Response to Reviewer's comments to the manuscript esurf-2023-10:

Massive sediment pulses triggered by a multi-stage alpine cliff fall (Hochvogel, DE/AT)

By Natalie Barbosa, Johannes Leinauer, Juilson Jubanski, Michael Dietze, Ulrich Münzer, Florian Siegert, Michael Krautblatter.

Dear Anonymous reviewer, Dr. Georgie Bennett and Editor,

You will find below my responses to the comments made by an anonymous reviewer and Dr. Georgie Bennet. I am very grateful for their constructive comments and suggestions for improving the scientific significance, scientific quality, and presented style. Their comments appear in black text below while my responses are in blue. Direct modification to the manuscript or citation from the text are in green. The changes made to the manuscript are first detailed after each response and then appear on the manuscript with the tracked changes.

Best regards,

Natalie Barbosa, on behalf of the co-authors of this manuscript.

<u>Summary of changes made to the manuscript:</u>

We have adapted the manuscript to incorporate suggestions from both reviewers. The main changes in the revised version of the manuscript are related to the structure of the introduction and discussion sections, as well as the figure selection. In particular, we have:

1) Restructured the introduction to first introduce key processes addressed by this research, expand the literature review on sediment cascades and state the research and technological gap addressed by the study.
2) Combined Figure 6 and Figure 8 into a single figure (new Figure 6) that presents at a glance the temporal series of catchment sediment budget followed by the segregated sediment budgets by geomorphic zones.
3) Restructured the discussion section and put in context our results with the existing work on sediment cascades and numerical modeling.
4) Moved Figure 2 supplementary material to the manuscript (new Figure 8) to exemplify the decadal geomorphic change and the temporal series of changes at each geomorphic zone that leads to the current (2020) catchment morphology.
5) Modified Figure 5. We have plotted the yearly cumulative frequency of volumes calculated over 10 years on the y-axis. The previously presented results were misleading as the units of the y-axis resemble an exceedance probability plot. We have updated the image using the cumulative frequency volumes (m^3) instead of normalized yearly volumes ($m^3\ yr^{-1}$).
6) Added an explanatory diagram of the workflow. The diagram covers the creation of DSM from large format digital aerial imagery, the coregistration process to calculate elevation changes (DoD), the filtering of high uncertainty changes, and the final volume calculation (new Figure 1 supplementary material).
7) Added a field pictures that exemplifies the changes at the outlet after the 2016 cliff fall (new Figure 3 supplementary material)
8) Added a figure displaying the seismic record of the 6 sub-events that constitute the 2016 cliff fall for the closest seismic station (Oberdorf).

For detailed responses to specific reviewer comments please see the following pages of this document.

Thank you for your time and consideration!

Review summary RC1 by Anonymous referee #1

The subject is of great interest and the response of a catchment to a large contribution of landslides is important especially nowadays with climate change. The observations are worth to be published, but unfortunately there is a large overinterpretation of the results, low resolution in temporality is bad for interpretation, but enough for a short paper about observations. The pulses of sediment delivery in the sedimentary cascade need more time resolution and also better spatial resolution in space, the use of potential energy with distance stations seems not really relevant looking at the table 13 sup. Mat. It shows a very low percentage of less than 1% of total volume (I guess it is not percent), some mostly below 50%, which is not relevant to give interpretation, but maybe I misunderstood. In addition, Le Roy et al. used very close seismic stations.

We gratefully thank the Reviewer for their comments and time devoted to the manuscript. We would also always wish for a higher temporal resolution, but up to our understanding this is the first work that has measured entire catchment sediment dynamics at a high spatial resolution (20 cm) before and after a big rock slope failure (>10^5 m^3) and one out of few papers that illustrate the spatio-temporal patterns of sediment waves at a catchment scale in a temporal resolution of 2-to-3 years over a decade. We do not intend to resolve single debris flows but we want to decipher sediment dynamics on a (multi-) annual time scale. In fact, the temporal resolution of 7-time steps in 10 years is high enough to demonstrate the catchment wide-propagation of sediment waves, despite the coalesce of erosional events. We consider the temporal resolution a relevant time scale because sediment waves after a high sediment pulse occur in the range of years to a few decades (e.g., Baer et al., 2017).

We are aware of the greater distance between the Hochvogel and the seismic stations used to characterize the 2016 cliff fall compared to the original source Le Roy et al. (2019), however, the energy released by the event was easily sufficient to be recorded and discriminated. Table 13 sup. summarize the volume percentage of each identified sub-event from the total estimated volume. Our results show that regardless of the distance, the proportional contribution of the sub-events is consistent. The 2016 cliff fall followed a multi-stage behavior with almost half of the total volume being detached in the last event (sub-event #6). The total volume presented in the manuscript ($1.02*10^5$) is taken from the closest possible seismic station (Oberstdorf) (line 304) and the supplementary material aims to illustrate the uncertainty of the volume estimation when using farther stations (Line 224-225 Sup material). We also think that the number of 1% has been mistake because even if the sub-event 2 and sub-event 3 are considerably smaller than the other sub-events, block falls with a magnitude of 10^3 (Table 2) are relevant in the context of assessment of natural hazards and rockfall slope dynamics.

Finally, we carefully revise the interpretation of the results and strengthen the argumentation that leads to our conclusions. All the changes made to the manuscript appear on the revised version highlighted with the track changes. Those of particular relevance for the improvement of the manuscript are detailed in green below.

Change in the manuscript (line 86): We do not intend to resolve single events but rather decipher rockfall patterns and catchment sediment dynamics after an unusual sediment input to the catchment on a (multi-) annual time scale. Additionally, we complement the understanding of a single rockfall event by the use of high-resolution seismic records (e.g., Hibert et al., 2011; Lacroix and Helmstetter, 2011; Manconi et al., 2016; Fuchs et al., 2018; Dietze et al., 2017a). Despite the kilometric distance between the seismic stations and the Hochvogel summit, the energy released by the 2016 cliff fall allowed us to discriminate the event into a multi-stage detachment and estimate release volumes.

By the way many tables have no units (4, 5, 13 sup mat.) and axis legends in figs. sup mat 4, 5, 6.

Thanks for pointing out the lack of units in tables 4, 5, and 13 supplementary material. We understood thresholds as a unitless number of the underlying value but we changed all to meters now, which is the unit for the elevation changes. Similarly, to avoid further confusion, we have expressed the percentages in Table 13 as (%) and not decimal values. The x-axis legends in figs. Sup mat 4 and 5 were unfortunately cutting out. We have carefully included the original versions with the corresponding x-axis legends. Regarding Figure 6, we have clarified in the figure caption that the x axis corresponds to each sub-event.

Change in the manuscript (Figure 6): Figure 1. Volume estimation for each sub-event (1 to 6 in x-axis) using a Monte-Carlo simulation with 1,000 iterations for each seismic station.

The descriptions of the volumes form DoDs have less than 1% of error which is very small, consider some other factor, especially using eq. 7. A flow chart can improve and simplify the description for the DoD recreation. In addition, how do you create the grid, which interpolator is used… this brings some errors…

This is a very good point. The DoDs errors calculated using Eq.7 are proportional to the elevation change uncertainty [$\boldsymbol{\delta v}$]. A very important methodological step proposed in this manuscript is the implementation of a 7-parameter 3D similarity transformation described by Eq.1 which minimize the relative elevation uncertainty between datasets. Table 3 supplementary material shows that the relative elevation uncertainty calculated based on 30 representative well-distributed points is less than 0.4 m (two times the horizontal spatial resolution) for all pair of datasets used for the production of DoDs. On the other hand, we are aware of the many factors that lead to errors in the production of the DSMs. We carefully defined critical thresholds (LoD) in meters for each DoD based on image quality, shadow percentage, and slope characteristics (Table 4 and 5 in supplementary material). We want to stress that we calculated uncertainty for every single data set and process, i.e., erosion and deposition. For some time periods, the volume uncertainty is higher than 1%, but rarely higher than 2%, i.e., deposition at the rockface zone between 2012-2010, erosion and deposition at the outlet for the time interval between 2012-2010 and deposition at the outlet for 2018-2017 and 2018-2020. The most conservative approach to assess the volumetric error on steep slopes is presented in Table 6 supplementary material, and resulted in a standard deviation (σ) of 2.4%. Note that the aim of this analysis is to exemplify the inhomogeneity of the datasets and the need for knowledge-based defined thresholds for every single dataset and process. We stress the usage of non-interpolated DSMs (line 182) to warranty the calculation of changes in elevation only on areas with quality elevation points. Finally, we acknowledge that the error estimate certainty influences the calculations of the magnitude of sediment erosion, transport, and deposition, but will not alter the general conclusion on the 0-2 years reaction times to the more than 150,000 m^3 of sediment input and relaxation times beyond 10 years.

