Reviewer 1

The manuscript provides a comprehensive and data-rich investigation of periglacial mass movements in the Zelunglung catchment, Eastern Himalayas, and presents the first long-term analysis of sediment dynamics in this seismically active region since the 1950 Assam earthquake. The authors combine satellite data, field surveys, UAV imagery, and long-term meteorological and seismological data. The study offers a valuable case study on the interaction of tectonics, climate, and geomorphological processes in high mountain regions. The manuscript features a high diversity of data. The use of 30 satellite image datasets (1969–2022), UAV surveys, and field data is of great value. The methodology for identifying non-vegetated areas (NVA) is transparent and mostly comprehensible. The contextualization of the five documented events (1950, 1968, 1972, 1984, 2020) in relation to seismic and climatic changes allows for well-founded conclusions on their temporal evolution. The integration of satellite data, UAV data, visual interpretation, field measurements, and literature sources leads to robust results.

We are grateful for the reviewer's positive recognition of our manuscript. And we are very grateful for various lines of constructive criticism which were very helpful in improving analysis and the manuscript. Point-by-point replies can be found in the following:

(Please note that all references in this response, including line numbers, section titles, and figure/table numbers, are based on the Manuscript_trackchanges.docx file, so that the reviewer can clearly locate the revisions and compare them with the original content.)

1. **Quantification of Uncertainties:**
   a) **The uncertainties in deriving the NVA as a proxy for sediment volume could be treated more rigorously using statistical methods. A quantitative error assessment is missing.**

- **Author's response：**

We greatly appreciate this valuable comment. We fully agree that a rigorous statistical treatment would strengthen the reliability of the NVA as a proxy for sediment volume. The sediment volume of debris flow may be influenced by many factors, such as fan area, fan slope and sediment thickness. However, the scarcity of long-term debris-flow volume measurements in our study region limits the feasibility of developing a robust statistical model. Borehole method can give the accurate estimation of thickness, but is too expensive for our study. It should be pointed out that accurate estimation of sediment volume from the NVA is not the purpose of this study. Our emphasis lies not on the absolute volume of debris flows but on their temporal trends. Although uncertainties remain, the overall temporal trends of the two quantities are similar. Consequently, this study employs an approximate alternative approach, wherein the fluctuation in debris flow volume is inferred from changes in the area of the accumulation fan. Actually, many previous studies consider debris flow volume is empirically a function of the accumulation area (e.g. Iverson et al. (1998)). We acknowledge that the uncertainties in deriving the NVA as a proxy for sediment volume and could be treated more rigorously in future study, and we have highlighted this issue in the revised manuscript.

- **Author's changes in manuscript:**

We have added a new discussion section to emphasize both the validity and the limitations of using NVA as a proxy:

5.4 Limitation

Previous studies have shown that debris-flow volume is often empirically related to the extent of the inundation area (e.g., Iverson et al., 1998), which supports the use of NVA as a proxy for sediment volume. Multi-periodic periglacial debris flows are strongly associated with variations in the NVA of the alluvial fan, suggesting that NVA can capture long-term trends in debris-flow activity. In practice, however, the NVA includes a fixed portion of the area inundated by the main river and is therefore slightly larger than the actual depositional area caused by debris flows. Technically, the contribution of the main river to NVA cannot be entirely excluded. Nevertheless, the riverbank line remained stable from the 1980s to the 2010s, during which no large periglacial debris flows occurred (Figs. 11b and c; Zhang and Shen, 2011). It is therefore reasonable to assume that variations in river water level have little influence on changes in NVA, and that NVA primarily reflects the relative volume trends of sediment transported by debris flows.

Despite these considerations, several uncertainties remain in using NVA as a volume proxy. The absence of systematic depositional thickness measurements prevents direct conversion of NVAs into absolute debris-flow volumes, so NVA only reflects relative fluctuations rather than precise values. Delineation errors in historical imagery, particularly in earlier black-and-white aerial photographs with limited tonal contrast, may affect accuracy. The spatial resolution of imagery also varies markedly across decades, which inevitably affects the precision of NVA delineation and may lead to scale-dependent biases when comparing different periods. Error ranges for NVA were plotted to illustrate these uncertainties (Fig. 12d), and although they cannot be entirely eliminated, they do not alter the main analytical results. Moreover, the empirical relationship between inundation area and debris-flow volume may vary with local geomorphic and hydrological conditions, such as fan slope and gully confinement, further complicating volume inference and limiting the applicability of uniform statistical error models.

While accurate estimation of sediment volume from NVA is beyond the scope of this study, we acknowledge the associated uncertainties, which warrant more rigorous treatment in future study. Future studies that integrate high-resolution LiDAR, UAV photogrammetry, or borehole surveys with field-based volume measurements could provide more robust statistical assessments of the NVA–volume relationship. The application of dense stereo-pair techniques for DSM extraction from historical and modern satellite archives also has considerable potential to provide three-dimensional constraints on sediment thickness and deposition, thereby improving the translation from inundation area to sediment volume.

b) **The translation of NVA into actual sediment volumes should be discussed more critically.**

- **Author's response：**

We agree with the reviewer that NVA cannot be directly translated into absolute debris-flow volumes due to the absence of depositional thickness data. In this study, we use NVA only as a proxy to reflect relative changes in debris-flow activity through time, rather than to estimate exact sediment volumes. We have added a Limitations section to clarify this distinction more explicitly and emphasize the assumptions and uncertainties underlying this approach.

- **Author's changes in manuscript:**

We have added a new discussion section (5.4 Limitation) to emphasize both the validity and the limitations of using NVA as a proxy:

c) **For the differential elevation models shown, stable areas should also be presented, and the DoD values in those areas should be critically discussed. At minimum, the arithmetic mean, RMSE, maximum value, minimum value, and standard deviation should be reported.**

- **Author's response：**

Thank you for your suggestion. We have improved this part in the first revision. The reconstruction and differencing of DSMs are carried out in Pix4DMapper and Arcmap10.8. Since we did not deploy ground control points during drone photography, we generated DSM and DOM of September 9 in Pix4DMapper, and then selected 20 relatively stable points that were not affected by debris flow events as control points in Arcmap with DOM of September 9 as reference. These control points were then used in Pix4DMapper to generate the September 11 DSM and DOM. To determine the uncertainty for our UAV DSMs of difference (DoD) differencing result we follow methods outlined in Shugar et al. (2021). We identified a series of fifteen stable areas on old debris flow terraces adjacent to the valley floor (Mainly roads and unseeded farmlands) and retrieved the standard deviation of DoD values within these areas and used these to estimate a two-sigma DoD uncertainty. The resulting elevation uncertainty was ±0.493 m, corresponding to a DoD volumetric uncertainty of $\pm 1.85 \times 10^4$ m³ (Line 422). Owing to the large extent of the study area, and to avoid redundancy while presenting geomorphic changes in the debris-flow impact zone more clearly, we did not include the results from the stable areas in the manuscript figure, but we provide them here in this response (Fig. S1).

