it as the proportion of uplift that cannot be accounted for by U_{co}. Hence, topographic surface uplift can be represented as

$$\frac{dS_T}{dt} = U_{co} + U_{as} - E \quad (2),$$

Where the ratio between ~~U_{as}~~ and coseismic uplift rate (U_{co}) and aseismic uplift rate (U_{as}) is defined by the term α which represents the proportion of the total uplift rate that is caused by aseismic uplift, such that $(1 - \alpha)\,U = U_{co}$ and $\alpha U = U_{as}$. As previously described, we separate the generation of regolith from its removal by the ~~long term~~long-term erosion rate *E*.

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~~On long timescales (across many earthquakes), we can describe the sediment flux leaving an orogen as a function of the volume of weathered material (regolith) that is generated with time. Hence, I~~In our zero~~0~~-dimensional model the ~~volume~~ thickness of regolith (*R*) removed ~~exported~~ from the surface of the orogen is defined as~~can be described as~~

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$$\frac{dR}{dt} = \frac{CLRP}{dt} + \frac{W}{dt} - E \quad (3),$$

~~(3),~~

where *CLRP (Coseismic Landslide Regolith Production)* is the average thickness (m) of weathered material generated by coseismic landslides, all of which is assumed to be transportable, and *W* (m) is the thickness of rock weathering caused by all other mechanisms ~~-~~(simply the thickness of material removed from the bedrock when there is no regolith cover). ~~; *this*~~*W* is included to ensure erosion can continue even when regolith is not present. In our model weathering does not occur when there is a covering of regolith as the weathering rate for the Longmen Shan, our study site is unknown. This way of including weathering in our model allows it to be an emerging property rather than a fixed rate. ~~and *R* is the thickness (m) of weathered material stored as mobile regolith. Combining the uplift and erosion equations allows us to track the change in two surfaces; the change in the topographic surface is~~

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~~(4);~~

The elevation change (m) in the surface that is composed of intact bedrock (S_B) can now ~~n~~ be described as

$$\frac{dS_B}{dt} = U_{co} + U_{as} - \frac{CLRP}{dt} - \frac{W}{dt}$$ (4~~5~~);

We can now define our surface uplift again as a combination of the bedrock surface elevation and the regolith thickness:~~.~~

$$\frac{dS_T}{dt} = \frac{dS_B}{dt} + \frac{dR}{dt}$$ (5),

~~And the change in regolith thickness is~~

~~(6).~~

The model represents the average topographic surface uplift, regolith generation, and bedrock surface lowering for the area (*A*) of coseismic displacement of the largest possible earthquake for a~~the modelled~~ fault found within a mountain belt. The length of the modelled area (*L*) is set by the length of the surface rupture on the ~~modelled~~ fault that generates the maximum earthquake, while the width is the distance to the estimated line of zero strain based upon the dip of the modelled fault (θ) and the focus depth (*D*) (Li et al., 2014).

$$A = L * \left(\frac{D}{\theta}\right)$$ (6),

~~an area of that is set by the maximum area of displacement of the largest possible earthquake.~~ As surface uplift rates for mountain ranges are hard to define (England and Molnar, 1990), we set the model to a flux steady state, where *U* is set to equal the long-term erosion rate (*E*). For each timestep in the model, an earthquake with M_w>5 is randomly chosen from a power law distribution, and the coseismic rock uplift volume associated with this earthquake is calculated using an empirical scaling relationship (Li et al., 2014) between magnitude and rock uplift volume,

$$log\ (V_u) = 1.06(\pm 0.22)M_w - 8.40(\pm 1.44)$$ (7),

where V_u is the volume of rock uplift generated by an earthquake of magnitude M_w and is scaled by α and divided by the model area *A* to calculate ~~U_{co}.~~U_{co}. M_w 5 earthquakes are the smallest that regularly produce coseismic landsliding ~~and produce very little rock uplift~~so represent the smallest earthquakes of interest to our study (Marc et al., 2016b). We use an optimising algorithm to fit the uplift produced by equation 7 to ensure the model remains in a flux steady state. The algorithm uses the uncertainty within equation 7 to fit the model parameters so that the average uplift produced during a time step is equal to the long term erosion rate. The use of the α aseismic uplift scaling parameter has the effect of increasing the time-~~-~~averaged rock uplift of time steps of small earthquakes and decreasing the rock uplift of large earthquakes.~~We optimise the coseismic rock uplift within the setup of the model based on the relative importance of coseismic and aseismic rock uplift (α) and to ensure flux steady state. The addition of different proportions of aseismic rock uplift has a material effect on the modelled topographic~~

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~~surface uplift by causing large earthquakes to lower the rock surface. The large earthquakes have their uplift reduced while the weathering they produce does not change, resulting in lowering.~~

Regolith is generated in the model based on calculations of bedrock lowering by CLRP and weathering by other mechanisms. Malamud's (Malamud et al., 2004) scaling of landslide volume (V_l) and earthquake magnitude (Figure 2A)

~~log~~ $log\ V_l = 1.42M_w - 11.26(\pm 0.52)$ (8),

is converted to a depth of landsliding by dividing by the area of the model space (*A*). Alternative models of coseismic landslide volume as a function of seismic moment (Marc et al., 2016a; Robinson et al., 2016) cannot easily be scaled into a zero~~0~~-dimensional model space due to their reliance upon earthquake source depth and landscape metrics. These models describe the relationship between earthquake magnitude and total landslide volume as a curve around a hinge magnitude. The shaking produced by an earthquake correlates which the length and width of its surface rupture, however the width (depth) of the rupture is limited by the thickness of elastic crust. At a maximum magnitude (~M_w 6.75) the scaling between earthquake magnitude and shaking changes resulting in a curved relationship between total landslide volume and earthquake magnitude. This has the effect of reducing the importance of large earthquakes in the surface uplift balance. All empirical models relating coseismic landslide volume and earthquake magnitude have large uncertainties in them. W~~, w~~e acknowledge these uncertainties by applying a normal distribution of error using the uncertainty bounds on the landsliding volume produced by each earthquake (Figure 2A). The total new regolith generated by coseismic landslides is then calculated as the difference between the average depth of landsliding and the average thickness of the regolith ($V_l/A - R$). ~~Finally, all other weathering is calculated as the difference between the material removed from the mountain belt and CLRP.~~

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2.2 Model implementation: Longmen Shan