We appreciate the suggestion of a flow chart. We have included a detailed flow char in the supplementary material to warranty the reproducibility of our work.

Change in the manuscript line 145: 'The DSM follows the same grid from the orthophoto, but only high-quality elevation points identified by a multi-triangulation of at least 3 photographs are written in the non-interpolated DSM.'

Change in the manuscript (line 194): Note that the critical thresholds certainly influence the calculations of the magnitude of rockfalls, and sediment erosion, transport, and deposition, but will not alter the general conclusions on the rockfalls patterns at the slopes that constitute the summit and the sediment dynamic response to the input of sediment from the cliff fall in terms of reaction and relaxation times.

Change in the manuscript: Table 1. Contribution of rockfall magnitudes. Volumetric classification based on *(Whalley, 1974, 1984; Erismann and Abele, 2001; Krautblatter et al., 2012)*. * Error equal to total volume percentage error of 2.4 % (Table 6 supplementary material). Rockwall retreat refers to the horizontal retreat of the vertical rock cliff.

Change in the supplementary material (line 100): The volume inside a manually delimited extent of the cliff fall resulted in a mean of 142,047 m^3 and a standard deviation of 3 475 m^3 thus an uncertainty of 2.4% from the total volume. This uncertainty percentage is used in the decadal analysis of rockfall at the slopes that constitute the Hochvogel summit knowing that the 2016 cliff fall corresponds to a coalescence of at least 6 individual detachments

Change in the manuscript: 'Figure 2. Time series of geomorphic sediment budgets at the catchment. The bar plot depicts yearly volumes of erosion in red and deposition in blue. The yellow line indicates the net change calculated as the difference between erosion and deposition at each time interval. The estimated uncertainty of the absolute volumes follows Eq.7 and is less than 2%, thus, imperceptible due to the scale of the graph. We calculated uncertainty for every single data set and process, i.e., erosion and deposition. Sediment delivery ratio is expressed as the proportion of sediment leaving the basin and the total net erosion.'

Change in the manuscript (line 223)… (Williams et al., 2019), however, we do not intend to resolve single rockfalls but we aim to decipher the relative rockfall activity in the last decade for each of the rock faces slopes that constitute the summit (Dussauge-Peisser et al., 2002; Benjamin et al., 2020; Hantz et al., 2021). We assessed the volumetric errors due to the steep topography by the iterative calculation of the volume of a known event (2016 cliff fall) using all possible combinations of DSMs (Table 6 supplementary material).

Change in the manuscript (line 218): The proposed workflow for the calculation of volumes of changes in steep terrain using large format high-resolution aerial imagery results from the combination of previously published methodologies and the implementation of intermediate steps that responds to the particularities of the datasets. A summary of the methodological step is presented in Figure 1 supplementary material. Further research is needed to better determine the significant change and the uncertainty on the volume calculation of erosion and deposition in areas with steep and inhomogeneous terrain.

Change in the supplementary material (Figure 1):

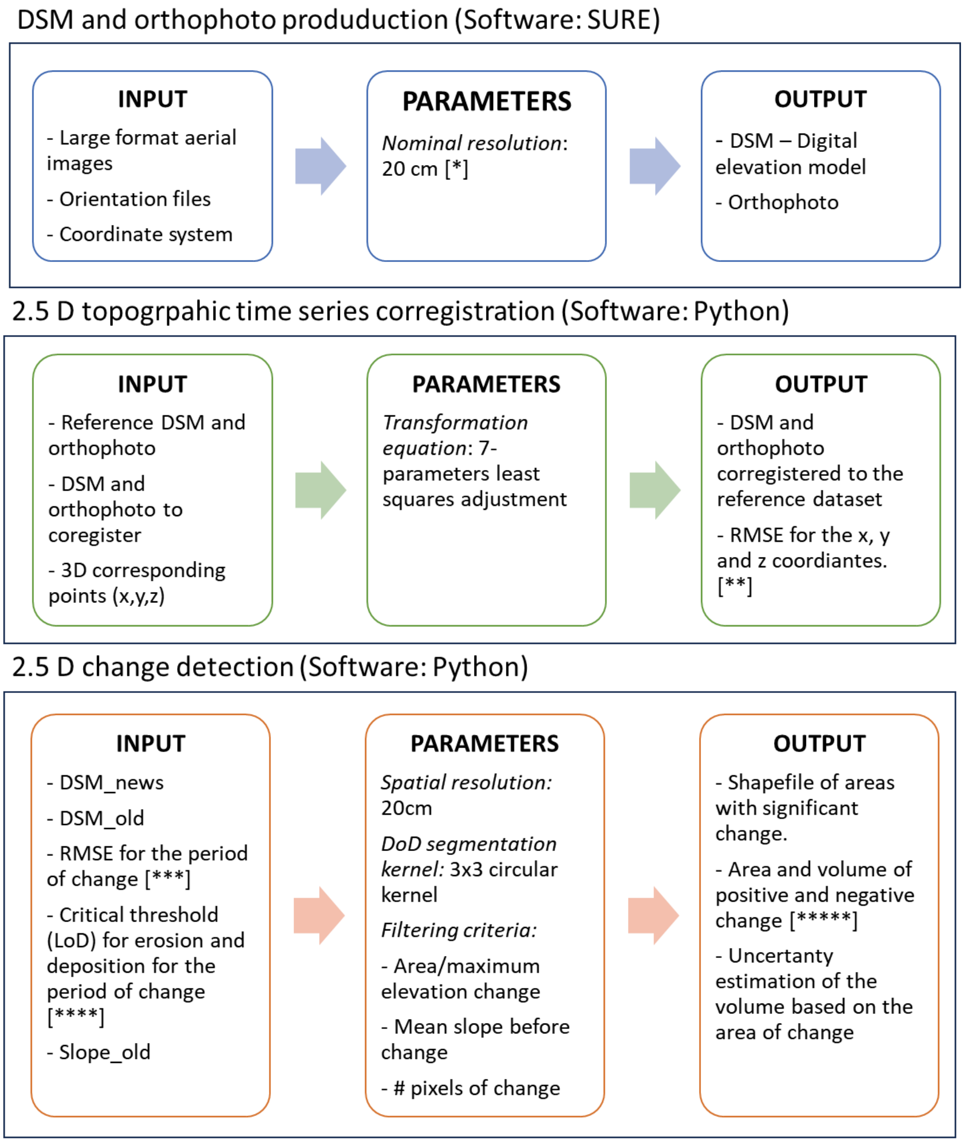


Figure 1. Summary of the methodological steps followed for the calculation of volumes of change in steep terrain. [*] The nominal resolution of the DSM and orthophotos is determined by the height of the flight defined by the surveying agency. [**] The RMSE (root mean square error) is a useful metric to reveal systematic errors and estimate the uncertainty between two datasets. [***] We calculate the RMSE for each dataset, i.e., each DoD combination, as a measure of error and use it for the error propagation. [****] The critical threshold (LoD following Wheaton et al., 2010) is determined for each process, i.e., erosion (negative change) and deposition (positive change) and each morphological zone that account for the topographic and shadowing influence on the photogrammetric reconstruction. [*****] The volumes of change are calculated only for areas of significant change according to the critical thresholds.

Some figures form the supplementary material can be included or merged with others in the main manuscript.

