Planform river channel perturbations resulting from active landsliding in the High Himalaya of Bhutan

Author response to comments from both referees

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Content

Color code
black - original comment from referee
blue - author response
green - text which will be added to the revised manuscript

1. Response to comments from Anonymous Referee #1

The manuscript presented by Palézieux et al. deals with the quantification of lateral channel migration induced by large creeping landslides. They used Fourier transform to separate natural channel amplitudes from landslides-produced variations. Using the inventory of Dini et al. (2020), they show that a large majority of creeping landslides cause lateral channel migration. Furthermore, they hypothesize that creeping landslides are primarily triggered by migrating knickpoints. Under this assumptions they back-calculate the timing of the onset of creeping landslides showing that a phase of activity alternated with a phase of slower movement/inactivity.

Lateral channel migration produced by creeping landslides is not very well quantified and the usage of Fourier transform a somewhat unique approach. Combined with the approach to constraint rates of activity the manuscript shows enough originality to be published.

1.1. Thank you for taking the time to read our manuscript. Your detailed comments have helped us improve a number of key aspects of the manuscript.

However, the authors should modify, clarify and/or reassess a couple of points. The manuscript contains a few assumptions which have to be discussed more in detail. The authors mention that seismic activity in the study area is low. This ob- servation is explained in the introduction. Hence, seismic activity is not responsible for triggering creeping landslides. So the authors assume now that knickpoint migration is mainly responsible for triggering creeping landslides. But what about hydrological and climatic influences? What about lithological weak point? Furthermore, migrating knickpoints are primary produced by seismic activity. How do the authors explain the knickpoints in the first place? Especially influences of climate as well as lithology have to be discussed more in detail.

1.2. Thank you. We agree that additional insight into the potential impact of regional geology and tectonics on knickpoint and landslide formation is warranted. However, we feel the discussion on landslide triggering is not relevant to this study. We plan to address these two topics in the following additions to the text (L165):

“The collision of the Indian plate with Asia generates uplift rates of 2-12 mm/yr (Burbank et al., 1996; Wesnousky, 1999, Lavé and Avouac, 2001) and shortening rates of 20-23 mm/yr (Lavé and Avouac, 2000; Burgess et al., 2012) along the Himalayan Arc. Geodetic measurements indicate there is little to no aseismic slip or creep along the Arc, suggesting the boundary is characterized by a strongly coupled fault system in which accumulated stresses are periodically released by large earthquakes (Stevens and Avouac, 2016). Recent studies suggested a several hundred year ‘information gap’ rather than a ‘seismic gap’ to be the culprit of the apparent seismic quiescence at the latitudes of Bhutan (Berthet et al., 2014; Hetényi et al., 2016). Two major events have been recorded in the region, one around 1100 A.D. with a magnitude close to M9 (Lavé et al., 2005; Kumar et al., 2010) and in 1714 A.D. with an estimated magnitude of M7.5–8.5 (Hetényi et al., 2016; Berthet et al., 2014; Le Roux-Mallouf et al., 2016). Results from previous authors indicate that the majority of horizontal shortening is accommodated by the Main Frontal Thrust (MFT) (Vernant et al., 2014), a finding supported by observations of fault offsets of several meters recorded in fluvial terraces on the MFT at the latitudes of Bhutan (Berthet et al., 2014; Le Roux-Mallouf et al., 2016). Long et al. (2019) and Adams et al. (2013) include a number of normal faults on geological maps covering our study region, suggesting a possible switch from compressional to transtensional, or extensional tectonics between the MFT and the northern border of Bhutan. Together, these insights indicate that our study area is likely to be subject to earthquake-induced ground accelerations that may trigger small- to medium-sized landslides, and temporarily reactivate larger slope failures. However, the majority of convergent strains are accumulated on the MFT, and as such, it is unlikely that knickpoints observed in our study region are the result of emergence of local thrust faults."