We test our model using the Longmen Shan due to the wealth of studies of the area both prior to and after the 2008 Wenchuan earthquake. These studies allow for the small number of~~the minimal~~ parameters in our model to be well constrained. The Longmen Shan marks the eastern margin of the Tibetan P~~p~~lateau and the western edge of the Sichuan Basin (Li et al., 2017a). Hillslopes are at their threshold steepness with pervasive bedrock and limited channel storage, ~~suggesting a~~which are typically associated with a bedrock landscape (Li et al., 2014; Ouimet et al., 2009; Parker et al., 2011). The front of the range is dissected by three parallel dextral-thrust oblique-slip thrust faults, two of which, the Yingxiu-Beichuan and Pengguan faults, ruptured during the 2008 Wenchuan earthquake (Hubbard and Shaw, 2009; Li et al., 2016; Parker et al., 2011). Prior to this earthquake, geodetic measurements recorded limited shortening rates suggesting a possible role for lower crustal flow in driving surface uplift (Clark et al., 2005; Kirby et al., 2003; Royden et al., 1997; Wang et al., 2012). However, significant shortening associated with the Wenchuan earthquake supports an important, possibly exclusively coseismic surface uplift element (Hubbard and Shaw, 2009).

To apply the model to the Longmen Shan we use a power law relationship of earthquake frequency and magnitude derived from historical earthquake records (Li et al., 2017b):

$N > M_w = 3.93 - 0.91M_w$ ~~(Li et al., 2017b)~~ (9)~~.~~

N is the number of earthquakes that occur above a certain magnitude in a year. The smallest earthquake we model is a M_w 5 which occur on average every 5 years.~~-~~ This relationship gives a return time of 1816 years for earthquakes of the same magnitude ~~o~~as ~~f~~the Wenchuan earthquake. Other studies (Densmore et al., 2007; Li et al., 2014, 2017a), have proposed a return time anywhere between 500 – 4000 years for a M_w 7.9 earthquake. We use the uncertainty in the frequency of Wenchuan-sized earthquakes to vary equation 9 to test the impact of earthquake frequency on exhumation and surface uplift. ~~As N_{min} corresponds to M_w=5, we get a minimum return time of an earthquake of 5 years. This power law relationship is varied in some experiments to match the uncertainties in the return time of Wenchuan sized earthquakes (Densmore et al., 2007; Li et al., 2014, 2017a).~~ We use an apatite fission track-derived exhumation rate of 0.62 (+0.14 -0.08) mm/yr (Li et al., 2017a) to represent the long-term ~~erosion rate and~~ sediment flux from the orogen (*E*). The model area is set by equation 6, using parameters derived from the Wenchuan earthquake.~~,~~ T~~t~~he length (*L*) is the surface rupture of the Wenchuan earthquake (240 km), the focal depth (*D*) was between 14 and 18 km deep and the dip angle ranged between 40 and 90° (Li et al., 2014). We use the average area, 2600 k~~K~~m^2~~-~~, provided by these parameters. ~~We set the model domain length to equal the length of the fault and its width to the deformation caused by the uplift of a M_w 8 earthquake (2600 km^2), consistent with the historical record and the observation that the 2008 M_w 7.9 Wenchuan earthquake ruptured almost the entire length of the fault (Li et al., 2014, 2019).~~ We ran the model for 25 Myr to allow multiple analyses over various timescales, and varied α between 0 and 1.

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2.3 Exhumation calculations within the model

We calculated exhumation for 2 kyr intervals, which is the average time our model takes to exhume 1.2 m of rock through the rock-regolith interface given our assumed value of *E*. This depth was chosen as broadly representing the recording timescale for cosmogenic radionuclides (Gosse and Philips, 2001). Exhumation is calculated as the difference between rock uplift (U_{co} + U_{as}) and bedrock surface uplift (S_B) over the recording time. We randomly chose 10,000 2 kyr samples from each~~our~~ 25 Myr run to produce a distribution of exhumation rates. We investigate the change in exhumation rates due to different proportions of coseismic and aseismic rock uplift and varying earthquake frequency and maximum earthquake magnitudes.

~~We performed two further numerical experiments: the first calculates exhumation rates for different proportions of coseismic and aseismic rock uplift, while the second calculates denudation rates for decreasing maximum earthquake magnitude.~~

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2.4 Cosmogenic radionuclide calculations

We also calculate the cosmogenic ^{10}Be flux out of the model through time. For each time step we add ^{10}Be atoms to the system using published production rates and attenuation lengths to simulate the depth profile of cosmogenic concentrations (Balco et al., 2008; Braucher et al., 2011; Granger and Muzikar, 2001).

$$P_{(z)} = P_0 e^{-z(\rho/\Lambda)} \quad (10)$$

The production rate (P) of ^{10}Be decreases exponentially with depth, z, based upon the density of the bedrock (ρ) and the attenuation length (Λ). The production rates (atoms per gram per year) and attenuation lengths (grams per centimetre squared) depend on the radiation being modelled, in our model we simulate spallation (production rate, 5.784 atg^{-1}y^{-1}, attenuation length, 160 gcm^{-2}), fast muons (production rate, 0.0418 atg^{-1}y^{-1}, attenuation length, 4320 gcm^{-2}) and slow muons (production rate, 0.014 atg^{-1}y^{-1}, attenuation length, 1500 gcm^{-2}) and combine them to give a total concentration at depth intervals set by the long term erosion rate (Braucher et al., 2011; Granger and Muzikar, 2001). ~~After a spin up time of 10kyrs, the model tracks concentration of ^{10}Be in the sediment leaving the model.~~ When an earthquake generates regolith the top depth intervals are mixed~~part of the column is mixed~~, and the constant erosion rate~~nal flux~~ is applied to remove regolith from the surface. -After a spin up time of 10 kyrs, the model tracks concentration of ^{10}Be in the sediment leaving the model. The spin up time is the time required for the concentrations to reach a stable concentration which is perturbed by earthquakes. ~~–~~As erosion in the model is constant, and set to the long-term ~~exhumational flux~~exhumation rate, any change in concentration represents the effect of ~~the~~ stochastic magnitudes of~~exhumation of bedrock by~~ EQTL on exhumation.