Thanks for the suggestion. We aimed for a simplified manuscript and carefully discriminated which figures were strictly necessary to illustrate the key aspects of the study. We have merged Figure 6 and Figure 8 in one to contrast in the same figure the catchment sediment budget and the discriminated sediment budget. Also, we transferred Figure 2 supplementary material to the main manuscript to illustrate that even if the temporal results of the time-series results in the coalescence of events, we can unravel patterns of sediment dynamics in the last decade at enough resolution to conclude that the decadal sediment flux of more than 400,000 m^3 of sediment is characterized by massive sediment waves that (i) exhibit reaction times of 0-4 years in response to a cliff fall sediment input, and relaxation times beyond 10 years, (ii) manifest faster response times of 0-2 years in the upper catchment and over 2 years in the lower catchments, (iii) undergo a rapid shift from sedimentary (10^2-10^3 mm/a) to massive erosive regimes (10^2 mm/a) within single years and (iv) show limited dependency to rainfall frequency and intensity.

The paper needs to be simplified and restructured and focused mainly on observation and less on speculations, for instance the relationship with precipitations can be just mentioned but as the rainfall intensity thresholds are very local and depends very much on the geometry of the deposit, its position, and the material granulometry that such analysis is useless.

Thanks for pointing out the many difficulties in relating rainfall intensity thresholds and debris flow initiation. In any case, we aimed to even suggest a rainfall intensity threshold. Our aim with the analysis of the precipitation data is to put in context the sediment redistribution in relation to climatic variables available in the region. Finding no or a not so clear relation to precipitation thresholds is also an interesting finding. In fact, we are not the first to suggest that sediment mobilization patterns are unlikely to be explained by commonly used rainfall-related climatic variables (Bennet, 2013), on the contrary, it opens the discussion of whether sediment waves create massive redeposition even with low precipitation inputs. We agree that the role of precipitation needs to be mentioned, thus, we dedicate one paragraph of our discussion to comment on the rainfall characteristics of the area and the rainfall intensity registered in the time intervals analyzed.

Change in the manuscript (lines 479): … Sediment transport depends on hydrological conditions and sediment supply, while superimposed debris flows are a common and efficient mechanism of sediment transport (Benda and Dunne, 1997; Schwab et al., 2008; Bennett et al., 2013; Clapuyt et al., 2019). The surrounding of the Hochvogel displays an increased mean seasonal (April-November) rainfall intensity over the last decades for events with durations of less than 4 hours (Figure 8a); however, the number of days with precipitation exceeding rainfall thresholds reported in the literature for sediment transport (2.2 mm/10 min) and debris flows initiation (3.8 to 9.6 mm/10 min and 5 and 15 mm/h) (Hürlimann et al., 2019) exhibit no notorious difference between the periods before and after the cliff fall proving no clear rainfall related apparent trigger for the massive sediment redistribution after the cliff fall. Note the increased number of days with exceeding rainfall thresholds of 10mm/h, 3.8 mm/10min, and 9.6mm/10min for the time interval when the cliff fall occurred (Figure 8b. 2015-2017: T4) while a depositional regime characterizes the sediment dynamics during this period as a consequence of the massive sediment production from the cliff fall. Conversely, the number of days exceeding common rainfall thresholds for the time interval between 2017-2018 (T5 in Figure 8b) characterized by massive sediment redistribution within the catchment is similar to pre-cliff falls intervals. These findings convey with previous studies where no clear rainfall apparent trigger for massive sediment redistribution was found (e.g.,(Bennett et al., 2013; Frank et al., 2019), while, numerical modeling demonstrates that both antecedent moisture and sediment storage are key for debris flow prediction (Bennett et al., 2013, 2014).

Specific Comments

- Lines 31-32 is not clear…

Thanks for pointing out the lack of clarity. We have rephrased this paragraph such:

Change in the manuscript (line 31): We observe the decadal flux of more than 400,000 m^3 of sediment, characterized by massive sediment waves that (i) exhibit reaction times of 0-4 years in response to a cliff fall sediment input, with reaction times of 0-4 years and relaxation times beyond 10 years, (ii) manifest faster response times of 0-2 years in the upper catchment and over 2 years in the lower catchments, (iii) undergo a rapid shift from sedimentary (10^2-10^3 mm/a) to massive erosive regimes (10^2 mm/a) within single years and (iv) show limited dependency of sediment redistribution to rainfall frequency and intensity.

- Line 66: blank after "system"
- Line 152: two dots at the end

Great! we have modified the manuscript accordingly.

- Line 157: meaning of M unclear to me!

Right, we have explicitly mentioned that M is the orthogonal rotation matrix.

Change in the manuscript (line 157): …and ω, φ, κ represent the rotation Euler Angles used to calculate the orthogonal rotation matrix **M**, $m_{ij} = M(\omega, \varphi, \kappa)$.

- Line 160: r means point-to-point or points to surface?

This is a very important question. We performed the calculation point-to-point. We have replaced the word 'surface' for dataset to avoid further confusion.

Change in the manuscript (line 150): To minimize the 3D distance between a reference dataset (DSM and Orthophoto) (21.09.2018) and the interest datasets….

Change in the manuscript Line (155): …vectors of coordinates of the corresponding points at the interest dataset $s(x, y, z)$ and reference dataset $r(x, y, z)$

- Lines 170: 2.5 what?

Thanks for pointing out. We emphasize that our datasets are 2.5**D** datasets.

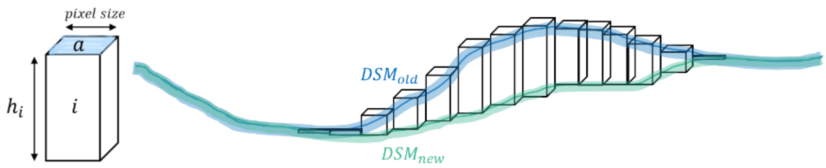
- Eq 3 and 4: are you sure of the necessity of n?

The variable n: number of pixels conceding with a meaningful change is of great importance because we calculate the volumes using only the pixels over or under the critical threshold.

Change in the manuscript (line 180): n is the number of pixels conceding with a meaningful change, i.e., pixels over or under a critical threshold.

- **From lines 210 to 218 unclear, what doe mean v'? You use only one sigma?**

Thanks for pointing out the misleading description. We performed a pixel-to-pixel change detection and defined v as the individual pixels of volume as shown in the image below. We are aware of the many challenges when estimating elevation uncertainty from photogrammetric DSMs. We didn't use the standard deviation (sigma) as a measure of error because it includes only random errors, reflects only how precise the data is but doesn't tell us how accurate is the data in the presence of biases. Instead, we use the RMSE (Root Mean Square Error) to evaluate the vertical accuracy between the datasets used for the DoD. The RMSE is a useful metric to reveal biases and includes random and systematic errors.



Change in the manuscript (line 211): The cell of volume v is calculated such Eq (5):

Change in the manuscript (line 186): Thus, we evaluated the uncertainty of the elevation change (δ_{DoD}) after the 3D-coregistration using 30 independent well-distributed points on stable areas with complex topography for each DoD independently (supplementary Table 2). The uncertainty of the elevation change (δ_{DoD}) is measured as the RMSE of the elevation difference in stable areas with complex topography and ranges between 30 to 40 cm (supplementary Table 3).

- Line 223: site of the paper of Williams…

Thanks for the suggestion. The paper from Williams et al., 2019, The importance of Monitoring Interval for rockfall Magnitude-Frequency Estimations, exemplifies the coalescence of rockfalls when the monitoring interval is bigger than the frequency of the events. We have included it as a reference for Line 223.

Change in the manuscript line 123: We acknowledge the occurrence of coalescent events, given the (multi-) yearly temporal resolution of the datasets (Williams et al., 2019), however, we do not intend to resolve single rockfalls but we aim to decipher the relative rockfall activity in the last decade for each of the rockface slopes that constitute the summit (Dussauge-Peisser et al., 2002; Benjamin et al., 2020; Hantz et al., 2021).

- Line 285: error less than 1 %?