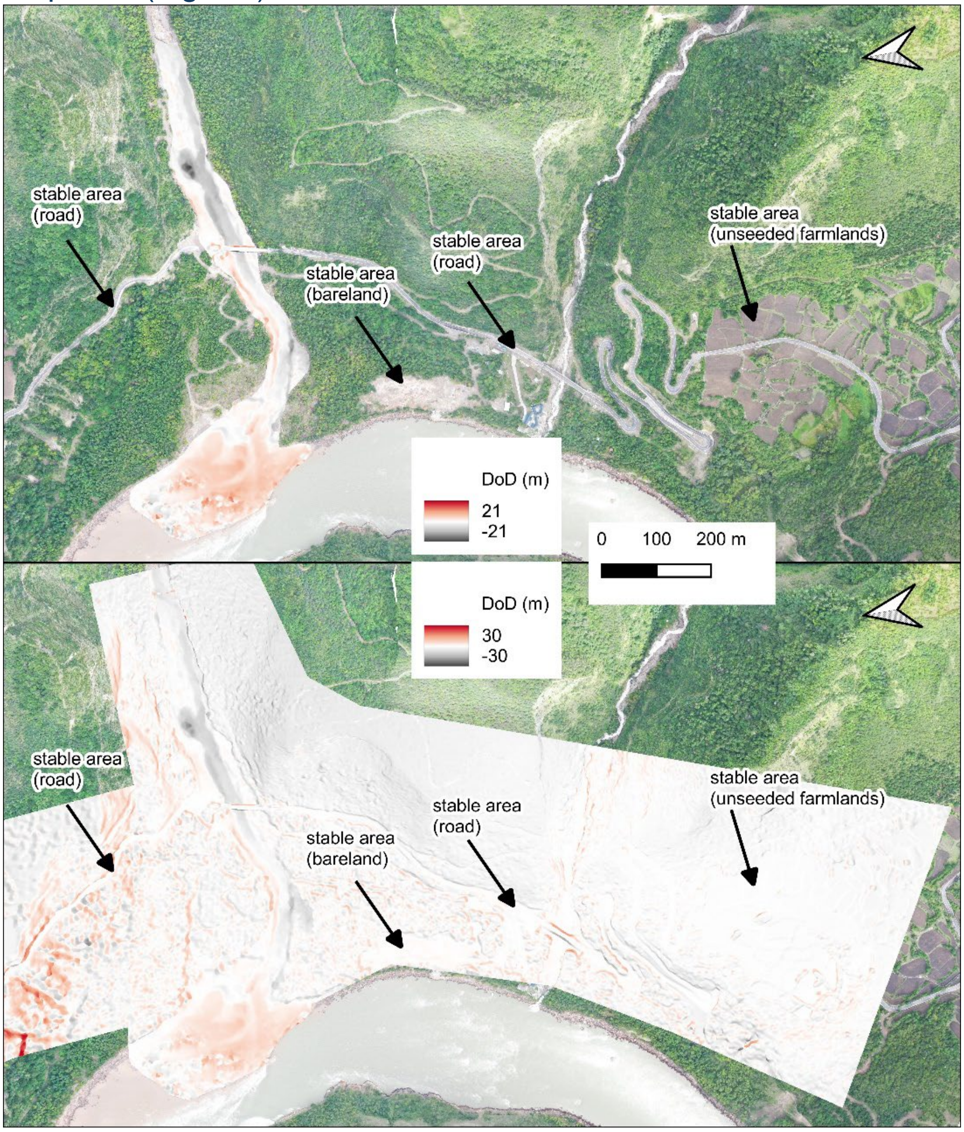

Figure S1. DoD results for the debris-flow inundation zone and geomorphically stable areas.

- **Author's changes in manuscript:**

We have already included the relevant additions in the first revision; please refer to Section 3.2.3 for details.

2. **Assessment of Climatic Control:**

   The attribution of the 2020 event solely to temperature rise is largely understandable but should be formulated more cautiously. The link between the sudden temperature increase (2.5 °C in 2018) and

immediate ice/rock instability appears more speculative than causal.

- **Author's response：**

Thank you for your suggestion. Yes, we agree with your perspective. In this revision, we have adopted a more conservative phrasing. In addition, we conducted a more in-depth analysis and found that the NVA has exhibited four peaks since 2000. These peaks likely correspond to the small flash-flood debris flow events described by Zhang et al. Interestingly, these peaks lag behind the summer temperature maxima by 2–4 years, which is consistent with the 2020 event occurring two years after the abrupt warming in 2018. Notably, similar lag phenomena have also been observed in other comparable regions(Deng et al., 2017; Stoffel et al., 2024). We consider this regular pattern as further evidence supporting the contribution of temperature.