(R1: L288, L314, R2:L80, 172, 315) We address knickpoint formation and propagation in this study region in a subsequent manuscript. In that study we evaluate the potential for climatic drivers to affect knickpoint formation, with uplift dominating topographic evolution during cool, dry climatic intervals, and knickpoint retreat dominating during warmer, humid periods. This is similar to that identified in the European Alps by Petit et al. (2017), and Leith et al. (2018). We use methods from river profile analysis in combination with field observations derived from large sedimentary plains in the center of the study region to estimate the location of maximum fluvial incision at the end of the current interglacial. We find the maximum upstream location of interglacial fluvial incision is projected to remain within the alluvial infill of the Inner Valley within the Wong Chhu basin, while erosion in the Puna Tsang Chhu basin likely propagates past the alluvial plains, driving baselevel fall in the Northern Valleys. We will include a more general discussion of potential climatic drivers in the revised manuscript.

1.3. To illustrate the spatial relationship of the knickpoints with respect to the lithological boundaries, we have added a geological map (Fig. 1) based on Long et al. (2011), to which we add the boundaries of the geomorphic domains (based on Norbu et al. (2003)), as well as the river network and the knickpoints we adopt in this study. We will add the following text to the discussion (R1:L314, R2: Fig 3):

"While several knickpoints are located within 4 - 5 km of the lower boundary of the South Tibetan Detachment System (STDS), which marks the contact between the Tethyan Himalayan Zone and the Greater Himalayan Zone, the apparent spatial association is likely accentuated by the relatively flat geometry of the STDS at these locations (the elevation of the contact at all knickpoint locations varies by less than 300 m over a contact length of 30 km) (Gansser, 1983, Long et al., 2011). The sedimentary units of the Chekha Formation overlying the STDS are indicated to have both a lower metamorphic grade than the underlying metasediments, with peak temperatures reaching between 500 - 600 ℃, while the underlying Greater Himalayan units likely reached 700 - 800 ℃ (see Long et al. 2019 and references therein). Combined with a significant increase in shear strain indicators in rocks above the SDTS (Long et al., 2019), the rocks in the region of, and structurally overlying, the STDS are likely to be more erodible than the metasedimentary units underlying the detachment (i.e. downstream of the contact). As such, any knickpoints passing across the contact may be expected to diffuse as erosion accelerates upstream, rather than be stalled and accentuated on the boundary."

1.4. The large scale of the landslides discussed in this manuscript means that they can be considered to be insensitive to triggering by seismic, climatic, or hydrological influences. Such features are almost always associated with large-scale (10's - 100's of meters), long-term (10 - 100 kyr) landscape perturbations (e.g. Agliardi, 2013), and while once initiated, displacement rates may vary with e.g. groundwater levels, a persistent long-term change will be required to alter the boundary conditions (e.g. permanently raise the groundwater table in a >1 Mm3 landslide) enough to generate an observable geomorphic response using our methods. We will add the following text to the introduction (R1: L86, 88/89, 92, 363, R2: L150, L411):

"In this study, we investigate the co-evolution of large creeping landslides and major river channels in NW Bhutan. The scale of the landslides addressed in this study have areas ranging between approximately 0.03 km^2 and 3 km^2, and as such, can be considered typical of large slope instabilities observed in mountainous environments (Crosta et al. 2013; Agliardi et al., 2013). Such large landslides have been shown to modify topography at the scale of the mountain flank, and shear displacements commonly extend to depths of several hundred meters (Hungr et al., 2014; Bonzanigo et al., 2007; Agliardi et al., 2013; Handwerger et al., 2021). While little absolute dating evidence exists, it is generally accepted that the initiation of many such features in the European Alps pre-date the last glacial maximum (e.g. Tibaldi et al., 2004, Leith et al., 2018), while the onset of the present-day interglacial likely both reactivated existing large features, and led to the development of new ones in response to changes in e.g. valley floor elevation, confining stress, thermal regime, and groundwater levels (e.g. Graemiger et al., 2020, Riva, 2018, Leith et al., 2018, McColl, 2013). Present-day displacement rates for such large landslides are difficult to constrain, as displacement fields tend to be strongly heterogeneous, and while local observations of rates can be on the order of 10's of mm/yr (e.g. Teshebaeva, 2019), it is more common to find displacement rates on mapped large landslides at, or below the accuracy of modern observation techniques (~ 1 mm/yr, e.g. Dini, 2019a). Combined with morphological observations, monitoring of such slope instabilities indicate that displacements can best be characterized by a combination of long-lasting activity, episodic reactivations, and/or continuous slow creep (e.g. Crosta et al. 2013). Accelerations up to rapid velocities (m/hour, (Hungr et. al., 2014)) or greater may be expected to eventually lead to catastrophic failure, however, based on morphological and sedimentary evidence we do not expect many, if any of the landslides in our dataset have achieved such rates, and more likely creep at similar rates since their formation.