We appreciate the suggestion on double-checking the error percentages. The volume of the 2016 cliff fall ($1.31*10^5$ m^3) was calculated using the manual segmentation of the point cloud which allows a more precise delimitation of the detached area; thus, we assumed the volume with less uncertainty. However, we follow a conservative approach and propagate the errors based on the highest elevation uncertainty, i.e., 0.38 m, thus:

$$\delta V = A\delta v$$

$$\delta V = 4777[m^2] * 0.38[m]$$

$$\delta V = 1824\ [m^3]$$

We agree with the reviewer that the associated error 1.3%, is more than 1%. This cannot be inferred from the presented results due to the scientific notation.

- Figure 3, is not sufficient to illustrate the events…

We agree with the reviewer that image 3 is not sufficient to illustrate the multi-event characteristic of the rockfall detachment, however, the goal of Figure 3 is to make the reader familiar with the rockfall event and the photogrammetric volume estimation. We described the multi-event characteristics and the 6 sub-events separately in Figure 4. We prefer to keep the figures separated for clarity, as the results correspond to different techniques.

- Table 2 and line 317: there must be a discussion between these two numbers.

We think that the results have been mistaken. Table 2 corresponds to section 4.1 that describes a single rockfall event – 2016 cliff fall –. We calculated the cliff fall volume by two different methods: (i) DSM photogrammetric differencing and (ii) high-resolution seismic analysis. We discuss the difference between the 2016 cliff fall volume calculated from the photogrammetric point clouds (1.31 m^3) and the seismic analysis (1.02 m^3) (Table 2) in lines 305 and 306. On the other hand, line 317 corresponds to section 4.2 which describes the decadal rockfalls patterns at the summit. The total volume of $1.713 * 10^5$ m^3 of sediment corresponds to the decadal total volume that includes the 1.31 m^3 cliff fall but not exclusively.

- Figure 8: difficult to understand

Thank you for the comment. We combined Figure 6 and Figure 8 to homogenize the graphical representation of the sediment budgets.

<u>Change in the manuscript:</u> Figure 3. Time series of geomorphic sediment budgets. a) Geomorphic sediment budgets at the catchment scale. b) segregated sediment budget into the four geomorphological zones. Left column: The bar plot depicts yearly volumes of erosion in red and deposition in blue (units at the left axis). The black line indicates the sediment delivery ratio expressed as the proportion of sediment leaving the geomorphic zone from

the total net erosion (units at the right axis). Right column: yearly net change calculated as the difference between erosion and deposition. The estimated uncertainty of the absolute volume is less than 2% thus, imperceptible due to the scale of the graph. Dark grey polygons highlight the temporal stamp at which the cliffs fall took place. Lighter grey indicates the system response two and four years after the event.

- Lines 457-459: unclear

Change in the manuscript (lines 457-459): Bi-annual rockwall retreat rates for the five years prior to the cliff fall averaged 6.5 mm y^{-1}, slightly exceeding short-term (< 10 years) rock wall retreats for limestones (Draebing et al., 2022). The maximum pre-cliff fall rockwall retreat corresponds to 9.5 mm y^{-1} between 2012 and 2014. The rockwall retreat rates are consistent with previous findings of enhanced rockfall activity for carbonate cliffs (Krautblatter et al., 2012).

- Line 471: that is true, but some authors have already worked on that (Williams…)

Thank you for suggesting literature that enriches our manuscript. The paper from Williams et al., 2019, The importance of Monitoring Interval for rockfall Magnitude-Frequency Estimations, provides 'data that evidence a path dependency between sequential rockfalls, whereby smaller events preferentially occur proximal to, or directly in the location of other later rockfalls.' Also, the authors enhance the importance of the high temporal resolution when mapping rockfalls to describe how rockfalls are likely to respond to discrete triggers or the timescales of rockfall response to controlling mechanisms. Line 471 states: The triggering mechanism for this multi-stage event is hard to constrain and needs further research. As pointed out earlier, rainfall intensity thresholds and other rockfall triggering mechanisms are very local and our observations on possible factors such as preceding dry and hot summer days and intense rainfall up to 1.4 mm/10min with a time lag of less than 1h before the three final cliff falls are insufficient to suggest any triggering mechanisms and left us only with conjectures. Despite this, we have expanded our discussion based on the findings of Williams et al., 2019.

Change in the manuscript (line 471): Despite of the greater distance between the Hochvogel summit and the seismic stations used to characterize the 2016 cliff fall compared to the source of (Roy et al., 2019), the energy released by the 6 sub-events was sufficient to record and discriminate them. Regardless the high temporal resolution achieved with the seismic analysis compared to the photogrammetric records, the triggering mechanism for this multi-stage event is hard to constrain because of the lack of high-resolution climatic datasets at local scales. Among common rockfall triggering factors are precipitation and cyclic thermal stressing (Dietze et al., 2017b, 2021). Climatic records from the surrounding of the Hochvogel (Station located at Obersdorf) showed that the multi-stage event is preceded by a phase of several dry and hot summer days. In the night before the first block fall,. …. Contrary to rockfall observations from high temporal monitoring of cliff evolution (Williams et al., 2019), the sub-events prior to the cliff fall are unlikely to follow a pattern of increasing frequency and volumes through time, and even if rockfalls at the proximity of the 2016 cliff fall are mapped as early as between 2010-2012 and 2012-2014, precursory rockfall behavior and triggering mechanism are beyond of the scope of this study.

- Line 479: “regimen” I am not sure it is correct…

Thank you for pointing this out. We have changed the word ‘regimen’ for ‘regime’ throughout the manuscript.

- Lines 500-503: unclear…

Thank you for pointing this out. We have improved the whole paragraphs to better present our findings in relation to the role of precipitation in the increased sediment remobilization after the cliff fall.

Change in the manuscript (line 500): Typical geomorphic responses to disturbances include increased rates of sediment remobilization, transport and deposition (e.g., Owens et al., 2010; Bennett et al., 2013; Baer et al., 2017; Frank et al., 2019; Savi et al., 2023), however, sediment export from the basin rarely reflects changes in sediment transfer within a catchment (Walling, 1983; Walling and Collins, 2008; Burt and Allison, 2010) due to the high variability in time and scale of sediment morphodynamics. The catchment sediment budgets at the Hochvogel clearly suggest a perturbation in the system with at least a year reaction time evidenced in the shift between predominant deposition to increased erosion. The segregated sediment budget (Figure 6a) and the time series of spatial distribution of erosion and deposition (Figure 7) provide insides on the predominant processes controlling the transfer of sediment within the slope. Conceptual models on sediment cascades on landslide-prone catchments propose the temporal accumulation on slopes from landslide deposits that become available for further remobilization (Harvey, 2001). Sediment transport depends on hydrological conditions and sediment supply, while superimposed debris flows are a common and efficient mechanisms of sediment transport (Benda and Dunne, 1997; Schwab et al., 2008; Bennett et al., 2013; Clapuyt et al., 2019). The surrounding of the Hochvogel displays an increased mean seasonal (April-November) rainfall intensity over the last decades for events with durations of less than 4 hours (Figure 8a); however, the number of days with precipitation exceeding rainfall thresholds reported in the literature for sediment transport (2.2 mm/10 min) and debris flows initiation (3.8 to 9.6 mm/10 min and 5 and 15 mm/h) (Hürlimann et al., 2019) exhibit no notorious difference between the periods before and after the cliff fall proving no clear rainfall related apparent trigger for the massive sediment redistribution after the cliff fall. Note the increased number of days with exceeding rainfall thresholds of 10mm/h, 3.8 mm/10min, and 9.6mm/10min for the time interval when the cliff fall occurred (Figure 8b. 2015-2017: T4) while a depositional regime characterizes the sediment dynamics during this period as a consequence of the massive sediment production from the cliff fall. Conversely, the number of days exceeding common rainfall thresholds for the time interval between 2017-2018 (T5 in Figure 8b) characterized by massive sediment redistribution within the catchment is similar to pre-cliff fall intervals. These findings convey with previous studies where no clear rainfall apparent trigger for massive sediment redistribution was found (e.g.,(Bennett et al., 2013; Frank et al., 2019), while, numerical modeling demonstrate that both antecedent moisture and sediment storage are key for debris flow prediction (Bennett et al., 2013, 2014).