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3. Results and discussion

3.1 Coseismic landslide regolith production

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~~Observations of the 2008 Wenchuan earthquake and its aftermath allow us to constrain export rate of landslide generated regolith from mountain belts. Over 60,000 landslides were produced by the earthquake, a total volume of approximately 3 km^3 (Li et al., 2014; Parker et al., 2011). Landslide deposits follow a power law magnitude frequency relationship where the majority of landslides shorter than the hillslope length (Malamud et al., 2004; Marc et al., 2016a). The rate at which landslide deposits can be evacuated from a catchment is typically related to the capacity of the fluvial system to transport the influx of sediment (Croissant et al., 2017; Yanites et al., 2010). However less than half of the total volume of the regolith produced by the Wenchuan earthquake is connected to the channel network immediately after the earthquake (Li et al., 2016). This lack of~~

~~connectivity increases the residence time of regolith in the landscape due to the reliance on stochastic hillslope processes, such as debris flows for remobilisation into the channel (Croissant et al., 2019). The rapid stabilisation of the smallest landslides, many without being remobilised, indicates that a patchy regolith layer remains on the hillslope for much longer than a decade, likely centuries to millennia (Fan et al., 2018). Further extending the residence time of regolith within catchments is that many coseismic landslides occur within the upper parts of catchments where streams are small and have a low transport capacity, limiting their ability to transport the voluminous coarse landslide debris.~~

Within our ~~the~~ model, regolith generated by the largest earthquakes can remain on hillslopes for ~1000 years (Figure 2A). The average thickness of new regolith that is produced in an earthquake (expressed as volume per area; i.e., a depth)~~,~~ is a strong function of both the pre-existing depth of regolith prior to new failures, the magnitude of the earthquake, and stochastic differences in the volume of landslides for a given earthquake magnitude (Figure 2B). The primary control on the total landslide volume produced by an earthquake magnitude is the strength of the shaking, with topography and rock strength as secondary factors (Marc et al., 2016a; Valagussa et al., 2019). If shaking can produce similar volumes of landsliding regardless of how much bedrock or regolith is on the hillslopes, landslide deposits in a mountain range with widespread regolith will contain less fresh bedrock as regolith will make up a greater proportion of material mobilised by the earthquake. As regolith makes up a greater volume of the landslide deposits, ~~we assume that~~ less bedrock weathering occurs. This effect will be particularly powerful in areas where large earthquakes occur frequently in similar locations~~The declining production rates with pre-existing regolith thickness result from the armouring effect of the existing material, which new landslides must cut down through before striking fresh rock~~. However, the distribution of earthquake ~~frequencies~~ magnitudes exerts a stronger influence on total regolith production through time, as more frequent small earthquakes can only ever weather small depths of regolith from the bedrock (Figure 2B). The way coseismic landslide regolith production (CLRP) declines with existing regolith thickness is reminiscent of soil production functions described for ~~environments without landsliding~~soil mantled landscapes (Heimsath et al., 1997), and by analogy, we term the non-linear relationship between regolith production rate and the average depth of weathering by landslides seen here a *coseismic landslide regolith production function* (CLRPF). However, unlike a “traditional” soil production function, two elements of stochasticity are inherent to a CLRPF. One reflects the role of shielding of the bedrock surface (S_B) from lowering when the regolith layer is thicker than the average depth of the generated landslides (Larsen et al., 2010), and that thickness is dependent on the past history of landsliding in the model. The other reflects the inherent randomness in the size and distribution of the landslides that occur in response to an earthquake of a given magnitude, i.e., within equation (8).

As expected, total seismic regolith production is dominated by the largest earthquakes, which produce the largest mean landslide volumes (Malamud et al., 2004) (Figure 2B). Summing through time, earthquakes produce 42% of the total regolith generated by the model; M_w>7 earthquakes account for ~65% of the total earthquake~~-~~generated regolith and so 27% of the total regolith production. However, because smaller earthquakes occur much more often (which produce little regolith allowing the layer to thin), the time- and spatially-averaged regolith layer is predominantly thin – the modal thickness is only 0.02m, and the mean is 0.03m (Figure 2B inset). Thus, the model shows that although mountain belt regolith cover appears thin almost

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all the time, at times it can be thick enough to severely affect the short-term exhumation rates of the mountain range. The Longmen Shan is primarily classified as a bedrock landscape with little storage, but significant volumes of sediment remain in the mountain range after the earthquake, in a similar way as simulated by the model ~~This result matches closely with observations of the Longmen Shan as a bedrock landscape with little storage~~ (Fan et al., 2018; Ouimet, 2010; Parker et al., 2011). Variability in the surface uplift through time (Figure 2C) is affected by the pre-earthquake regolith thickness and therefore the sequence of earthquakes which occur before it. Where large earthquakes are closely spaced in time (and space), pre-existing regolith can limit~~s~~ weathering of the bedrock ~~surface, encouraging~~surface, encouraging uplift of the topographic surface in areas. In catchments close to active faults the bedrock is likely to be heavily fractured and the shaking is more intense, producing larger landslides with greater densities (Marc et al., 2016a; Meunier et al., 2013; Valagussa et al., 2019). If the regolith is not fully removed from these catchments in between earthquakes it is possible that the CLRPF may encourage greater surface uplift. In our model the regolith produced by earthquakes is spread evenly across the landscape, which does not occur in reality. The density of landslides is greatest closest to the fault line and rapidly spreads out as you travel further from the fault (Marc et al., 2016; Meunier et al., 2013; Valagussa et al., 2019). Even in the most impacted catchments landslide density is rarely above 10% per Km^2, suggesting that remobilisation of landslide regolith on the hillslope may be rare unless the regolith can remain in the catchment for multiple earthquake cycles (Dai et al., 2011; Marc et al., 2015; Parker et al., 2011, 2015). CLRPF is therefore, likely to be a local effect mainly impacting catchments close to active fault belts.~~(Marc et al., 2015; Parker et al., 2011, 2015)~~ Ultimately, t~~T~~his interaction between surface uplift and regolith depth is controlled by: 1. the time between earthquakes; 2. the magnitude of the previous earthquake; and 3. the rate of regolith removal. The closer together, in both time and space, large earthquakes occur and the slower regolith is removed from hillslopes, the greater the impact of CLRPF will be on surface uplift.