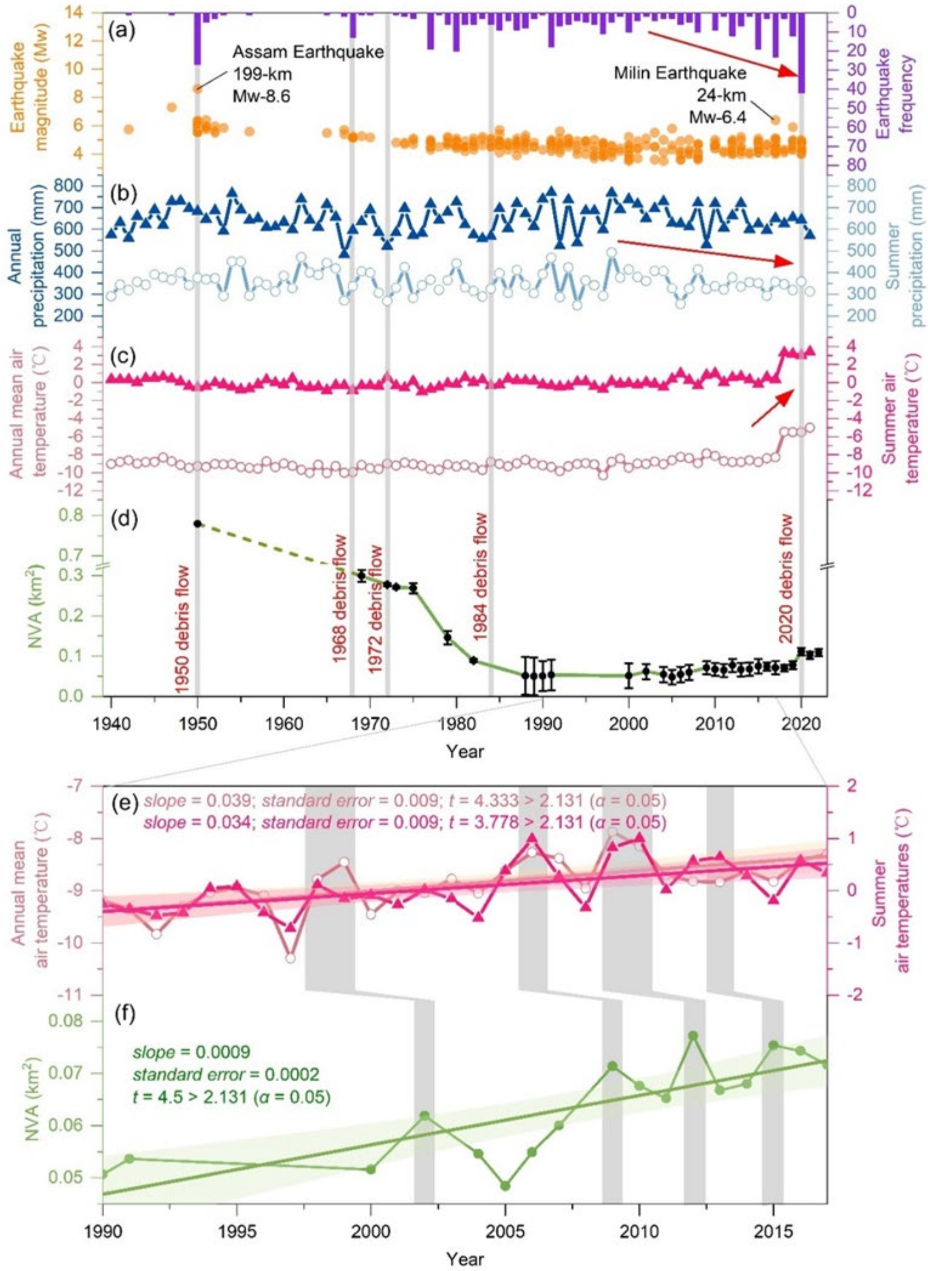

Figure 12: (a) Seismic events within a 200 km distance to the Zelunglung from 1940 to the present. (b) Changes in the annual mean and summer air temperatures in the Zelunglung from 1940 to the present. (c) Changes in the annual and summer precipitation in the Zelunglung from 1940 to the present. (d) Changes in the non-vegetated area of the Zelunglung alluvial fan from 1969 to the present (although the deposition of the 1950 event did not happen at the Zelunglung's outlet like the later events, we plot the NVA of the 1950 event as the starting point). (e) Changes in the annual and summer precipitation in the Zelunglung from 1990 to 2017. (f) Changes in the non-vegetated area of the Zelunglung alluvial fan from 1990 to 2017.

- **Author's changes in manuscript:**

We have updated the figures and conducted a more in-depth analysis and discussion. Please refer to the revised manuscript for details.

3. **Structure and Readability:**
   The text is very data-heavy, but at times difficult to follow. A clearer structuring of the results (e.g., subchapters for each individual event) would be helpful.

- **Author's response:**

Thank you for your suggestion. We have revised the structure of the Conclusions section.

- **Author's changes in manuscript:**

The "4.1 Rapid glacier changes" section has been moved to the study area description, as it is based on literature review. The "5 Multi-periodic sedimentation in the confluence" section has been incorporated into "4 Results." The final "4 Results" section is divided into three subsections: "4.1 Multi-periodic glacial debris flows," "4.2 Sediment characteristics of the 2020 event," and "4.3 Multi-periodic sedimentation in the confluence." Section 4.1 mainly focuses on analyses of historical single debris-flow events, including a brief introduction to the 2020 event, while Section 4.2 presents a detailed sedimentological analysis of the 2020 typical event.

4. **Comparison with Other Regions / Studies:**
   A broader contextualization of the Zelunglung cases in comparable scenarios would be beneficial, particularly with regard to recurrence intervals, mobilized volumes, and downstream effects on river systems. This should be incorporated into the discussion.

- **Author's response:**

Thank you for your suggestion; we have added the relevant discussion.

- **Author's changes in manuscript:**

We have added the relevant discussion in the following sections:

5.2 Debris flow recurrence intervals and future risk

In catchments where rainfall is the primary triggering process, such as the Multetta catchment in the Alps, debris-flow recurrence intervals have been shown to be insensitive to climate warming (Qie et al., 2024). This is because sediment supply in such catchments is controlled by weathering processes, whose rates are far lower than sediment supply from glaciers, permafrost, or other cryospheric processes. Zhang et al. (2022a) predicted that cryosphere degradation driving the increasing sediment yield in cold regions is likely to shift from a temperature-dependent regime toward a rainfall-dependent one in the next century. But in tectonically active high-altitude areas, the temperature-dependent and the earthquake-dependent regimes will alternate over the coming decades. The case of ZLL demonstrates that glacial detachment caused by the 1950 earthquake was not entirely flushed out of the channel but partly remained, providing a large amount of readily available sediment for debris-flow activity over the following forty years, thereby lowering the climate-triggering threshold for debris flows. Trends in NVA suggest that, as the legacy sediment is gradually depleted, debris-flow magnitude and frequency stabilize (Fig. 12d), making current debris-flow activity more dependent on climate warming. A similar phenomenon occurred in the nearby periglacial Peilong catchment (Wang et al., 2021). After decades of quiescence, sediment retained upstream following the 1981–1982 earthquakes created favorable conditions for three large debris flows between 1983 and 1985, after which activity declined. In recent decades, climate warming has promoted sediment accumulation through glacier movement and permafrost thaw, leading to highly active debris flows in 2015. Regardless of the regimes, sediment transport follows a mobilization–storage–remobilization pattern (Berger et al., 2010), and debris-flow recurrence intervals are controlled by the ease of these processes. Under an earthquake-dependent regime, the mobilization and storage phases are brief, with seismic events causing abrupt, large-scale sediment mobilization and substantial immediately available sediment storage; the remobilization of such sediment often requires only a minor triggering threshold. In contrast, under a temperature-dependent regime, sediment mobilization induced by climate-warming-driven glacier and permafrost degradation requires a relatively longer preconditioning period than in earthquake-dependent regime, and debris flows must exceed a higher triggering threshold to remobilize the sediment before it reaches a certain storage magnitude (Savi et al., 2021). Nonetheless, compared with non-glacierized catchments, ZLL still exhibits high sediment mobilization and storage capacity, and once sufficient sediment has accumulated, future hydrological changes induced by climate warming will further facilitate sediment transport (Hirschberg et al., 2020).