Numerical models seeking to track the development of large landslides in similar settings typically implement plastic constitutive models that combine a prescribed progressive strength reduction (attempting to capture the progressive weathering of a rock mass), with a shear-strain weakening of frictional and cohesive properties (representing mechanical rock mass damage). Although such boundary conditions will ultimately lead to global slope failure as material strength is allowed to reduce below that required to maintain topographic stresses, associated failures will tend to propagate from the most highly loaded slope toe, to the crest. This results in both an anomalously deep sliding surface, and a short interval between initiation of damage at the toe and global slope failure, which is inconsistent with observations of in-situ stepping landslides in the landscape today. Implementing a progressive removal of mass within the associated valley, either through the removal of a glacier load (e.g. Riva et al., 2018), or erosion of bedrock in the valley floor (e.g. Hou et al., 2014), has the effect of addressing both of these issues by progressively loading hillslope elements close to the upper surface of the buttress, and effectively migrating a damage zone down the hillslope. Such elasto-plastic constitutive models typically adopt model steps as a proxy for time, modulated by the rate of prescribed buttress removal, or strength degradation (e.g. Spreafico et al., 2020), and as such cannot truly capture time-dependent behaviour (including the onset of failure, and creep rates). Nonetheless, these observations that such large landslides require a) progressive weathering, b) strain-dependant damage, and c) progressive buttress removal indicate that isolated contributions from climatic or groundwater changes, weak lithology, or seismic activity cannot explain the presence of landslides discussed in this manuscript."

Another point are the methods, which seems to contain a few flaws. Especially when calculating the planform channel offset DL. The calculated channel axis, probably derived from the DEM, is crossing the hillslope (Figure 6). Resulting in negative values in the distance distribution of the landslides. Especially the distance distributions (Figure 6 bottom) pose some questions. Please, check the comments in added in the supplement file.

1.5. We realize that we have not clearly addressed certain properties of the distance calculations. We have modified figure 6 (Fig. 2 in this document) to better illustrate the two types of distance distribution and we will rephrase the corresponding lines as follows (R1:L243, L22-230, L338, R2: L221, L416, L335, L419, L243, L335, L416):

"We evaluate the amplitude of river channel sinuosity (D_{va}), and landslide impingement into the valley (D_L) in a reference system described in terms of the valley axis. In this case, the x-coordinate of the landform (channel or landslide) is determined by the upstream distance from the rangefront, while the y-coordinate is determined with respect to the valley axis (e.g., positive on the true left of valleys, negative on the true right). Since the Fourier transform measures the quantity of each frequency component in terms of peak-to-peak amplitudes, the absolute position of the zero-datum has no impact on our derived amplitudes of sinuosity. To calculate landslide impingement, we first derive the median distance to the river channel by reprojecting our landslide features in a coordinate system relative to the river channel (Figure 2). We then compare this to the median distance derived from the reference valley axis coordinate system, each normalized by the minimum distance to the channel, and the y-position of the lowest cell in the landslide, respectively, in order to align the toe of the landslide (assumed to be the lower ⅓ of the landslide mass) in the two coordinate systems. For cases in which D_L is positive, the curvature of the landslide toe with respect to the valley axis exceeds the amplitude of channel sinuosity with respect to the landslide toe (i.e. the landslide offset dominates the channel form), while zero, or negative values of D_L indicate the landslide toe is relatively straight with respect to the channel, and the river has likely abandoned the landslide toe. This metric allows us to directly compare the amplitude of sinuosity derived from the Fourier transform, with the apparent landslide impingement described by the complex 3D geometry of the landslide toe, without users having to manually locate features on the landslide, for example, the upstream and downstream corners, or the point of maximum displacement (Figure 2). We recognise this is a complicated approach, however, as quantifying this relationship is entirely novel we feel it is important to provide an objective measure to consistently capture this hillslope - channel interaction within a range of mountainous landscapes."

Especially the discussion needs further improvement since a lot of the written paragraphs belong to the Methods or Results. Rarely any of the Results are put into perspective with previous research.