~~If a landscape has less frequent earthquakes, faster regolith removal and smaller earthquakes a thin regolith layer is more likely (assuming that earthquakes are responsible for the majority of regolith generation) and the landscape will be less sensitive to the CLRPF.~~

3.2 Regolith generation and volume budgets of ~~by~~ earthquakes ~~and volume budgets~~

Our model demonstrates that t~~T~~he contribution of earthquakes to the uplift and weathering budgets of mountains varies with earthquake magnitude, frequency, and the relative contribution of aseismic erosion, i.e., erosion not directly related to earthquakes such as meteorological~~metrological~~ triggered landsliding or soil production. When coseismic rock uplift is the dominant uplift mechanism, we can classify four distinct landscape response styles at different earthquake magnitudes (Figure 3A and C zones 1-4). On average, an earthquake of magnitude M_w<5.6 lowers the topographic surface (S_T). Here, the ~~erosion~~ flux of regolith (E) out of the model space is greater than the rock uplift produced by the earthquakes (Zone 1 in Figure 3A~~.~~ ~~Zone 1~~). For earthquakes with magnitudes 5.6 < M_w < 7.6~~6.4~~ the bedrock surface (S_B) rises because the rock uplift rate is greater than the typical regolith generation rate (Zones 2-3~~Figure 3A. (Zones 2-3)~~). The regolith thins because the CLRP is

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less than the erosional flux (*E*) out of the model~~.~~ (Zone 2~~Figure 3A. (Zone 2)~~). Conversely CLRP exceeds erosional flux in earthquakes with magnitudes M_w>6.4 so the regolith layer increases in thickness (Zones 3-44). ~~Earthquakes with 5.6<M_w<7.6 (Figure 3A. (2-3)) cause net bedrock surface uplift.~~ The largest earthquakes ~~>~~M_w >7.6 ~~(Zone 4)~~ lower the bedrock surface due to the large volumes of regolith produced (Zone 4). However, much of the regolith is not removed before the next earthquake resulting in a net topographic surface uplift, primarily due to thickening of the regolith. For a purely aseismic uplift scenario, where earthquakes produce landslides but do not create rock uplift (Royden et al., 1997), earthquakes with M_w>6.5 would cause bedrock surface lowering while smaller earthquakes would permit bedrock surface uplift due to low CLRP. Earthquakes with M_w>6.5 produce a thick layer of regolith which can persist until the next earthquake, limiting bedrock surface weathering and resulting in net uplift of the bedrock surface.

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3.3 Earthquakes and exhumation

We explore how earthquakes affect the exhumation of mountain belts through direct calculation of exhumation of rock at the bedrock surface (S_B) relative to the topographic surface. ~~First, to understand how stochastic earthquakes might affect exhumation rates, we measured the distribution of 10,000 randomly chosen exhumation rates averaged across 2kyrs years (the equivalent to the bedrock surface being lowered by ~1.2m). Large earthquakes create variability in exhumation rates.~~ There is very little (~1%) variability in erosion rates in mountain ranges with earthquake magnitude M_w<5.0. However, the introduction of stochastic weathering of many tens of cm of the bedrock surface by earthquakes with M_w>7 introduces variability in exhumation. When large earthquakes are present, exhumation rates have a standard deviation of 0.055-0.081 mm/yr (9-14% of the long-term exhumation rate), and a range of 0.77-0.89 mm/yr, with the lower figures reflecting a greater contribution of aseismic uplift (Figures 4A and 4B). Increasing the frequency of Wenchuan-like earthquakes from 4kyr to 500-year return produces more variable distributions of exhumation rates, with the standard deviation of exhumation rate increasing from 0.044 mm/yr (7% of long-term average) to 0.076 mm/yr (12% of the long-term average) (Figure 4C). Taken together, our model results suggest that up to 14~~5~~% of the variability in a sample of exhumation rates from a single geographical region could be associated with the time since the last large (M_w>7.0) earthquake. However, this variation may only be seen in exhumation or surface uplift records with recording times of less than 1000 years (Figure 5A). Pre-Wenchuan earthquake measurements of cosmogenically-derived erosion rates were between 40% and 60% lower than low-temperature thermochronometrically derived exhumation rates (Ouimet, 2010). Stochastic exhumation of low-~~-~~concentration bedrock by EQTL may explain some of that difference.

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Cosmogenic radionuclides provide a record of potential earthquake-driven changes in exhumation because they have a relatively short averaging time that is close to the frequency of large earthquakes in many mountain belts. Our modelling results demonstrate the scale of stochastic variability in surface uplift and exhumation. We extended this analysis by simulating cosmogenic concentration in the model to estimate the potential impact of a large earthquake on both the cosmogenic concentration through time and the distribution of cosmogenic concentrations that are likely to be measured. W~~-~~e assume each earthquake thoroughly mixes the regolith ~~We represent each earthquake as thoroughly mixing the regolith~~ down to ~~its~~ its average weathering depth. The cosmogenic analysis (Figure 5B) shows that immediately after a large earthquake, mixing of low concentration bedrock material with higher concentration regolith lowers the concentration of radionuclides exiting the model. Regolith exiting the mountain range has a lower cosmogenic nuclide concentration for 200-300 years after the earthquake, after this period of low concentrations there is a peak of concentration higher than the ~~long term~~long-term average (500 years after the earthquake) before a rapid return to the long term average concentration (Figure 5B). In the case of a representative magnitude $M_{\mathrm{w}}\sim$~~-~~8 earthquake, the concentration falls initially by around one third. However, the process of mixing also increases the concentration of nuclides close to the regolith-bedrock interface compared to the values before mixing, so that as the regolith is slowly eroded through time the lower half releases concentrations *greater* than the long-term average. Therefore, in landscapes with frequent $M_{\mathrm{w}}>7$ earthquakes and regular long-term storage of regolith, but ~~with poor recording of major events~~without a detailed historical record of major earthquakes, it is possible to record more variable cosmogenic concentrations than might be expected, including positive as well as negative excursions from the long-term mean (Figure 5B).

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These modelling results provide testable predictions of the exhumation-related changes to cosmogenic concentration caused by large earthquakes. Hence, we sought to examine whether the predicted variability might represent some of the variability associated with cosmogenic erosion rates in seismically active areas using a global dataset compiled by Harel et al. (2016). Harel et al. (2016) collated detrital cosmogenic ^{10}Be concentrations for 59 geographical areas, separated into areas of similar climates, and recalculated the erosion rates using consistent production rate and shielding corrections. ~~We compared the probability density distribution of erosion rates from within these geographic regions~~ After ~~(~~limiting our regional sampling~~es~~ from the Harel et al. dataset to those sites with >18 measurements and basins larger than 10^5 m^2 to limit sampling bias (Dingle et al., 2018; Niemi et al., 2005), we compared the probability density distribution of erosion rates from within those geographic regions~~)~~ to seismicity, ~~proxied~~ as represented by~~using~~ the 475 year return peak ground acceleration (PGA) derived from a global seismic hazard map (Giardini et al., 1999; Harel et al., 2016) (Figure 6A). Due to the size of the geographical areas there may be multiple seismic hazard levels recorded;~~,~~ we simply use the mean value to classify the area. The use of a single number to characterise a large area can underestimate the potential PGA. While a single number may not accurately describe the entire area, it does allow us to compare the variability of denudation rates with seismic hazard. ~~By separating the geographical regions in coseismic seismically and aseismic regions~~We then crudely classify the regions as dominantly coseismic or dominantly aseismic:~~,~~ regions with thrust faults and erosion rates greater than the median are deemed coseismic, while slowly eroding regions with no thrust faults are aseismic. "Mixed" regions are those that do not fall under either of these classifications.~~,~~ ~~W [in what??] We then grouped these geographic regions into seismically active and inactive regions, noting the dominant sense of faulting, as this affects the distribution of coseismic landslides.~~