5.3 Effects on river geomorphology

Comparable processes have been documented in other periglacial catchments. In the Sedongpu catchment, located downstream of ZLL, a sequence of ice-avalanche–debris-flow damming events between 2018 and 2024 repeatedly blocked the Yarlung Tsangpo, triggering frequent channel shifting, narrowing, and bed aggradation(Gao et al., 2023). In Peilong catchment, sustained supply of glacial debris flows has aggraded the channel by ~53 m since 1983. Despite occasional incision by outburst floods, the transport capacity of the main river was insufficient to counteract the persistent input from debris flows, resulting in long-term channel aggradation(Wang et al., 2021). In Switzerland, the 2025 Birch Glacier collapse mobilized 6×106 m3 ice–rock mixture, entraining large quantities of debris and causing significant riverbed aggradation, instantaneously damming the Lonza River and forming a lake that posed considerable geomorphic and hydrological impacts on the downstream valley (Yin et al., 2025). In the Indian Himalaya, the Meru Bamak debris flow transported ~7.9 × 10^6 m^3 of sediment, with ~6.5 × 10^6 m^3 deposited at the glacier front. The resulting fan forced the Bhagirathi River to shift ~150 m laterally, fundamentally altering local fluvial morphology(Kumar et al., 2019). These events illustrate that debris flows in periglacial catchments, due to their massive sediment supply and extremely high energy, exert geomorphic impacts far exceeding those of rainfall-triggered events. These processes not only reshape alluvial fans and trunk channels at a local scale, but also profoundly influence river systems through damming, outburst flooding, and channel avulsion. Their impacts are characterized by both sudden catastrophic disturbances and long-term cumulative effects, underscoring the decisive role of periglacial debris flows in shaping river morphology and regulating hydrological processes in high mountain periglacial environments.

5. **Further Suggestions with Line References:**
   a) **Line 11: The phrasing that the earthquake "triggered debris flows" should be improved. Earthquakes do not directly trigger debris flows but may prepare material for them. Ultimately, a significant amount of water is still needed for debris flows to occur.**

- **Author's response：**

Thank you for your suggestion. We have revised the phrasing accordingly and have also reviewed the rest of the manuscript to avoid similar expressions elsewhere.

- **Author's changes in manuscript:**

We have revised Line 11 as follows:
Periglacial debris flows in alpine mountains are influenced by strong earthquakes or climatic warming and play a crucial role in delivering sediment from hillslopes and downslope channels into rivers.

   b) **Line 33: The statement “rising temperatures and increased extreme precipitation events” requires a citation.**

- **Author's response：**

Thank you for your suggestion. We cited the studies by Giorgi et al. (2016), Luan and Zhai (2023), Castino et al. (2016), and Frich et al. (2007) and Myhre et al. (2019) to demonstrate that in high mountain regions such as the Alps, the High Mountain Asia, and the Andes, and even globally, there is a regional trend of increasing extreme rainfall events under the context of climate warming. Correspondingly, we referenced several regional and global statistical studies (Wang et al., 2024; Zhang et al., 2023) to support the evidence that, under this context, the frequency and magnitude of glacier-related hazards have increased.

Refenence:

Castino, F., Bookhagen, B., and Strecker, M. R.: Rainfall variability and trends of the past six decades (1950–2014) in the subtropical NW Argentine Andes, CLIM DYNAM, 48, 1049–1067, https://doi.org/10.1007/s00382-016-3127-2, 2016.

Frich, P., Alexander, L., Della-Marta, P., Gleason, B., Haylock, M., Klein Tank, A., and Peterson, T.: Observed coherent changes in climatic extremes during the second half of the twentieth century, CLIM RES, 19, 193–212, https://doi.org/10.3354/cr019193, 2007.

Giorgi, F., Torma, C., Coppola, E., Ban, N., Schär, C., and Somot, S.: Enhanced summer convective rainfall at Alpine high elevations in response to climate warming, NAT GEOSCI, 9, 584–589, https://doi.org/10.1038/ngeo2761, 2016.

Luan L. and Zhai P.: hanges in rainy season precipitation properties over the Qinghai-Tibet Plateau based on multi-source datasets, Climate Change Research, 173–190, 2023.

Myhre, G., Alterskjær, K., Stjern, C. W., Hodnebrog, Ø., Marelle, L., Samset, B. H., Sillmann, J., Schaller, N., Fischer, E., Schulz, M., and Stohl, A.: Frequency of extreme precipitation increases extensively with event rareness under global warming, SCI REP-UK, 9, 16063, https://doi.org/10.1038/s41598-019-52277-4, 2019.

Wang, H., Wang, B.-B., Cui, P., Ma, Y.-M., Wang, Y., Hao, J.-S., Wang, Y., Li, Y.-M., Sun, L.-J., Wang, J., Zhang, G.-T., Li, W.-M., Lei, Y., Zhao, W.-Q., Tang, J.-B., and Li, C.-Y.: Disaster effects of climate change in High Mountain Asia: State of art and scientific challenges, ADV CLIM CHANG RES, 15, 367–389, https://doi.org/10.1016/j.accre.2024.06.003, 2024.

Zhang, T., Wang, W., Shen, Z., and An, B.: Increasing frequency and destructiveness of glacier-related slope failures under global warming, SCI BULL, 69, 30–33, https://doi.org/10.1016/j.scib.2023.09.042, 2023.

- **Author's changes in manuscript:**

  We have revised the statement on Line 30 and updated the corresponding citation in the References section：

  Under climate change, characterized by rising temperatures and more frequent extreme precipitation events(Castino et al., 2016; Frich et al., 2007; Giorgi et al., 2016; Luan and Zhai, 2023; Myhre et al., 2019), high-altitude regions are increasingly affected by more destructive and frequent ice/rock avalanches, as well as low-angle glacier detachments (Wang et al., 2024; Zhang et al., 2023).

c) **Line 81: The percentage of glaciation within the catchment should be calculated and provided.**

- **Author's response：**

Thank you for your suggestion. We have added information on the proportion of glacier area.

- **Author's changes in manuscript:**

We revised Line 87-88 to:

The catchment extends over 41.21 km², with 17.06 km² (41.4%) covered by glaciers (RGI 7.0).

d) **Line 88: What time period do the referenced earthquakes cover? Although historical earthquakes are mentioned, the exact time frame would be interesting to know.**

- **Author's response：**

Thank you for your suggestion. The time span of the earthquakes shown in the figure 1b covers 1940–2020, which is consistent with the historical earthquake data used for statistical analysis later in the text. To avoid any potential confusion for readers, we have added this information to the figure caption.