Review summary RC2 by Georgina Bennett referee #2

This paper investigates the sediment cascade following a large alpine rockfall in Switzerland. It uses digital photogrammetry to detect volumes of erosion and deposition of sediment through the sediment cascade over a multi-year period. It uses seismology to detect individual rockfall events within the periods of analysis. It finds that 97% of sediment is delivered by a large rockfall event in 2016 that delivers sediment into the downstream debris flow channel. This sediment is remobilised from the upper part of the channel within 1-2 years but then moves more slowly through the catchment and results in overall deposition within the lower catchment even 4 years afterwards. The fluvial system below the outlet incises in response to a reduction in sediment supply creating large terraces. The authors suggest that the response time of the system will be much longer i.e to fully export all the sediment from the rockfall event from the system but needs ongoing monitoring.

I really enjoyed reading this manuscript, having worked on the Illgraben sediment cascade during my PhD, also using digital photogrammetry to extract valuable information on sediment production and transfer from aerial photographs. The team use state of the art photogrammetric techniques to carefully quantify volumes of sediment through the system and accounting for the various uncertainties resulting from topography, shadowing etc. The use of seismology to try to identify individual rockfall events and complement the photogrammetric record is excellent, though I can't comment on the techniques here as a non-seismologist. The combination of photogrammetry and seismology to deal with the issue of coalescence I think is quite novel. Overall, the analysis seems very rigorous and robust and is well presented with a well-designed series of figures. The findings are interesting, particularly the timing of rockfall events leading up to the main failure will be interesting to the rockfall hazard and prediction community. The increase in erosion (by debris flows) in the upper catchment will also be of interest to hazard managers though longer-term monitoring is needed to capture full response of the system to the large rockfall event.

Thanks for these very encouraging comments! We appreciate the time spent on the review of the manuscript and the detailed and constructive comments. Your contribution has enriched the discussion and improved the quality of the presented results.

Main comments

Whilst the resolution of rockfalls achieved through the combination of photogrammetry, visual inspection and seismology is very good, the information on debris flow events is less detailed, with only bulk measurements of sediment volumes remobilised over the multi-year periods, presumably mostly by debris flows. Was it not possible to identify individual debris flow events from the seismic records as well as the rockfalls or would this require closer seismometers?

Thanks to point this out. Unfortunately, the seismic stations in the surroundings of the Hochvogel are at the closest 11 km (Obersdorf station) and the energy released by single debris flows is not enough to appropriately distinguish them. In order to better monitor the debris flow activity, a closer seismograph network is needed.

Change in the manuscript line 444: The energy released by the rockfalls associated with the 2016 cliff fall was sufficient to be recorded despite the distance of the seismic stations (the closest station located at 11 km); therefore, we elucidate the multi-stage detachment of possibly 6 events with exact timing (3 block falls followed by 3 cliff falls). Contrary, the energy released by individual debris flows event is considerably less, thus challenging the usage of the seismic network available for the whole study period.

Analysis of rainfall data to explain patterns of sediment remobilisation through the system are somewhat of an afterthought in the discussion and more could have been made of this to try to explain patterns of remobilisation (i.e. debris flow activity) in figures 6 and 8.

Thanks for the suggestions for improving the understanding of patterns of sediment remobilization. Indeed, the analysis of rainfall data is an afterthought in the discussion because our aim for the manuscript is to constrain the spatio-temporal sediment cascade at a catchment scale in relation to the cliff fall. We appreciate the suggestions on related work. We have restructured the discussion section and concluded that there is no clear rainfall apparent trigger for the massive sediment redistribution after the cliff fall, rather, we want to open the discussion for other factors such as the increased sediment input as key factor influencing the massive sediment remobilization, as you suggest as topic of discussion. Nevertheless, the current monitoring at the Hochvogel includes a rain gauge that might serve for a better constraint on the sediment remobilization in relation to the rainfall patterns since 2018, but we consider this analysis beyond of the scope of this manuscript.

Change in the manuscript (line 500): Typical geomorphic responses to disturbances include increased rates of sediment remobilization, transport and deposition (e.g., Owens et al., 2010; Bennett et al., 2013; Baer et al., 2017; Frank et al., 2019; Savi et al., 2023), however, sediment export from the basin rarely reflects changes in sediment transfer within a catchment (Walling, 1983; Walling and Collins, 2008; Burt and Allison, 2010) due to the high variability in time and scale of sediment morphodynamics. The catchment sediment budgets at the Hochvogel clearly suggest a perturbation in the system with at least a year reaction time evidenced in the shift between predominant deposition to increased erosion. The segregated sediment budget (Figure 6a) and the time series of spatial distribution of erosion and deposition (Figure 7) provide insides on the predominant processes controlling the transfer of sediment within the slope. Conceptual models on sediment cascades on landslide-prone catchments propose the temporal accumulation on slopes from landslide deposits that become available for further remobilization (Harvey, 2001). Sediment transport depends on hydrological conditions and sediment supply, while superimposed debris flows are a common and efficient mechanisms of sediment transport (Benda and Dunne, 1997; Schwab et al., 2008; Bennett et al., 2013; Clapuyt et al., 2019). The surrounding of the Hochvogel displays an increased mean seasonal (April-November) rainfall intensity over the last decades for events with durations of less than 4 hours (Figure 8a); however, the number of days with precipitation exceeding rainfall thresholds reported in the literature for sediment transport (2.2 mm/10 min) and debris flows initiation (3.8 to 9.6 mm/10 min and 5 and 15 mm/h) (Hürlimann et al., 2019) exhibit no notorious difference between the periods before and after the cliff fall proving no clear rainfall related apparent trigger for the massive sediment redistribution after the cliff fall. Note the increased number of days with exceeding rainfall thresholds of 10mm/h, 3.8 mm/10min, and 9.6mm/10min for the time interval when the cliff fall occurred (Figure 8b. 2015-2017: T4) while a depositional regime characterizes the sediment dynamics during this period as a consequence of the massive sediment production from the cliff fall. Conversely, the number of days exceeding common rainfall thresholds for the time interval between 2017-2018 (T5 in Figure 8b) characterized by massive sediment redistribution within the catchment is similar to pre-cliff fall intervals. These findings convey with previous studies where no clear rainfall apparent trigger for massive sediment redistribution was found (e.g.,(Bennett et al., 2013; Frank et al., 2019), while, numerical modeling demonstrate that both antecedent moisture and sediment storage are key for debris flow prediction (Bennett et al., 2013, 2014).

Some of the literature on the topic of quantifying sediment cascades has been overlooked – see suggestions below. Additionally, a paragraph on the utility of numerical models for untangling controls on debris flows, i.e. relative importance of sediment supply versus transport capacity, and predictive power into the future under climate change would be useful in the discussion.

We appreciate the suggestion for enrichment of the discussion. We have included related work on numerical models in relation to our observations.

Change in the manuscript line 530: Numerical models aiming to assess the role of changes in precipitation, runoff and air temperature on sediment yield and debris flow activity based on climatic predictions suggest a reduction in both sediment supply and debris-flow, while identified sediment input into the sediment cascades as key parameter for debris flow activity (Hirschberg et al., 2021). The presented results exemplify how sediment input produced by a cliff fall resulted in the sediment continuity from the rockface to the outlet, however, the degree of continuity measured as the negative net change decrease considerable during the four years after the cliff fall (Figure 6 right). The results align with recent observations on the key role of sediment supply in landscape connectivity (Heckmann and Schwanghart, 2013), sediment continuity (Joyce et al., 2018) and debris flow occurrences (Bennett et al., 2013; Baer et al., 2017; Hirschberg et al., 2021; Battista et al., 2022). Remaining key questions deals with the interactions of sediment supply and hydrological conditions and the timing and mechanisms, e.g., sediment exhaustion, required to reestablish the pre-event morphodynamics where the rockface is decoupled from the fluvial system. Predictions on the sediment cascades at the Hochvogel required a deeper understanding on the rockfall triggering factors and rates of sediment production, currently object of research. On the other hand, sediment storages resulting from geomorphic processes such as high magnitude slope instability and paraglacial and glacier sediment storages, are often landforms decoupled from the present-day geomorphic process, therefore, studying the conditions that leads to increased sediment transport and reconnection of those systems support the prediction of geomorphic impact under a changing climate.