~~Seismically active~~Coseismic landscapes, as expected, have~~d~~ higher average cosmogenically-determined erosion rates with higher standard deviations (Krustal-Wallis H-test statistic=14.14, p-value=0.00017) (Figures 6A & 6B). Relief is a major control on erosion rates, with steeper catchments having higher erosion rates than shallower ones (Montgomery and Brandon, 2002). The most seismically active mountain ranges are also among the most varied in relief as they have some of the steepest catchments in the world. Therefore, we need to test whether variability in erosion rates is more closely related to variation in catchment steepness or the seismicity of the area. Within the database compiled by ~~(~~Harel et al., 2016~~)~~ they include a normalised channel steepness index which we use to compare the impact of catchment steepness on erosion rate. The channel steepness index equation is derived from the stream power equation,

$$M_x = \left(\frac{E}{K{A_0}^m}\right)^{\frac{1}{n}} \quad (11)$$

Where M_x is the steepness index, E is the erosion rate, K is the erodibility coefficient, A_0 is a reference area of 1m^2 and m and n are empirical relations. The index is normalised by assuming fixed values for m and n (Harel et al., 2016). We would expect that in areas with highly variable steepness indexes the erosion rates are also more variable. ~~The most seismically active mountain ranges are also among the most varied in relief with some of the steepest catchments in the world.~~ We find that while areas with higher seismicity have more variable erosion rates, the variation in erosion rates correlates much more closely~~r~~ with~~towith~~ the variation in steepness index (Figures 6B&C). Steeper basins in tectonically active mountain ranges are more susceptible to coseismic landsliding (Li et al., 2017a; Marc et al., 2016a) so will have more variable denudation rates through time, depending on the residence time of the landslide regolith and the frequency of earthquakes, than shallower basins. ~~The variation of catchment steepness in a landscape correlates with denudation rates much more strongly than seismicity across the globe (Figure 6C). On average steeper basins in tectonically active landscapes could have higher landslide densities and larger volumes of coseismic generated regolith than shallower basins.~~ This suggests that landscapes with more variation in basin ~~form~~ relief could enhance the temporal perturbations in denudation rates produced by earthquakes, but the contribution of tectonics to long term variation is difficult to isolate.

We further explored the role of averaging time by ~~exploring~~ examining how this may change with different contributions from seismic and aseismic uplift. After a large earthquake that produces tens of centimetres of instantaneous weathering of S_B, exhumation rates measured with different averaging times converge to the long-term mean rate within hundreds to thousands of years of a particular earthquake (Figure 5A). Bedrock surface exhumation rates are impacted by both surface uplift and lowering rates so as a result the time scale of the perturbation is impacted by the dominant form of uplift in the mountain range. As a result, the more dominant coseismic uplift is in a landscape, the longer the recording time needs to be before a reliable exhumation record can be made. Landscapes with more frequent earthquakes have more variable exhumation rates which require longer averaging times to achieve accurate measurements of the long-term average exhumation rate. Regardless of the frequency of earthquakes in a mountain range, the events of the greatest magnitude remain uncommon while being the dominant contributors to weathering. Hence the relationship between exhumation rate and averaging time is consistent with the Sadler effect that has been described for sedimentary systems (Schumer and Jerolmack, 2009). Unlike sedimentary systems, where it is possible to measure sedimentation rates from timescales of seconds to millions of years, there are few measures of exhumation that we can use and many of these have long averaging times. Thermochronometric methods average across timescales of 10^5-10^7 years, much longer than the ~~averaging~~ recurrence times of individual earthquakes. There is a possibility

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that cosmogenic radionuclide analysis~~ may~~ record individual earthquakes, where earthquake-~~-~~triggered landslides weather bedrock that has a low cosmogenic concentration (Wang et al., 2017; West et al., 2014), although enhanced erosion during and immediately after an earthquake complicate the cosmogenic signal in practice.

Despite representing close to half of the weathering flux of mountain belts, stochastic earthquakes still remain substantively missing ~~substantively~~ from our models of the development of mountain~~s~~ belts. The modelling here demonstrates that stochastic uplift and exhumation by large earthquakes is likely to be averaged away across the timescale of most thermochronometers, with the variability in uplift and exhumation~~is~~ ~~temporal variability~~ representing around 15% of the average exhumation rate. Even when a large earthquake occurs at the edge of a mountain belt, as has occurred in the Wenchuan region, the variable exhumation signal is further shredded by sediment transport, over the residence time of the regolith, by floods and debris flows, such that even sinks that are within 40 km of the epicentre show limited evidence for large earthquakes (Zhang et al., 2019). This result along with our model demonstrates the importance of understanding ~~how is~~the processes by which and the time taken for landslide sediment to be mobilised out of catchments. Without improved understanding of the cascading nature of sediment transport from catchments it is unlikely we will be able to identify earthquakes other than ~~This suggests that the signal of a single earthquake could be discernible only~~ within smaller basins or sinks immediately adjacent to the epicentre (Howarth et al., 2012). Large basins (greater than 10,000 km^2) have been shown to be large enough to average out the perturbations in cosmogenic radionuclide concentrations caused by large landsliding events (Dingle et al., 2018; Marc et al., 2019). While the largest basins are able to offer reliable estimates of long-term erosion rates, the detrital cosmogenic nuclide concentrations from smaller basins will be more affected by bedrock landsliding caused by earthquakes. Therefore, smaller basins ~~While these basins will offer reliable estimates of long-term erosion rates, the aim in this exercise is to identify variations from this, thus smaller basins~~ could be suitable targets to recognise variations in erosion rates due to earthquakes. Our model suggests that the impact of a large earthquake is not necessarily big enough to perturb the denudation rate of an orogen for the whole of a cosmogenic nuclide recording time.~~.~~ The combination of averaging times, shredding, and the relative contributions of large earthquakes to long term exhumation rates~~—~~ help us to understand the lack of clear signatures for single earthquakes in sedimentary or exhumation records.