- **Author's changes in manuscript:**

We have revised the figure title to:

Historical earthquakes from 1940 to 2020 were sourced from the United States Geological Survey (USGS) National Earthquake Information Center (NEIC) (https://earthquake.usgs.gov/earthquakes/search/).

e) **Line 107: While there is a clear increase in temperature, the precipitation data, in my opinion, shows no discernible trend. The cited precipitation trend of 0.65 mm/decade may be due to measurement uncertainty. Thus, its climatic significance is questionable. There are strong fluctuations and differences over time, which should be discussed more thoroughly. A general statement about increasing precipitation should be avoided.**

- **Author's response：**

We sincerely thank the Reviewer for their careful review. We agree with the Reviewer's point that the observed increase in precipitation rates may fall within the uncertainty range of the data. As suggested, we have re-analyzed the data by calculating the standard error of the slope (Fig. 2). The results show that the slope value is 0.065, the standard error is 4.215. The t-statistic value is approximately 0.0153, which is much smaller than the critical t-value of 2.086 at the significance level of α=0.05. This indicates that the trend is not statistically significant. In the revised manuscript, we have clarified that there is no significant trend in precipitation over the study period, aligning the discussion with the updated statistical analysis.

Author's changes in manuscript:

We have updated Figure 2, and changed the L120 as: The annual precipitation ranges from 514 mm to 972 mm, exhibiting notable inter-annual variation, with no distinct trend over the past 20 years.

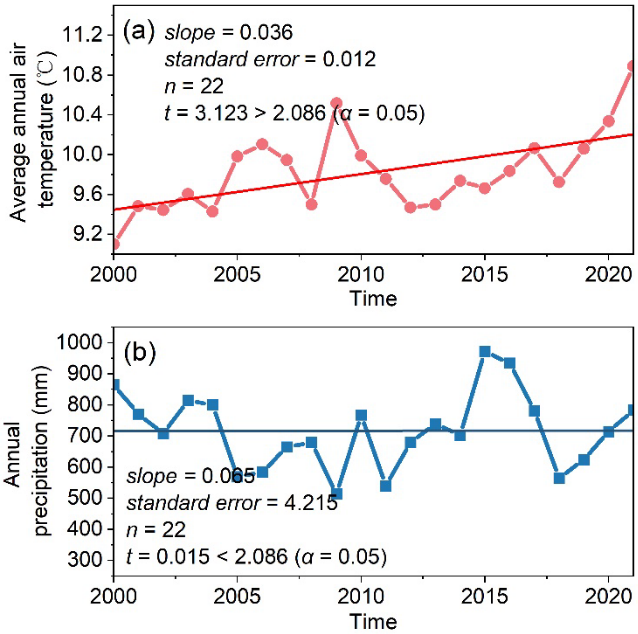

Figure 2: Annual temperature and precipitation data from 2000 to 2021 at Linzhi Meteorological Station. (Data source: https://www.ncei.noaa.gov/maps/annual/).

f) **Line 112: A subheading "satellite images" should be inserted here.**

- **Author's response:**

Thank you for your suggestion. We have inserted the subheading "3.1.1 Satellite images" and also listed the earthquake and meteorological data used under "3.1.2 Earthquake and climate."

- **Author's changes in manuscript:**

We have inserted the subheading "3.1.1 Satellite Images" in L151 and additionally added the following subsections:

3.1.2 Earthquake and climate

Earthquake and climate datasets were used to investigate the potential linkages between these factors and debris-flow occurrence. Earthquake records within approximately 400 km of the ZLL catchment during 1940–2020 were obtained from the United States Geological Survey (USGS) National Earthquake Information Center (NEIC) (https://earthquake.usgs.gov/earthquakes/search/). In addition, gridded mean values of annual mean air temperature, summer air temperature, annual precipitation, and summer precipitation for the ZLL catchment during 1940–2021 were derived from the 1-km monthly precipitation and mean temperature dataset for China (1901–2021) (Peng, 2019, 2020). The reliability of these datasets has been verified against 496 independent meteorological observation stations across China (Peng et al., 2019) .

g) **Lines 128–130: The procedure (cross-sectional morphology, debris flow particle characteristics, and the extent of damage to the Zhibai Bridge) should be described in more detail.**

- **Author's response：**

Thank you for your suggestion. We have provided a more detailed description in this section, including the specific locations of the survey, the sampling sites, and the instruments and methods used for the measurements.

- **Author's changes in manuscript:**

We revised Lines 180–192 as follows:
We conducted three field surveys at ZLL between 2020 and 2022. The first survey (September 9, 2020) employed a DJI MAVIC-2 UAV to perform geomorphological photogrammetry of the downstream channel and alluvial fan. During the second survey (September 11, 2020), we combined low-altitude UAV photogrammetry with measurements from an IMETER LF1500A laser rangefinder to characterize the downstream channel morphology, particularly near Zhibai Bridge, to analyze debris-flow erosion and deposition patterns. UAV photographs also provided close-up views of inaccessible upstream sections. Tape measurements were used to determine bridge displacement and boulder sizes on the fan, while low-altitude UAV orthophotos supported post-event interpretation of boulder distribution. Fine-grained deposits (< 100 mm) were sampled from the fan apex for laboratory analyses. The third survey (December 21, 2022) used UAV imaging to generate a complete 3D view of ZLL (Fig. 1d).

h) **Lines 138–139: Potential sources of error and uncertainties should be discussed.**

- **Author's response：**

Thank you for your suggestion; we have added a discussion on errors and uncertainties.

- **Author's changes in manuscript:**

We have added a new section to discuss the potential sources of error and uncertainties:

5.4 Limitation
Previous studies have shown that debris-flow volume is often empirically related to the extent of the inundation area (e.g., Iverson et al., 1998), which

supports the use of NVA as a proxy for relative debris-flow magnitude. Multi-period periglacial debris flows are strongly associated with variations in the NVA of the alluvial fan, suggesting that NVA can capture long-term trends in debris-flow activity. In practice, however, the NVA includes a fixed portion of the area inundated by the main river and is therefore slightly larger than the actual inundation area caused by debris flows. Technically, the contribution of the main river to NVA cannot be entirely excluded. Nevertheless, the riverbank line remained stable from the 1980s to the 2010s, during which no large periglacial debris flows occurred (Figs. 11b and c; Zhang and Shen, 2011). It is therefore reasonable to assume that variations in river water level have little influence on changes in NVA, and that NVA primarily reflects the relative volume trends of sediment transported by debris flows.

Despite these considerations, several uncertainties remain in using NVA as a volume proxy. The absence of systematic sediment thickness measurements prevents direct conversion of NVAs into absolute debris-flow volumes, so NVA only reflects relative fluctuations rather than precise values. Delineation errors in historical imagery, particularly in earlier black-and-white aerial photographs with limited tonal contrast, may affect accuracy. The spatial resolution of imagery also varies markedly across decades, which inevitably affects the precision of NVA delineation and may lead to scale-dependent biases when comparing different periods. Error ranges for NVA were plotted to illustrate these uncertainties (Fig. 12d), and although they cannot be entirely eliminated, they do not alter the main analytical results. Moreover, the empirical relationship between inundation area and debris-flow volume may vary with local geomorphic and hydrological conditions, such as fan slope and gully confinement, further complicating volume inference and limiting the applicability of uniform statistical error models.