The start of the introduction could do with some restructuring. Instead of emphasizing several times near the beginning the lack of studies on sediment cascades (there have been quite a few), I would introduce the key processes of landslides, rockfalls debris flows and define the sediment cascade, say what has been done before and then identify gaps, e.g. lack of research on impacts of extreme events on sediment transfer in following years and why this is important e.g. under climate change…Also you could mention some of the technological gaps a bit more, e.g. the challenge of constructing DEMs from aerial photographs in mountainous landscapes (I'm not sure how many studies have achieved this) and therefore unlocking the spatial coverage and historical perspective that aerial photographs offer, the problem of temporal resolution and coalescence when considering photogrammetric records alone, which you target by using seismic records together with photogrammetry.

We strongly appreciated the comment on the introduction. We have restructured the introduction section following the suggestions, expand on the literature review on sediment cascades and emphasize the research gap filled with the publication of this manuscript.

Change in the manuscript line 44: Recent high-magnitude rockfalls in the European Alps raised attention to the potential of catastrophic cascading sediment transport and their societal impact (e.g., Piz Cengalo Bergsturz (Baer et al., 2017)). Sediment cascades define the dynamic process of sediment mobilization and deposition within a landscape that encompasses the continuous travel of sediment particles from their source, through the river network, and to eventual deposition in sediment sinks (Burt and Allison, 2010). Key driven processes to sediment cascades are landslides and rockfalls acting as sources of sediment, and debris flows and sediment transport as mechanisms of sediment remobilization. A handful of studies have focused on sediment cascades on active mountain environments controlled by landsliding (e.g., Benda and Dunne, 1997; Wichmann et al., 2009; Bennett et al., 2013; Heckmann et al., 2016; Clapuyt et al., 2019) as landslides provide and condition the input of sediment volumes into the sediment cascade (Benda and Dunne, 1997; Tucker, 2004). Attempts to better understand decadal to centennial erosion rates and sediment yield at a basin scale include geomorphological observations and spatial pattern analysis (Schrott et al., 2003; Theler et al., 2010), monitoring of sediment fluxes and construction of sediment budgets (Dietrich et al., 1982; Becht et al., 2009; Brown et al., 2009; Heckmann et al., 2016; Joyce et al., 2018), numerical modeling (Wichmann et al., 2009; Heckmann and Schwanghart, 2013; Bennett et al., 2014; Battista et al., 2022), and application of the connectivity framework (Borselli et al., 2008; Fryirs, 2013; Heckmann and Schwanghart, 2013; Bracken et al., 2015). These approaches incorporate both spatial and temporal variability in the operation of the sediment cascades at a diversity of scales, however, they lack key observations on rare and high-magnitude events and the subsequent sediment transfer at high spatial resolutions.

A disturbance in terms of landscape dynamics, is an event fairly extreme that produces a measurable response in the rate or type of processes occurring in the landscape. The system response time to a disturbance is the combination of the reaction time, the time needed for a system to start responding, and relaxation time, the time taken for the system to complete the response and adjust to the change. Short reaction times are of particular concern, while long relaxation times expand the temporal activity of processes that might result in catastrophic societal outputs (Owens et al., 2010) for example, debris flows. Debris flows serve as a link to hillslope-channel coupling by connecting large parts of rock walls to the channel network (Heckmann and Schwanghart, 2013; Bennett et al., 2014). Debris flows rapidly mobilize < 102 to >109 m3 of sediment (Jakob, 2005) along great distances reaching infrastructure and populated areas. While debris flows are typically considered transport-limited processes (Gregory and Lewin, 2014), numerical simulations suggest that continuous delivery of sediment from upslope areas to the location where debris flows are initiated maintains the supply of material available for transport, thus, impacting the persistence and magnitude of sediment pulses in the system (Heckmann and Schwanghart, 2013). Several studies have collected data from massive rock slope failures (e.g., Dussauge-Peisser et al., 2002; Heckmann et al., 2012; Fischer et al., 2012; Krautblatter et al., 2012; Guerin et al., 2020) which are a major landscape evolution process and significantly contribute to sediment yields by sporadic production of a considerable (<103 m3 km2 yr-1) amount of debris (McSaveney, 2002; Korup et al., 2010; Krautblatter et al., 2012). In the coming decades with enhanced rainstorm activity, massive sediment redistribution primarily by debris flows in alpine catchments will be a key hazard and challenge in alpine communities, thus, constraining rates and sediment cascades response times to suddenly increased sediment input by landsliding is paramount for prediction and early warning.

Developments in digital photogrammetry allow the 3D reconstruction of landscapes from images taken using a diversity of platforms (Eltner and Sofia, 2020). Large format digital photogrammetry with (multi-)year temporal resolution and high-spatial resolution (20 cm) covering vast areas, presents a valuable, yet unexplored, data source for geomorphic changes in the last decade. Reconstruction of elevation models from nadir-view images in mountainous landscapes is challenging (Fawcett et al., 2019). Photogrammetric models of steep terrain and pseudo-vertical walls include random errors still difficult to minimize and quantify accurately, yet allow the unlock of a historical perspective and provide insights on sediment cascade spatial patterns in climate-sensitive landscapes (e.g.,(Fabris and Pesci, 2009; Berger et al., 2011; Bennett et al., 2012; Savi et al., 2023). Despite the temporal resolution that results in the coalescence of events, a combination of techniques such as high-resolution seismic investigation provides a potential complement to the photogrammetric record.

This paper reports the massive sediment redistribution triggered by the multi-stage failure from the Hochvogel dolomite peak during the summer of 2016. We evaluate the spatio-temporal morphodynamics at a catchment scale before and after the cliff fall by means of multi-temporal high-resolution aerial photogrammetry between 2010 and 2020. The (multi-) annual photogrammetric surveys provide information on detachment areas and failed volumes. Still the temporal resolution is limited to the recurrence interval between two consecutives surveys, i.e., one to two years. We do not intend to resolve single events but rather decipher rockfall patterns and catchment sediment dynamics after an unusual sediment input to the catchment. Additionally, we complement the understanding of a single rockfall event by the use of high-resolution seismic records (e.g., Hibert et al., 2011; Lacroix and Helmstetter, 2011; Manconi et al., 2016; Fuchs et al., 2018; Dietze et al., 2017a).The combination of seismic information with high-resolution wide-extent photogrammetric reconstructions resulted in (i) identification of the spatial and temporal contribution of rockfall material from the four rock slope catchments that constitute the Hochvogel summit, (ii) quantification of (multi-) annual series of sediment budgets erosion rates before and after the cliff fall evidencing the dramatic inversion of deposition and erosion processes, (iii) time series of sediment cascading and (iv) estimation of the system reaction time and redistribution controls with respect to rainstorm intensity and frequencies. To our knowledge, this paper is one of few publications showing the cascading sediment response of an alpine catchment to a massive rock slope failure. This enables a better understanding of catchment morphodynamic responses to high magnitude rock fall, propagation, and persistence of sediment waves through alpine catchment system and future hazard scenarios where increased sediment availability and seasonal extreme heavy rainfall are expected.

Otherwise, more minor comments throughout as annotated on the attached PDF.

I think my comments constitute minor to moderate revisions to this paper before I think it is ready for publication in ESurf. All the best with your revisions, Georgie Bennett.

Specific Comments

Line 205. What is considered to be false rockfalls and why?.

'False rockfalls' are defined as vertical changes that correspond to poor edge depiction and result in over-elongated areas in the z component in relation to their horizontal area. The slopes at the Hochvogel are mostly highly fractured and horizontally layered, thus, rock falls preferentially follow a pseudo-cubic form.

Change in the manuscript line 197: The filtering processes focus on the identification of 'false' rockfalls, defined as over-elongated polygons in the z component in relation to their horizontal area generated due to poor edge depiction.

Figure 5.b) Magnitude-Frequency curves. Exceedance probability plot?

Thanks for pointing out the misleading y-axis units. We have plotted the yearly cumulative frequency of volumes. This is the reason for the misleading y-axis values that indeed suggest an exceedance probability plot. We have updated the image using the cumulative frequency volumes (m^3) to avoid such confusion. Now, you can see that the y-axis is in the range of 0 to 667 (total number of identified events).