4. Conclusions and implications

Our simulations show that the regolith generated by large earthquakes can reduce the rate of weathering and exhumation of rock due to its~~their~~ potentially long residence time on hillslopes. Reducing exhumation rates also increases the uplift rate of the bedrock surface, but~~ however,~~ these effects are small when compared to the ~~impact~~role of the magnitude and frequency of earthquakes. ~~the while the regolith generated by large earthquakes can reduce the rate of weathering and hence exhumation, increasing uplift of the bedrock surface, the magnitude of this effect is small relative to the background rates of rock uplift and the frequency distribution of earthquakes.~~ These results demonstrate that background tectonic processes and rates are the dominant control on the surface uplift, while the more important role for large earthquakes is their control on weathering.

Small earthquakes contribute very little to both uplift and weathering resulting in below average rock exhumation being recorded if a large earthquake does not occur during the averaging time of the exhumation record ~~when large earthquakes are unaccounted for~~. While large earthquakes do produce higher than average rock exhumation rates, the slow ~~and stochastic~~ removal of regolith from the orogen reduces the magnitude and timescale of the signal. The relatively long timescales of exhumation records prevent the recording of orogen-scale variation in exhumation due to a single earthquake. A better understanding of the controls on bedrock weathering by earthquake triggered landslides is required to identify signals of earthquakes in sedimentary records. Higher resolution exhumation records and the growing recognition of the complex nature of ~~sediment cascades~~exporting landslide sediment from mountainous catchments will help to explore this problem.

Author Contributions

All authors contributed to the writing and ideas of the paper. The model and project design were produced with discussion from all authors. OF wrote the model with assistance from DEJH, TCH and AH. TCH, XF and RH formulated the overall project aims. ~~.~~

~~XF, GS, OF designed the methodology for the collection and analysis of the multitemporal landslide inventory; OF, DH, TCH, AH designed the model and experiment, which OF wrote; TCH, XF, RH formulated the overall project aims.~~

Competing interests

The authors declare no competing financial interests.

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Figures

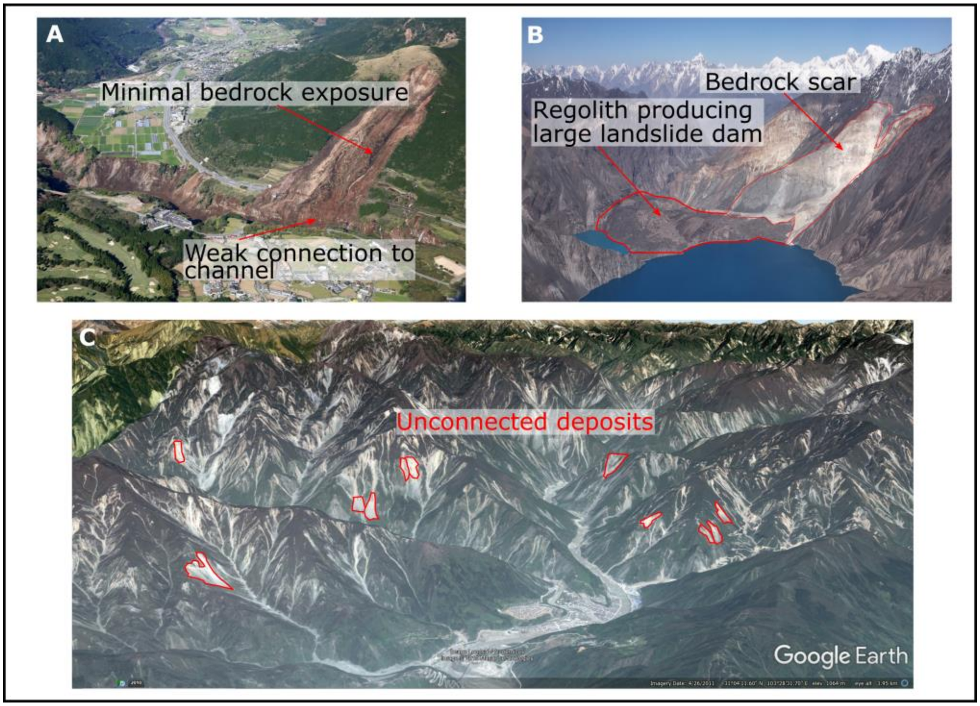

Figure 1. Landsliding can generate large volumes of sediment but only the largest deposits consistently transport it off the hillslope. The volume of bedrock eroded is also dependent on the thickness of regolith on the hillslope before the landslide occurs. A) shows landsliding from the 2016 Kumamoto Earthquake which occurred in thick volcanic deposits which reduced bedrock rock erosion. B) shows that in bedrock dominated areas, such as the Usoi Dam in Tajikistan (produced by the 1911 earthquake), significant volumes of regolith can be generated by landsliding but little measurable erosion as the regolith produced has remained in the catchment as a landslide dam for over 100 years. The 2008 Wenchuan earthquake produced over 60,000 landslides (C), many of which have significantly smaller transport lengths than the hillslope (highlighted in red) and so cannot be easily removed from the catchment. For these reasons we define landsliding as weathering rather than as erosional agents. ~~Landslides in thick regolith can remobilise sediment while causing little erosion as seen in the 2016 Kumamoto Earthquake (A). During earthquakes in landscapes with little pre-existing regolith, huge volumes of regolith can be generated coseismically e.g., 1911 Usoi Dam, Tajikistan, (Red line highlights the landslide scar) (B). The 2008 Wenchuan earthquake caused more than 60,000 landslides (C), which have areas varying by many orders of magnitude. Some of the small landslides will remobilise pre-existing regolith but the total volume of that~~

~~remobilised regolith is unknown.~~ Photo A is sourced from https://blogs.agu.org/landslideblog, Photo B is from https://www.mergili.at/worldimages/picture.php?/9330 , Photo C is sourced from Google Earth, using imagery provided by Landsat/Copernicus and Maxar Technologies, 2019 and draped over a digital terrain model. © Google Earth