Future research integrating high-resolution LiDAR, UAV photogrammetry, or borehole surveys with field-based volume measurements would enable more rigorous statistical assessments of the NVA–volume relationship. The application of dense stereo-pair techniques for DSM extraction from historical and modern satellite archives also has considerable potential to provide three-dimensional constraints on sediment thickness and deposition, thereby improving the translation from inundation area to sediment volume.

i) **Line 140: This should be supported by a graphic. The methodology should be explained better using visual examples.**

- **Author's response：**

Thank you for your suggestion. We have prepared a conceptual diagram illustrating the identification of NVA to help readers better understand. The inundation of debris flow on the alluvial fan often destroys vegetation cover and causes the affected area desertification. Based on differences in color, tone, texture, and shading between vegetated and non-vegetated areas in satellite imagery for a given year, we delineated the debris flow inundation zone (i.e., NVA) for that year. When subsequent debris flows occurred and extended beyond the gully outlet, three scenarios were observed: (1) the subsequent debris flow was of a larger magnitude, exceeding the previous inundation zone; (2) the subsequent debris flow was smaller in magnitude but caused damage to newly established vegetation; and (3) the subsequent debris flow was very small in scale, confined to the channel or a very limited area along its banks, and did not affect vegetation. The third scenario is more appropriately classified as a minor seasonal flood with negligible sediment transport compared with debris flows. Therefore, in our interpretation and statistical analyses, the NVA was restricted to the first two scenarios.

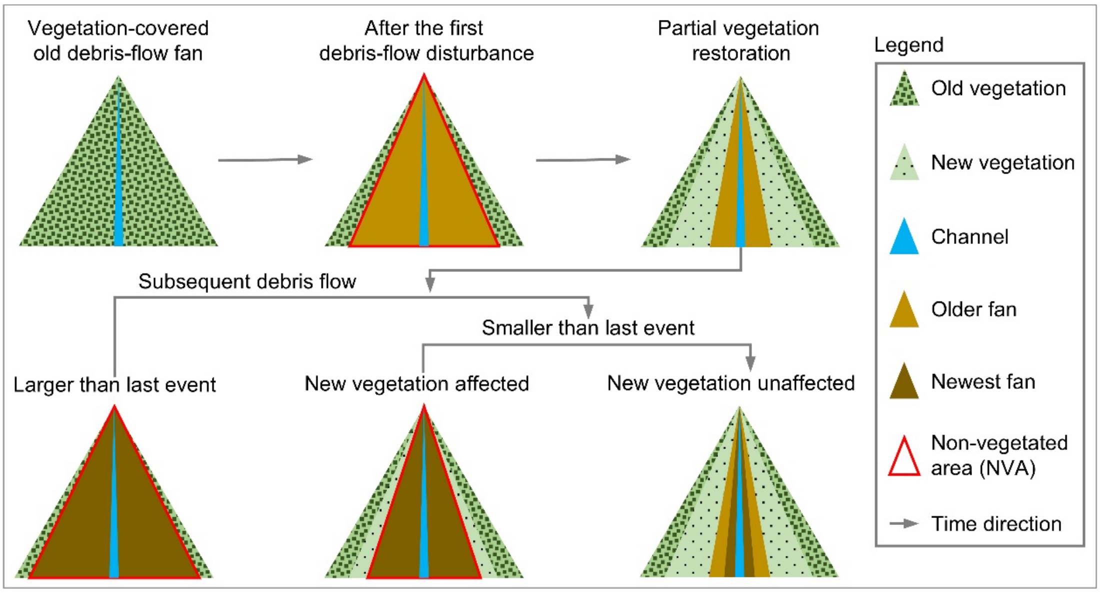

Figure 3: Conceptual illustration of non-vegetated area (NVA) interpretation

- **Author's changes in manuscript:**

We have added a conceptual diagram illustrating the identification of NVAs in the manuscript (L214–L215), and provided a more detailed explanation in L202–L210:

Based on differences in color, tone, texture, and shading between vegetated and non-vegetated areas in satellite imagery for a given year, we delineated the debris flow inundation zone (i.e., NVA) for that year. When subsequent debris flows occurred and extended beyond the gully outlet, three scenarios were observed: (1) the subsequent debris flow was of a larger magnitude, exceeding the previous inundation zone; (2) the subsequent debris flow was smaller in magnitude but caused damage to newly established vegetation; and (3) the subsequent debris flow was very small in scale, confined to the channel or a very limited area along its banks, and did not affect vegetation. The third scenario is more appropriately classified as a minor seasonal flood with negligible sediment transport compared with debris flows. Therefore, in our interpretation and statistical analyses, the NVA was restricted to the first two scenarios.

j) **Line 158: The heading "Results" should be inserted here.**

- **Author's response：**

Thank you for your suggestion. We have inserted the "4 Results" section heading here.

- **Author's changes in manuscript:**

We have inserted the "4 Results" section heading here.

k) **Line 331: The value range of the DoD figure should be symmetrically centered around zero (e.g., –21 m to +21 m) to visually balance erosion and deposition and facilitate interpretation. Stable areas should also be shown, and a DoD error assessment should be carried out.**

- **Author's response：**

Thank you for your suggestion. We have updated the DoD range to –21 m to +21 m (Fig. 10). In our first revision, we quantified the DoD volumetric uncertainty as ±1.85 × 10^4 m^3 (Line 422). Owing to the large extent of the study area, and to avoid redundancy while presenting geomorphic changes in the debris-flow impact zone more clearly, we did not include the results from the stable areas in the manuscript figure, but we provide them here in this response (Fig. S1).