Change in the manuscript Figure 4. Erosional events between 2010 and 2020. i.e., primary and secondary rockfalls grouped by slope orientation. a) slope orientation, cumulative frequency per slope, and sediment production per year. b) Frequency-volume curves for the 667 erosion events on a logarithmic scale.

Line 325. How did you classify failures into different process types?.

We classified the failures by their volume following the volumetric classification based on Whalley, 1974, 1984; Erismann and Abele, 2001; Krautblatter et al., 2012.

Change in the manuscript line 324: However, when considering the contribution of rockfall magnitudes following the volumetric classification based on Whalley (1974, 1984); Erismann and Abele (2001) and Krautblatter et al. (2012)…

Line 378-379. The outlet flood plain was filled with new debris that impacted the dynamics of the riverbed. How? Do you expand on this later on?

Thanks for pointing out this interesting observation. We have included a detailed description.

Change in the manuscript line 378-379: The bi-yearly temporal resolution masks the highly dynamic sediment transport, however, the formation of a terrace of almost 3 m evidence the deposition of at least 2.60 (±0.03) $*10^4$ m^3 after the cliff fall. Field evidence suggests the infill of the outlet flood plain with new debris that impacted the dynamics of the riverbed (Figure 3 Supplementary material). The pre-event channel of the Jochbach River is filled with up to 4 m of material in its deeper part at the end of 2017 (one year after the cliff fall) (Figure 7, morphodynamic zone D). The infill results in a migration of the channel to the center of the Outlet flood plain marked by a discontinuous erosional area in Figure 7 for 2017-2018, and finally the formation of a main channel towards the north, evident in Figure 7 by the continuous erosional pattern for the time interval between 2018 and 2020.

Figure 7. (1), (2), (3) and (4) mark the position of morphological blockages. Theses are not clearly defined and perhaps describe more what theses features area in the caption.

Change in the manuscript Figure 5. Time-series of spatial distribution of erosional (red) and depositional (blue) areas with black arrows as an indication of sediment continuity based on the net changes. (A) rockface (B) upper channelized debris flow channel, (C) widened dispersed debris flow channel, and (D) outlet to the Jochbach river. (1), (2), (3), and (4) mark the position of morphological blockages corresponding to slope changes that promotes deposition thus attenuation in the sediment flux.

Line 396. 'However, a braided channel characterizes the lower outlet sink suggesting an ongoing adjustment to the depleted sediment delivery ratio as a consequence of the cliff fall event.' This is a bit vague and surely the river cares about the total sediment delivery rather than the sediment delivery ratio?

Thanks for pointing out the vagueness of the phrase. Definitely, the sediment delivery ratio masks the unusual sediment delivery to the outlet after the cliff fall. We have combined this description with the changes to the manuscript described above in *Change in the manuscript line 378-379.* You can find a detailed depiction of the changes at the outlet in the images below.

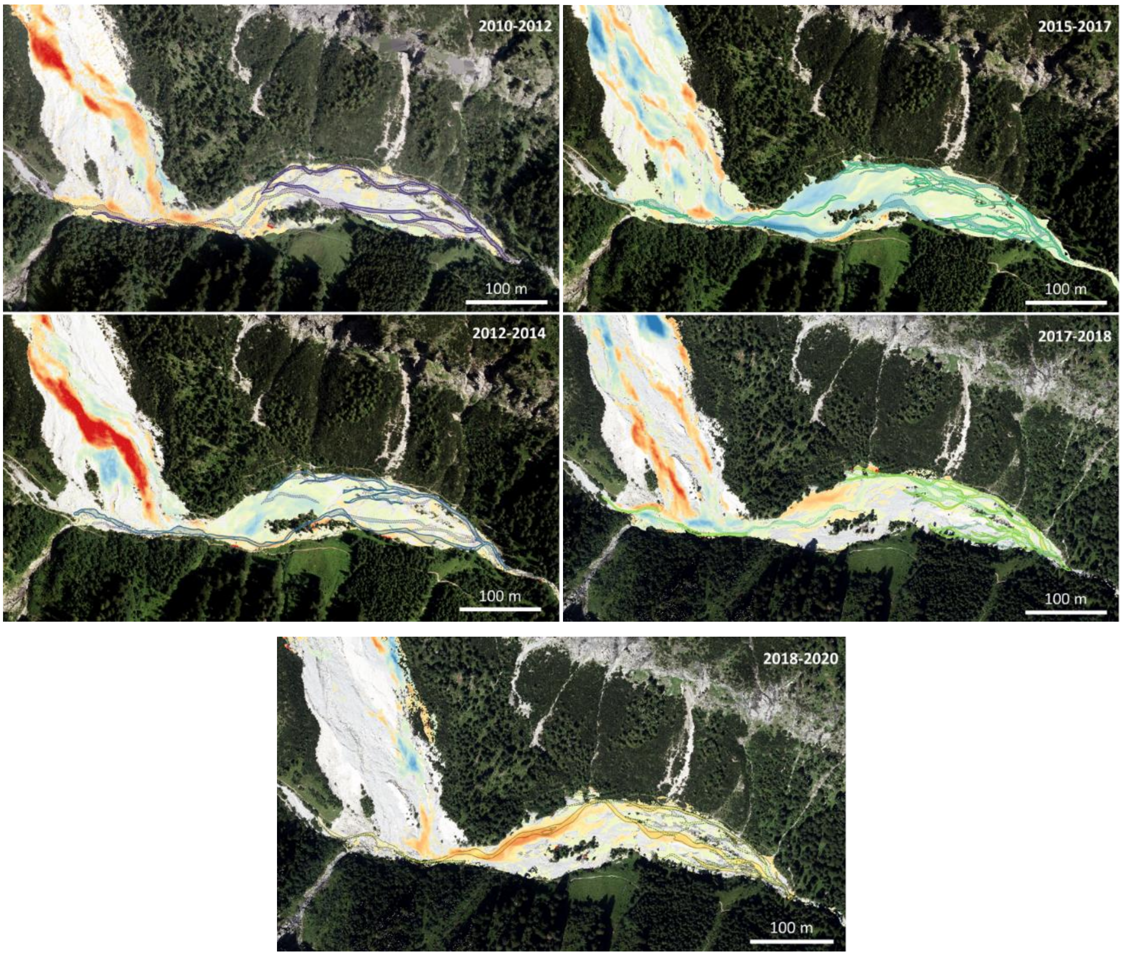


Figure 8. Could you combine figure 6 and figure 8…you could have the total system as 2 extra subplots on top of these segregated plots. The way you have shown the budget here is actually clearer to read than in figure 6.

Thank you very much for the suggestion. I think it is a good idea to combine both plots and homogenize the graphical representation of the sediment budget to improve clarity.