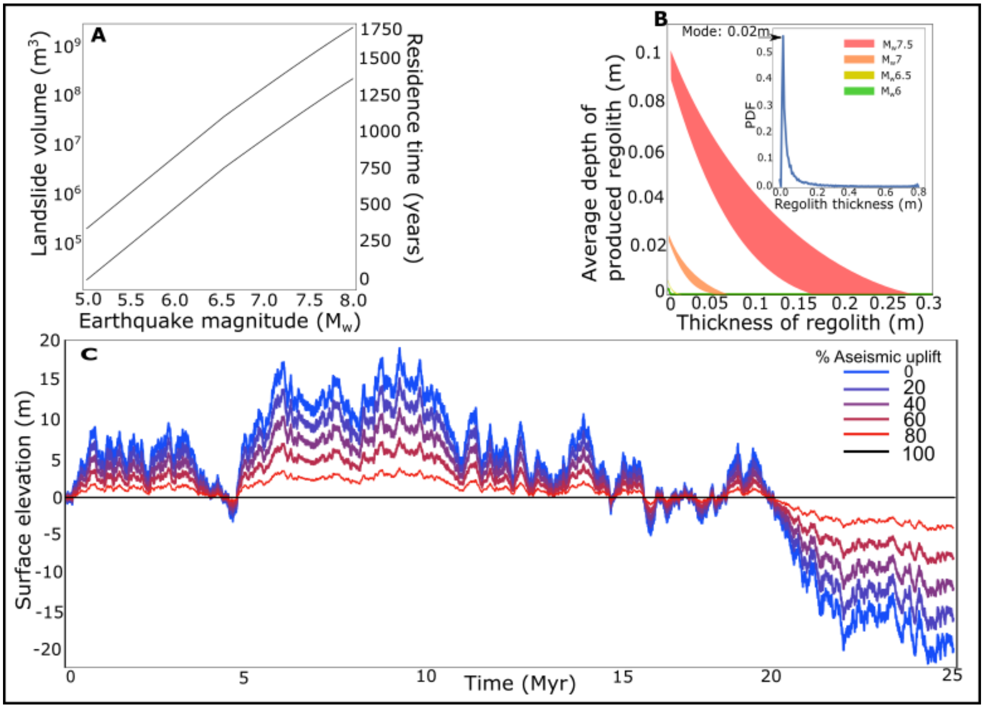
A
Landslide volume (m^3)
10^9
10^8
10^7
10^6
10^5
1750
1500
1250
1000
750
500
250
0
Residence time (years)
5.0
5.5
6.0
6.5
7.0
7.5
8.0
Earthquake magnitude (M_w)
B
Mode: 0.02m
Average depth of produced regolith (m)
0.1
0.08
0.06
0.04
0.02
0
0.05
0.1
0.15
0.2
0.25
0.3
Thickness of regolith (m)
PDF
0.5
0.4
0.3
0.2
0.1
0.0
0.0
0.2
0.4
0.6
0.8
Regolith thickness (m)
M_w7.5
M_w7
M_w6.5
M_w6
C
% Aseismic uplift
0
20
40
60
80
100
Surface elevation (m)
20
15
10
5
0
-5
-10
-15
-20
0
5
10
15
20
25
Time (Myr)

Figure 2. The average depth of regolith produced by an earthquake is impacted by the earthquakes’~~its~~ magnitude and the ~~volume~~ thickness of regolith that is on the hillslope before the earthquake occurs. (A) ~~Malamud (2004)~~ (Malamud et al., 2004)’s scaling of landslide volume with magnitude and their average residence time in the Longmen Shan based upon an erosion rate of 0.62mm/yr. The two lines represent the minimum and maximum volumes of landsliding generated, within the bounds on equation 8. (B) Variability of ~~sediment~~ regolith production ~~rates~~, expressed as volume per area, with existing depth of regolith on the hillslope, for four representative earthquake magnitudes. Coloured areas represent the variability of the landslide volume produced by an earthquake, randomly sampling ~~from~~ within the bounds of equation 8. These Coseismic Landslide Regolith Production functions (CLRPF) emerge from the model rather than being set in advance, and the variability at each magnitude is driven by noise inherent in the relationship between magnitude and landslide size (equation 8). Inset shows the probability distribution function for regolith thickness across the whole model run, integrating the effects of the CLRPF through time. A small but nonzero spatially averaged modal regolith thickness persists, but significantly larger thicknesses regularly occur. (C) Variability of surface elevation through time for model runs with identical earthquake sequences, but with varying additional proportions of aseismic uplift. The assumption of steady state prevents any long-term permanent uplift, all variations in surface elevation are driven by the sequence of earthquakes and changes in regolith thickness. ~~During times of thick regolith rapid surface uplift can occur despite the model being in a fixed flux steady state over longer timescales.~~ Increasing the aseismic contribution to uplift reduces the uplift of large earthquakes, resulting in much less variable surface uplift and therefore exhumation.

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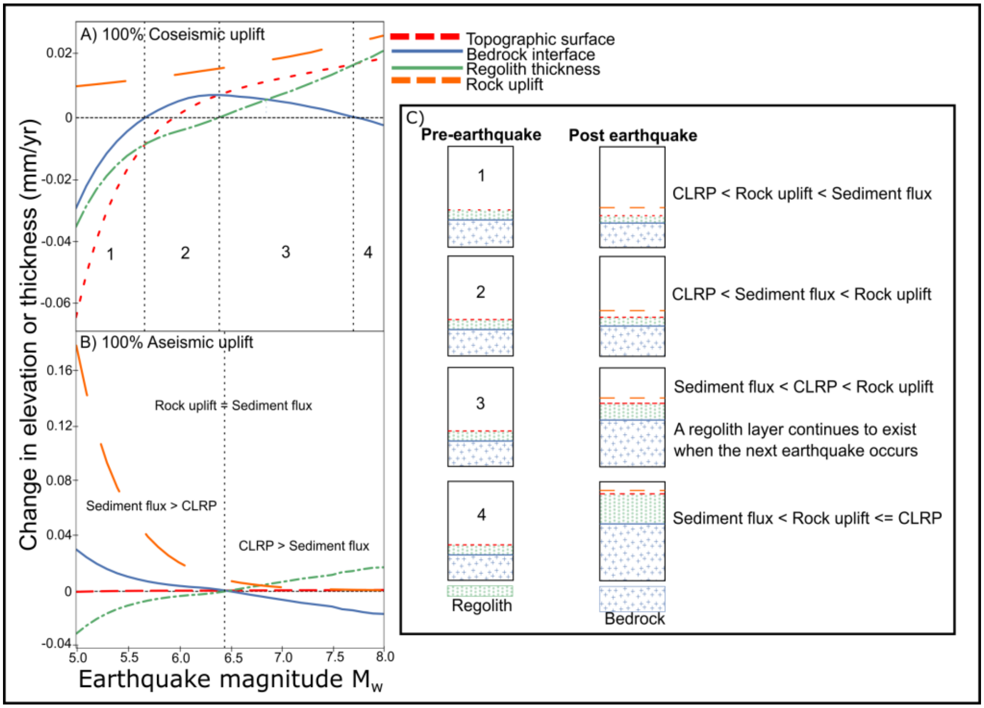