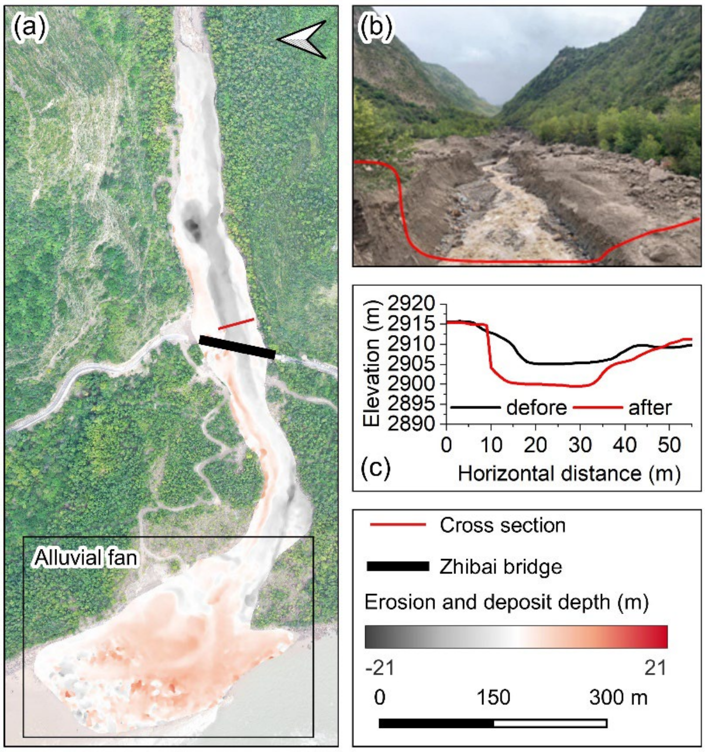

Figure 10: Geomorphic changes of the channel and alluvial fan after the debris flows of 2020. (a) Erosion and deposit depth caused by the debris flows. The base map is taken by UAV on 10 Sep 2020. (b) Photo of the channel after the debris flows. The red line represents the cross-section next to the Zhibai Bridge (photo taken on 11 Sep 2020). (c) Cross-sections before (black) and after (red) the debris flows.

- **Author's changes in manuscript:**

We have updated Fig. 10.

6. **Entire Results Chapter:**
   There is already extensive discussion included in the results chapter. A better separation between the results and the actual discussion would be desirable. This would give the paper a clearer structure and organization. Alternatively, the results and discussion could be merged into a single chapter. However, the current chapter structure suggests a clear separation between results and discussion, whereas in the text, these two sections blur together, and the actual discussion is ultimately rather brief.

- **Author's response：**

Thank you for your suggestion. We have reorganized the structure of the manuscript.

- **Author's changes in manuscript:**

We moved the “4.1 Rapid glacier changes” section to the study area description, as it is based on literature review. The “5 Multi-periodic Sedimentation in the Confluence” section was incorporated into “4 Results.” The final “4 Results” section is divided into three subsections: “4.1 Multi-periodic glacial debris flows,” “4.2 Sediment characteristics of the 2020 event,” and “4.3 Multi-periodic sedimentation in the confluence.” We consider these three subsections to present direct conclusions derived from our methods, including the basic characteristics of historical debris flows, detailed sedimentary features of the 2020 event, and the interpreted distribution of non-vegetated areas (NVA).

In the Discussion, the original “6.1 The dominant factor and future risk” was split into “5.1 The dominant factor for debris flows and sediment yield” and “5.2 Debris flow recurrence intervals and future risk.” We provide a more in-depth discussion of earthquake and climate influences, linking different events, NVA changes, and the effects of climate and seismic activity. In “5.2 Debris flow recurrence intervals and future risk” and “5.3 Effects on river geomorphology,” we performed comparative analyses addressing reviewer comments on recurrence intervals, sediment mobilization, and downstream impacts on the river system. A new subsection, “5.4 Limitations,” was added to discuss methodological uncertainties and directions for future research.

7. **Conclusion:**

This manuscript represents a significant contribution to the study of periglacial mass movements in high mountain regions. It is methodologically sound, thoroughly documented, and addresses a relevant topic in the context of climate change and geomorphological dynamics. The study is of great interest to the mountain and environmental geoscience community. After minor revisions regarding uncertainty analysis, structure, and clearer framing of climatic controls, the publication is fully recommended.

- **Author's response：**

We are grateful for the reviewer’s positive recognition of our manuscript. We greatly appreciate the constructive comments and have revised the manuscript accordingly.

Reviewer 2

Thank you for your appreciation! And we are very grateful for various lines of constructive criticism which were very helpful in improving analysis and the manuscript. Point-by-point replies can be found in the following:

(Please note that all references in this response, including line numbers, section titles, and figure/table numbers, are based on the Manuscript_trackchanges.docx file, so that the reviewer can clearly locate the revisions and compare them with the original content.)

1. **Page 3, Line 87. average gradient of 27.5% (not 275%)**

- **Author's response：**

Thank you for your careful review. Due to our oversight, we mistakenly wrote ‰ instead of %, and we have now corrected it.

- **Author's changes in manuscript:**

We have corrected “275%” to “275‰”.

2. **Page 15, line 96. better: stopped quickly.**

- **Author's response：**

Thank you for your suggestion. We agree that "stopped quickly" is better. We have revised "quickly stopped" to "stopped quickly" accordingly.

- **Author's changes in manuscript:**

We revised "quickly stopped" to "stopped quickly".

3. **Page 20, line 70. Lateral erosion took place ...**

- **Author's response：**

Thank you for your suggestion. We agree that "took place" is better. We have revised "happened" to "took place" accordingly.

- **Author's changes in manuscript:**

We revised "happened" to "took place".

4. **Page 20, line 74. Could part of the material be submerged? more likely it was eroded and washed away by powerful Yarlung Tsangpo stream.**

- **Author's response：**

Thank you for your suggestion. Yes, our consideration here was indeed not comprehensive. In fact, the ZLL debris-flow deposits contain a high proportion of boulders and coarse particles (as noted in the section 4.2.2), so some of the boulders may have been temporarily submerged by the river, but they are unlikely to be transported away by the strong flow of the Yarlung Tsangpo

River. Meanwhile, the fine-grained sediments within the debris flow could indeed be eroded and carried away by the main river, resulting in partial sediment loss. We have accordingly revised the relevant statements in the main text.

- **Author's changes in manuscript:**

We revised Lines 423–425 as follows:

the true volume may be seriously underestimated because part of the sediment may be submerged or washed away by the Yarlung Tsangpo River, which is a bias caused by the difference in data acquisition time and the errors associated with DoD processing.

5. **Page 21, line 76. Multi-periodic sedimentation ...**

- **Author's response：**

Thank you for your careful review. We have changed the initial letters of non-sentence-initial words to lowercase.

- **Author's changes in manuscript:**

We revised "Sedimentation" to "sedimentation".

6. **Page 22, line 11. In such case more important is not the distance from the epicenter, but distance from the earthquake source (causative fault). Energy is released not from the point (hypocenter), but from the entire source.**

- **Author's response：**

We agree with your comment. The maximum distance from the fault rupture zone to landslides indeed provides a more accurate upper bound, since seismic energy is released along the entire fault. We cited the long-distance effects of the 2015 Gorkha earthquake to illustrate the possible influence of the 1950 Assam earthquake on ZLL; however, we acknowledge that this comparison may not be appropriate, given the potential differences in causative fault length between earthquakes.