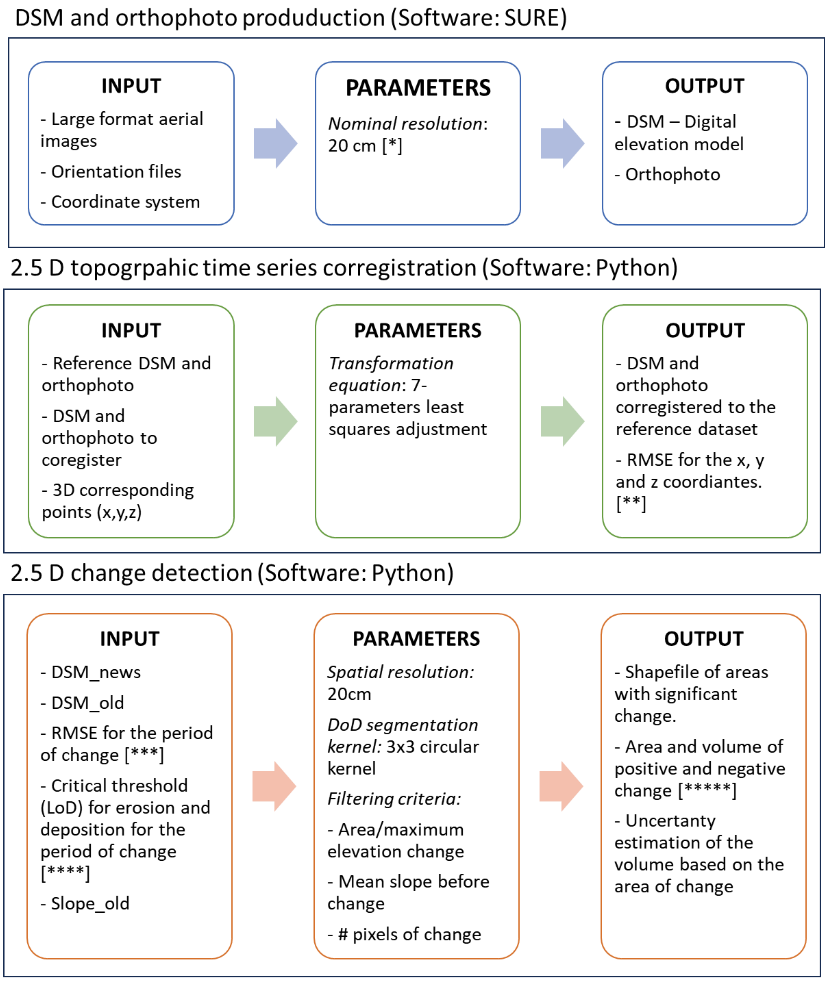
Line 440. I thought that textured surfaces were better for matching algorithms. Is it just to lower slope/less shadowing that lowers uncertainty here?

Thank you so much for pointing out the misleading selection of words. Indeed, smoother surfaces with low texture decrease the performance of matching algorithms, which at any case is our situation. In this phrase 'smooth' aimed to describe the more favorable geometry for the reconstruction, i.e., perpendicular to the nadir-view which corresponds to a lower slope angle to flat topography.

Change in the manuscript line 440: Lower uncertainty is achieved at the widened dispersed debris flow channel and outlet due to the more favorable geometry for the photogrammetric reconstruction., i.e., perpendicular surface to the nadir-view which corresponds to a lower slope angle to flat topography.

Line 441. Is this a workflow used elsewhere or did you design a new workflow? A figure showing this workflow even in the supplementary materials, allowing this to be reproduced, would be helpful.

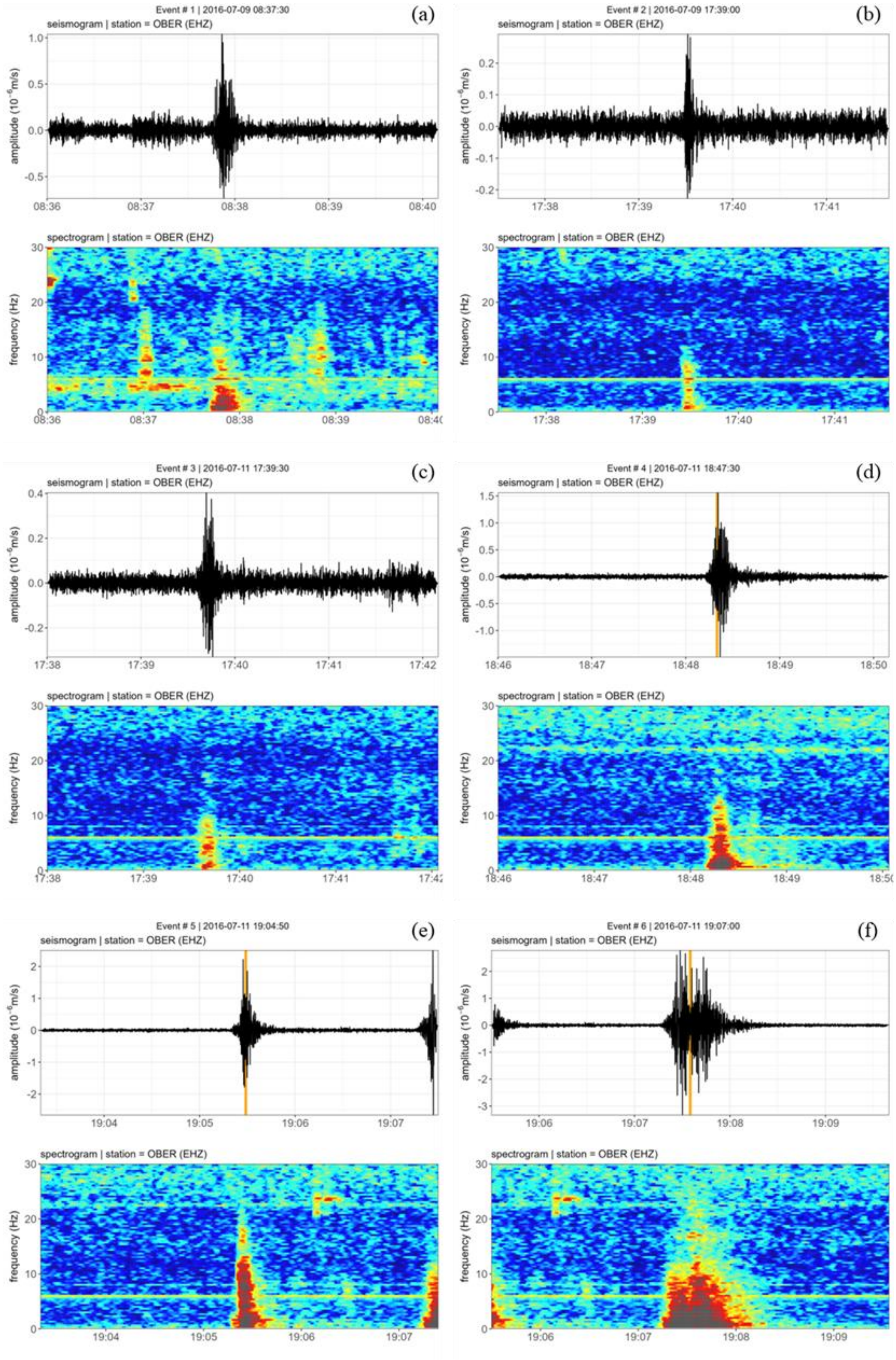
Great suggestion. We designed a workflow that responds to the particular challenges of using nadir-view high resolution aerial imagery on steep terrains. We have clarified this aspect in the manuscript *Change in the manuscript (line 218)* as well as included a figure with the description of the workflow in the supplementary material.



Change in the supplementary material (Figure 1): The workflow proposed for the calculation of volumes of changes in steep terrains using large format high-resolution aerial imagery results from the combination of previously published methodologies, i.e., semi-global matching algorithm (Hirschmüller, 2008), 7-parameter 3D similarity transformation (Akca, 2010), topographic change detection (James et al., 2012; Wheaton et al., 2010), and geomorphic sediment budget (Wheaton et al., 2010a), and the implementation of intermediate steeps, i.e., DoD segmentation and filtering of 'false rockfalls' based on morphometric characteristics, differential critical error, and volume error estimation based on the RMSE between the two surveys of interest. The intermediate steeps respond to the particularities of large format high-resolution aerial imagery acquired by different governmental survey agencies without the purpose of change detection analysis and the limitation of nadir-view acquisition to accurately map steep terrain. A summary of the methodological step is presented in Figure 1. Further research is need to better determine the significant change and the uncertainty on the volume calculation of erosion and deposition on areas with steep and inhomogeneous terrain.

Line 466. A timeseries plot showing these precursory failures across the different seismic stations/photogrammetric records and the final 2016 failure would be helpful to visualize this.

Thank you for the suggestion. We have added an image showing the precursory failures at the OBER station in the supplementary material.



Change in the supplementary material (Figure 5): Figure 6. 2016 cliff-fall precursory sub-event. Top image displays the amplitude of the seismic signal. Bottom image displays the spectrogram covering all frequencies up to 30 Hz. a) and b) are events 1 and 2 recorded the 09.07.2016, while c), d) and e) are recorded the 11.07.2016 with decreasing time between events until the final detached (f) sub-event 6, at 19:07 h.

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