Figure 3. Interplay of changes to the modelled rock uplift rate, the topographic and bedrock surface uplifts, and the resulting regolith thickness through time, classified according to earthquake magnitude. The total bedrock and topographic uplift produced by each earthquake magnitude through the model run is summed up and divided by the run time to produce a rate. A) represents a run with 100% coseismic uplift while B) is purely aseismic. Each time a recorded surface intersects the horizontal axis we separate the chart into a zone which is further described in the text and cartoons C). ~~The top graph represents a run with 100% coseismic uplift while the bottom is purely aseismic.~~

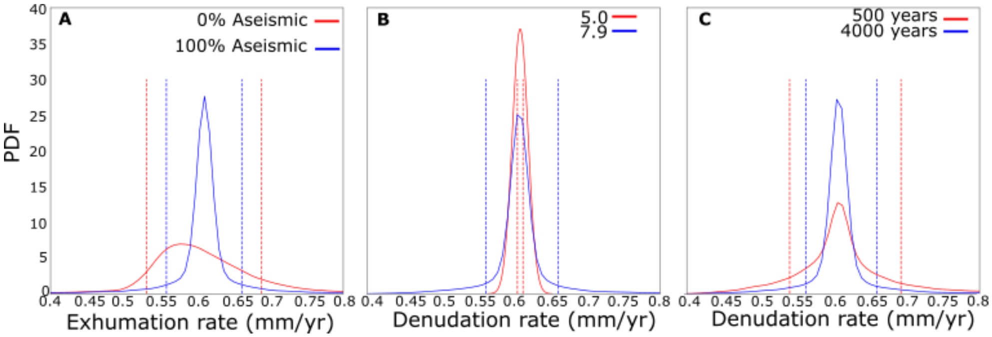

Figure 4. Variation of exhumation and denudation rates in various scenarios. Dashed lines indicate the position of the mean +/- the standard deviation of the distribution. A) Exhumation rates in different uplift regimes. B) Denudation rates while varying the maximum earthquake magnitude in a run, the run with a maximum magnitude 5 has only earthquakes of a magnitude 5. C) Denudation rates while varying the frequency of Wenchuan size earthquakes from every 500 to every 4000 years.

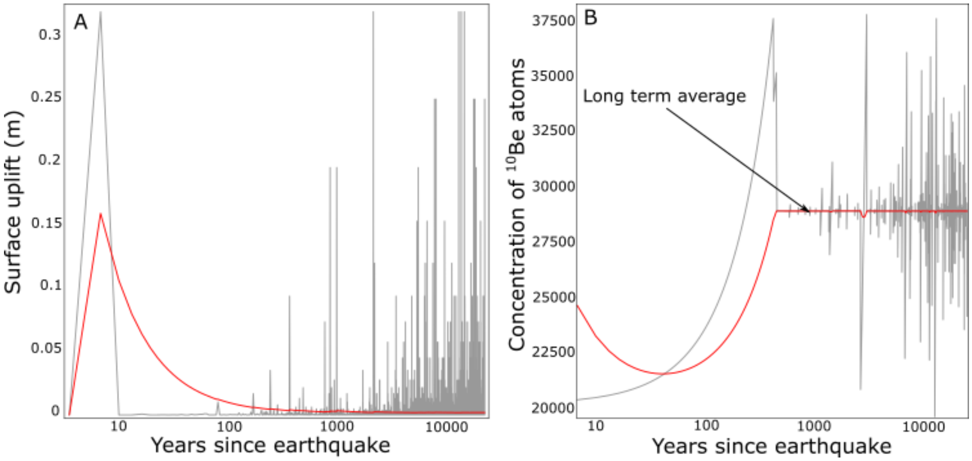

Figure 5. Variability of (A) Topographic surface uplift and (B) the recorded concentration of cosmogenic nuclides leaving the orogen after a representative magnitude 8 earthquake within the model run. Red lines are running means, averaged over the run time, while the grey is the real time change caused by individual subsequent earthquakes.

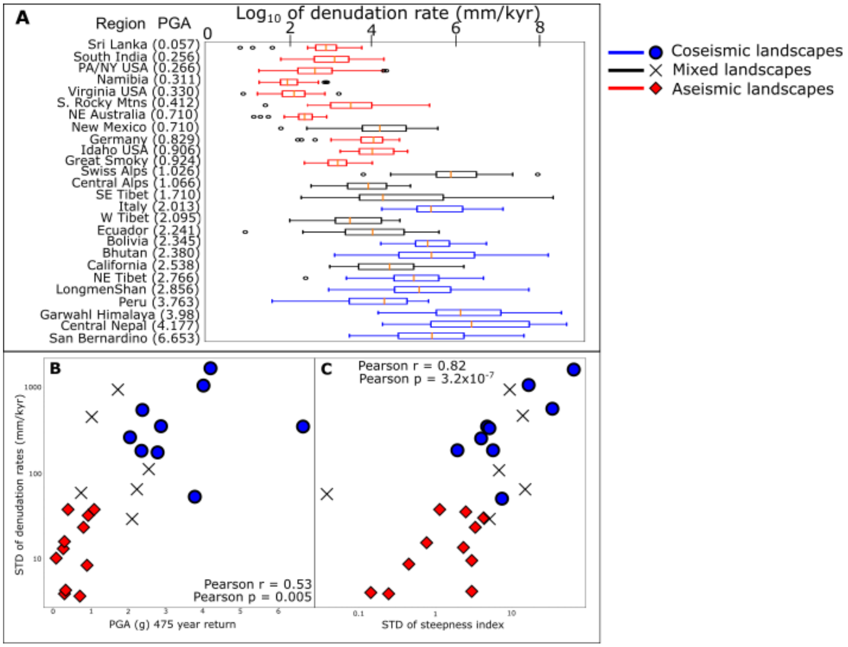

Figure 6. Reanalysis of detrital cosmogenic radionuclide derived denudation rates for mountain belts around the world compiled by Harel et al (2016), in the context of peak ground acceleration and tectonic environment. (A) A box plot indicating the median (central orange line), quartiles (end of box) and the range ('the whiskers') of denudation rates in the analysed localities ordered by their average seismicity (in brackets), defined as the maximum Peak Ground Acceleration of a 475-year return period (PGA). Points indicate values outside the range, ~~Median~~ ±1.5IQR. (B) Standard deviation (STD) of denudation rates for each mountain belt against seismicity represented by the 475-year return Peak Ground Acceleration (ms^{-2}). (C) Standard deviation of denudation rates for each mountain belt compared to the standard deviation of steepness indexes~~. Steepness index is the relationship between slope and drainage area (*k*) which is normalised by a reference concavity to allow global comparison~~. The areas of highest variability are found in steep, tectonically active mountain ranges.