1.6. We will reorganize the methods and results sections, and include a more in-depth comparison of our results with those presented in previous research. In particular:

- We present a new method to specifically evaluate the amplitude of channel sinuosity. We will discuss this with reference to previous methods to characterize path length sinuosity (e.g. Tarboton et al., 1988), and physical controls on planform curvature (e.g. Stark et al., 2006).
- (L93): While we believe our assumption that knickpoint migration leads to the initiation of large creeping landslides is intuitive, few authors have directly investigated such a relationship. We will discuss our findings with respect to fluvial incision-induced landsliding in Taiwan, Japan, and Papua New Guinea (Tsou et al. 2014, Hou et al., 2014, Hovius et al., 1998), and associated present-day relief in the Himalaya (Blöthe et al., 2015, Korup et al., 2010).
- We will add the following discussion (L25): "Aside from a limited study by Othman and Gloaguen (2013), we believe this is the only study to quantitatively evaluate the long-term interaction of fluvial channel morphology with deep-seated creeping landslides. Notably, Korup (2005) suggested that deep-seated creeping landslides can lead to "diversion of channels around deposits, causing incision of meandering gorges.", while Korup (2006) noted that an increase in weathering and secondary instability on large landslides tends to produce more subdued hillslope morphology, and may reduce rates of long-term fluvial incision. Korup et al. (2006) were able to confirm these hypotheses, at least over Holocene timescales, by quantifying the effects of river blocking rock slides on the position, and cross-sectional geometry of adjacent river channels, however, these observations are limited to events that fail dynamically, and the implications for longer timescales, or creeping instabilities are not clear. Our results therefore contribute new tools to extend the current state-of-the-art, and aid the quantification of both landscape evolution, and large creeping landslide activity from geomorphological datasets."
- We will include the following discussion (R1: L373): "Our unique approach allows us to suggest (with some assumptions) the initiation of the oldest landslides currently observed within our study area may occur soon after the MPT. Although this is consistent with the findings of Korup and Schlunegger (2007), who suggest giant landslides may be features of mountain belts at all stages of evolution, the assumed ages presented in this manuscript are significantly greater than those currently reported in literature, which, to date either constrain maximum ages as post-LGM (e.g., McCalpin, 1995, Agliardi et al., 2013), the last interglacial (e.g. Tibaldi et al., 2004, Baroň et al., 2013), or in a unique case in the Polish Tatra mountains 280 ka (Szczygieł et al, 2019). Constraining the timing of deep-seated landslide initiation, or long-term displacement history is, however, notoriously difficult, as heterogeneity due to (for example) parasitic slope failures cause problems for the interpretation of dating evidence. In addition their position in active mountain belts means that glacial activity commonly overprints any evidence for displacement prior to the LGM. We see some correlation between the density estimate for landslide ages, and timing of marine isotope stages (Figure 3), indicating landslide initiation may be at least partly controlled by long-term climatic influences. By providing evidence to suggest that the

initiation of some large creeping rock slope instabilities may exceed most previous estimates by an order of magnitude, we hope to inspire new approaches to better constrain conditions controlling the onset of instability in such environments (e.g., by numerical modelling, improved geomorphological analyses, or dating of speleothems).

Regarding the general structure: The introduction is too long (10 pages). Therefore, I would recommend to revise how necessary certain explanations of methods are (e.g. lateral channel migration is explained in the Introduction as well as in the Methods) and if there is the possibility to add another section "Regional setting".

1.7. We will restructure the introduction, remove redundant sections (e.g., L56, 114), and move sections relevant to the technical aspects of our study to the methods section. We will create a separate section characterizing the study area and will focus the geological description more closely on NW Bhutan (see above 1.3). In line with your comments to line 314 and figure 2 we have added a geological map showing the spatial relationship between the lithological contacts, geomorphic domains, glacial overprint, river network, and knickpoints (Fig. 2).

Regarding the sentence structure and usage of scientific terminology: Even though methods are explained in quite the detail, often terminology is used without proper definition and in varying contexts. Examples are mentioned in the technical details. Furthermore, sentence structures are often too long and too complicated which results in grammar mistakes, sometimes leading to sentences which are hard to understand.

1.8. We will reformulate the methods section to be more precise with respect to terminology, units, and equations and will adapt the terminology throughout the manuscript accordingly.

2. Response to comments by Laure Guérit

The authors propose to develop a measurement of the lateral deviation of river channel due to creeping landslides. They work on a previously published catalogue of creeping landslides in Bhutan and they show that most of these landslides are associated with rivers that deviate from a ´normal˙ path. To go further, they propose that creeping landslides are associated with migrating knickpoints that are able to destabilise hillslopes. In addition to the landslide offset, they thus estimate an age since the knickpoint has passed and build a rate of channel offset which they interpret in terms of landslide/channel dynamics through time.

2.1. Great summary, thanks!

The approach is interesting and supported by very clean and elegant figures. I think it is of interest for publication but the manuscript requires thorough revisions. I do not see any major issue with these revisions so I'm confident the authors will be able to address them.

2.2. Thank you very much for your input. We hope the following responses support your interpretation.Thank you also for your constructive and detailed comments. We agree with your remarks regarding the structure, terminology, and precision of language of our manuscript and have noticed that we have not well presented our working hypotheses and line of reasoning.

First of all, I think that the manuscript should be reorganized as currently, all the sections are mixed. The introduction is extremely long and does not present clearly the context. The geological setting must be expanded and should be a separate section to ease the reading.

2.3. (R2:L45, L58) We aim to restructure the introduction such as to detail our assumptions and hypotheses thoroughly and concisely (see also paragraphs below). We will remove redundant paragraphs/lines (e.g. L56, 114) in order to present only the necessary previous research without anticipating information belonging to the methods chapter. We will move the characterization of the study area to a separate section following the introduction and focus the geological description more closely on NW Bhutan. In this context we will also add a geological map (Fig. 1) with the river network and the outlines of the geomorphic domains and add the geomorphic domains as suggested to the long profiles.

This is similar to a comment by Reviewer 1. for further details, please see our response 1.3.

In line with your comments we will homogenize the methods section with respect to the level of detail with which each method is presented (e.g., L110), remove repetitions (e.g., L261), and correct the commented equations, units, and terminology (e.g. Fig. 5, L244, 251, 254, 255, 272 (Eq. 13), 278).

More importantly, a lot of results are within the discussion, which does not really discuss the results. This is a bit confusing and it makes the manuscript quite difficult to follow. As a consequence, it is difficult to get a clear idea of the results.

2.4. (R2: L356, L396) In the results section we will expand the pointed-out statements (e.g. lines 307-312 and 316) and include those parts of the discussion, which are more suited to be presented at this location. We will rephrase and restructure the paragraphs for flow of reading and clarity of argumentation. We agree that a thorough discussion of our results and particularly the integration with respect to previous research is lacking and will rewrite the chapter accordingly. We will reformulate the conclusions to be more explicit and coherent where commented and to be in line with the discussion.

This is similar to a comment by Reviewer 1. For further detail, please see Response 1.6.

Second, some working hypothesis must be better explain and/or justify. For example, the authors mention that tectonic activity is very low and that it can not be responsible for the landslides. They thus associate landslides with migrating knickpoints. But then, what is driving these knickpoints ? And what about climate and lithology ? I identify other aspects that must be clarified in the attached annoted document.

2.5. We agree that we have not addressed our assumptions regarding the origin and type of knickpoints in our study area in detail (comments to lines 150, 172, and 396). We will add additional text to address this in the revised manuscript:

This is similar to a comment by Reviewer 1. For further detail, please see response 1.2.

Third, I have some issues with the units and names used by the authors. A striking one is the designation of delta chi, a measure in meter, as a time. This is detailed in the attached document.

2.6. We had previously discussed this point, and felt ‘normalized’ would help readers unfamiliar with chi plots grasp the concepts we present. However, at your suggestion, we have changed our terminology for referring to chi from ‘normalized time’ to ‘interval’. We have also corrected equations 13 and 14, where the units should now be correct (R1: L346):

Eq. 13: $\tau = \frac{\chi}{K A_0^m} \chi$

with K: erodibility [$m^{0.9}$ a^{-1}], A_0 the reference drainage area, m = 0.45, and n = 1.

Eq. 14: $R = \frac{D_L}{\Delta\tau} = \frac{K A_0^m D_L}{\Delta\chi}$

with D_L: planform channel deviations [m].

We have noticed that there is an error in the terminology of the different distance distributions, which we will correct in the revised manuscript. We have also updated figure 6 (Fig. 2 in this document) to better illustrate the difference between the distance distributions with respect to the original channel and with respect to the valley axis.

Finally, there are a lot of vague terms like process, low, insights, and of multiple ways to say the same thing (for example comment on Figure 5). Please check for consistency and simplify as much as possible. I also notice minor corrections to do (typo, missing information, missing captions, etc). Again, it prevents me from getting a clear idea of your objectives and results so I really suggest the authors to check the manuscript carefully and to be more explicite to gain in clarity and strength.

2.7. We have added two paragraphs to the introduction of our manuscript, which we would like to present here to better explain our working hypotheses regarding the formation and long-term evolution of large creeping landslides with respect to the knickpoints in our study area (comments to lines 58, 80, 123, 150, 172, and 441).

This is similar to a comment by Reviewer 1. For further detail, please see Response 1.4.

Figures

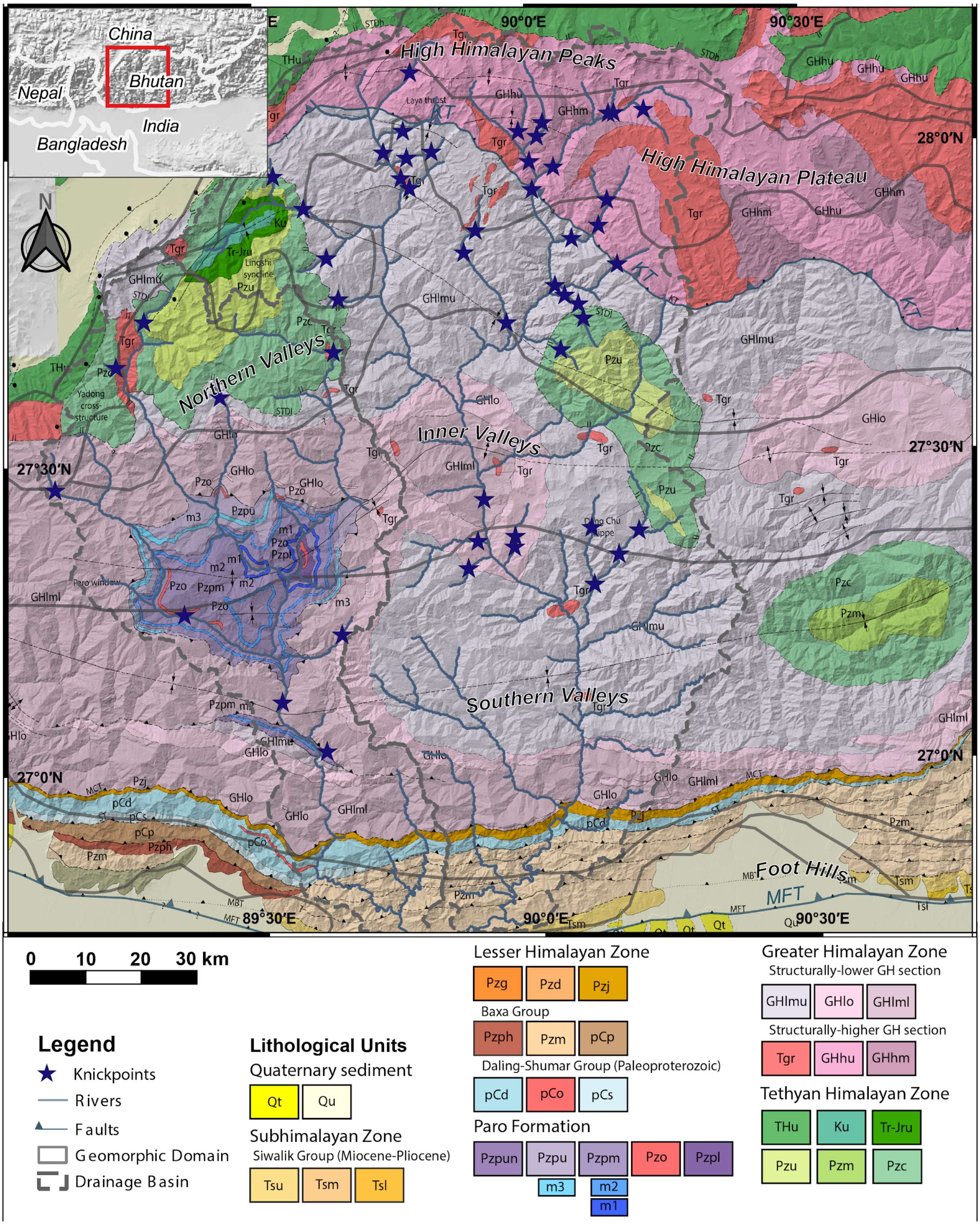

Figure 1: Geological map of NW Bhutan (Long et al., 2011, and references therein) with the two major drainage basins (dashed grey lines), geomorphic domains (thin grey lines, Norbu et al., 2003), mapped moraine ridges (orange), the river network, and the knickpoints (major: dark blue, minor: light blue).

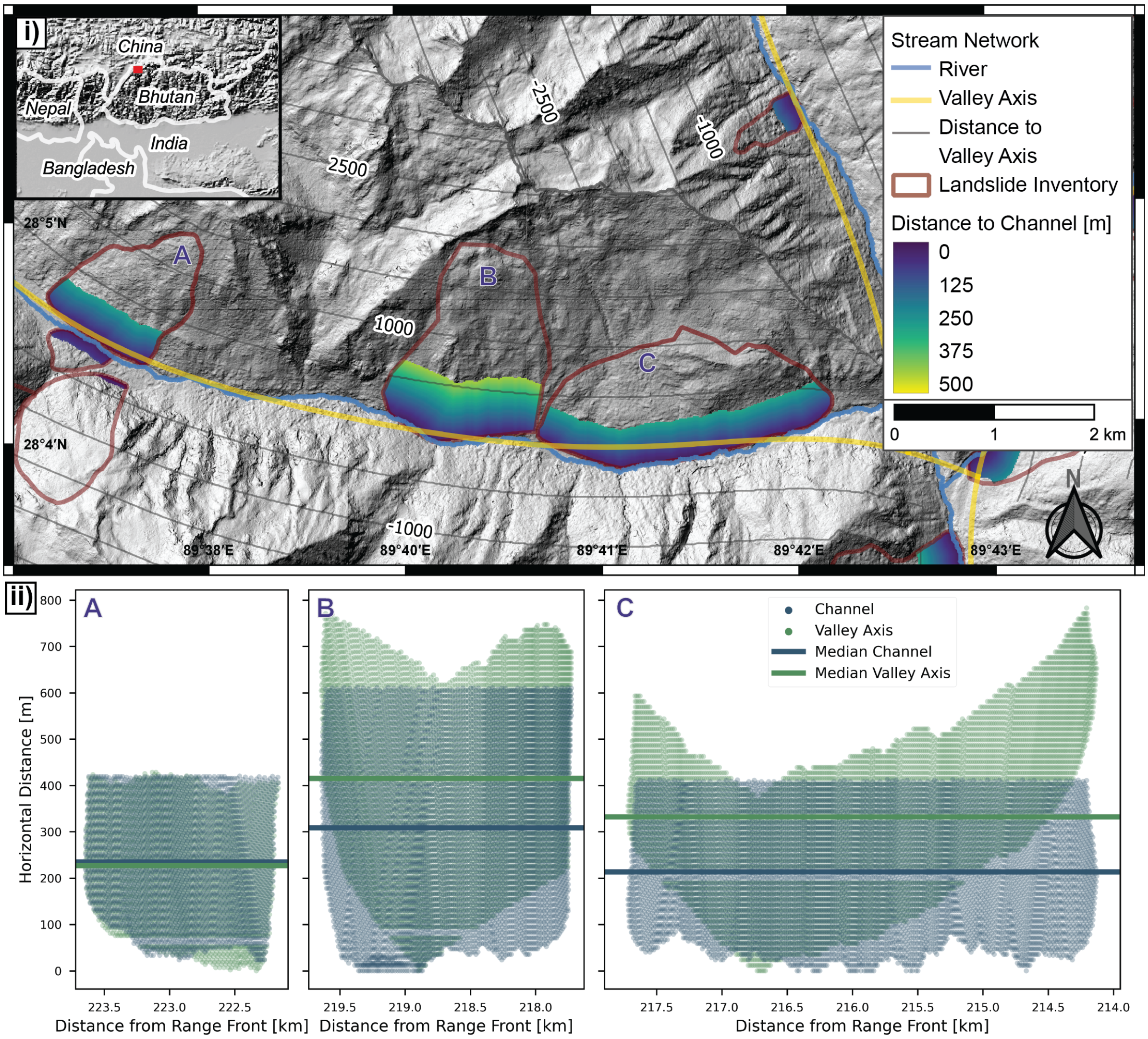

Figure 2: Examples of distance distributions for three landslides. Top: Distance away from the channel within the landslide polygon (red: outline of the entire polygon, color gradient: lowest third of the polygon). The landslide outlines are based on Dini et al. (2019b), the hillshade was derived from JAXA (2017). Bottom: Distance distributions of each pixel in the lowest third of the landslide polygon, with distance along the river network from the range front on the x-axis and the horizontal distance on the y-axis (blue: distance with respect to the original channel, green: with respect to the valley axis).

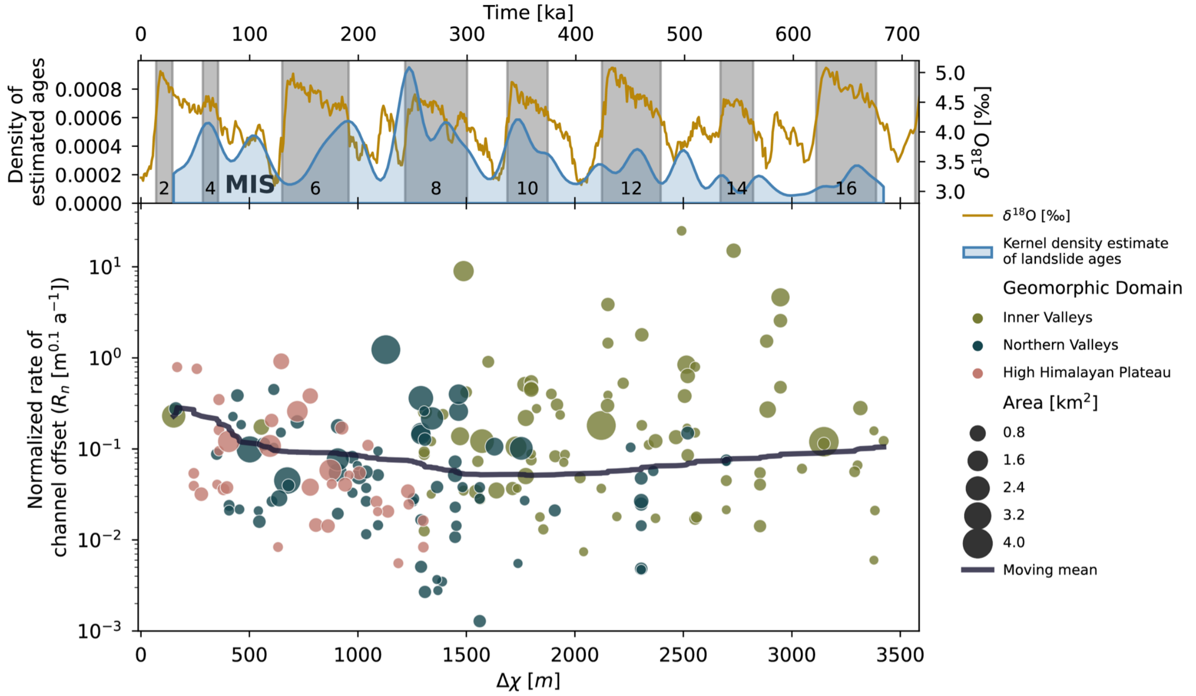

Figure 3: Landslide activity as a function of time. a) Normalized rate of channel offset R_n as function of Δχ [m], the interval between the landslide and the associated knickpoint. The size of the markers is scaled to the landslide area. Color represents the geomorphic domain. The dark grey markers correspond to the moving mean over the data. χ is converted to τ [ka] (K = 10^{-5} $m^{0.1}$ yr^{-1}, n=1, m=0.45) with Eq. 13. and can then be plotted on an axis of time (top axis).

b) Kernel density estimate of the estimated landslide ages (blue line) with the oxygen isotope variation (orange) and the marine isotope stages (MIS). Grey shaded areas (high $\delta^{18}O$) correspond to colder, glacial periods, white areas (low $\delta^{18}O$) to warmer, interglacial periods (Lisiecki and Raymo, 2005).

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