Nevertheless, previous studies have confirmed the strong impact of the 1950 Assam earthquake on the ZLL region. The 1950 Assam earthquake occurred at the Assam sub-Himalayan syntaxis and was triggered by rupture of the Mishmi Thrust (MT) and Main Himalayan Frontal Thrust (MFT). Coudurier-Curveur et al. (2020) recalibrated the aftershock distribution within the first four months following the mainshock and revealed proximal aftershocks near the ZLL basin (about 1 km away) with magnitudes up to Mw 5.5 (Fig. 1b). The 1950 earthquake directly caused severe damage to houses and temples in this region. The northernmost aftershocks further suggest that the influence of the MT fault extended beyond its distance to ZLL (Fig. 1b).

In the absence of detailed fault information, the epicentral distance curve can still serve as a quick and approximate estimation tool. For this reason, we have retained Figure 13 in the revised manuscript.

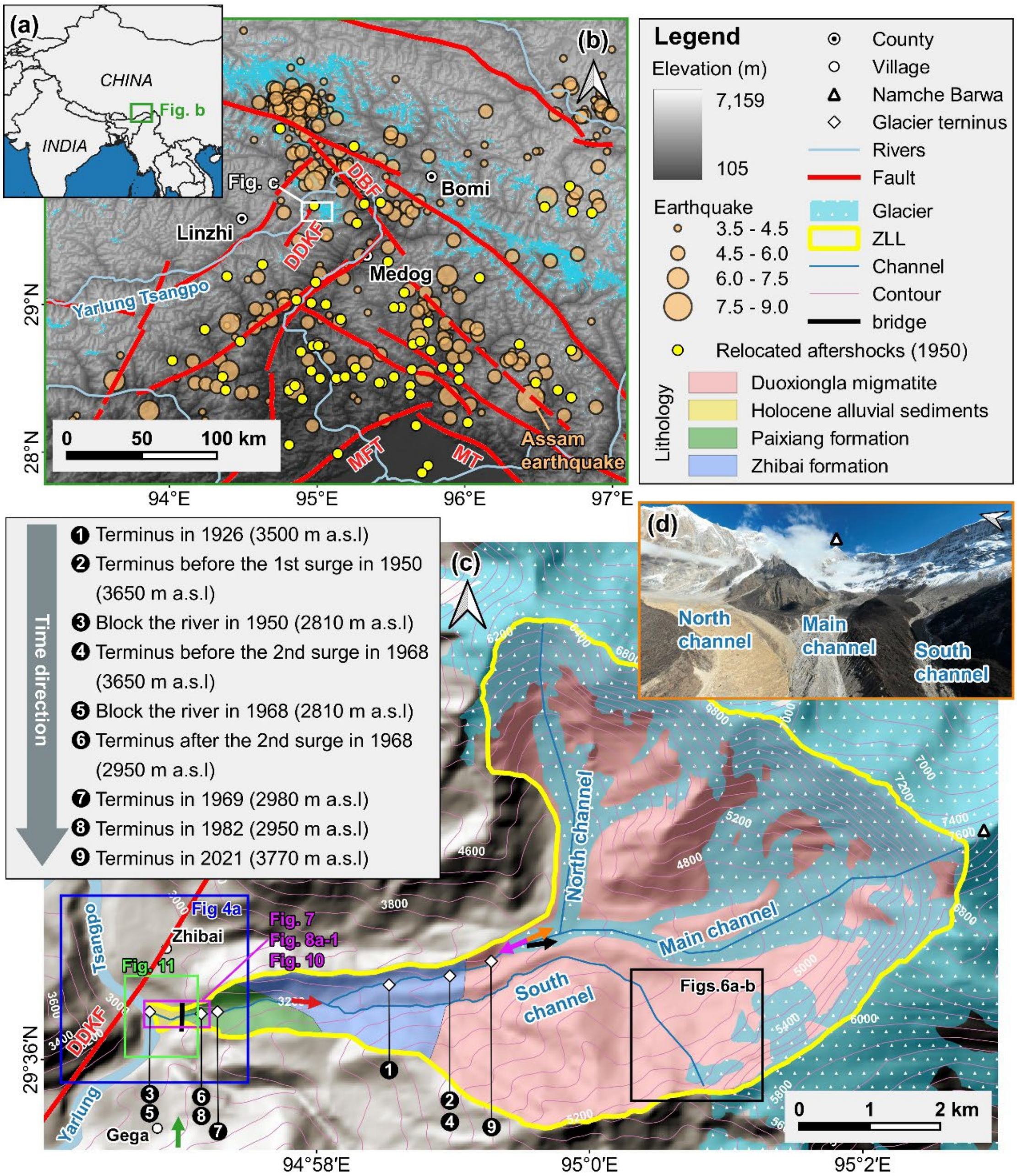

Figure 1: (a) Regional overview map of southeastern Tibet. (b) Regional settings of the eastern syntaxis of Himalayas. Fault data were obtained from Wu et al. (2024). Historical earthquakes from 1940 to 2020 were sourced from the United States Geological Survey (USGS) National Earthquake Information Center (NEIC) (https://earthquake.usgs.gov/earthquakes/search/). Relocations of aftershocks within the first four months following the 1950 Assam mainshock were taken from Coudurier-Curveur et al. (2020).(MFT: Main Himalayan Frontal Thrust, MT: Mishmi Thrust, DBF: Damu-Bianba Fault, DDKF: Daduka Foult) (c) Topographic, geological and glacier terminus change maps of the Zelunglung catchment. The lithological information is based on Zhang and Shen (2011), and the glacier map is derived from the RGI 7.0 dataset (RGI, 2023). The orange, rose-red, green, black and red coloured arrows represent the view angle direction of figures 1d, 5a, 5b, 6c and 6d. (d) Aerial photo of the Zelunglung glacier and channels on December 21, 2022.

- **Author's changes in manuscript:**

We deleted "Notably, the impact distance of a large earthquake can reach hundreds of kilometers. For example, the co-seismic landslides triggered by the 2015 Gorkha Mw 7.8 earthquake extended to a distance of over 130 km from the epicenter (Martha et al., 2017). The 1950 Assam earthquake, with its epicenter approximately 199 km from the ZLL, had a very high magnitude (Mw 8.6) and occurred in the tectonically active eastern Himalayan syntaxis. Coupled with subsequent high-magnitude aftershocks near the ZLL (Fig. 13), the seismic impact on the ZLL was significantly amplified despite the distance". (L461-466).

We added a sentence in L458-459 as follows: In the absence of detailed fault information, we conducted a rapid and preliminary assessment of the impacts of historical earthquakes using this curve.

We added a sentence in L468-470 as follows: Relocated aftershocks of the 1950 earthquake (Coudurier-Curveur et al., 2020) indicate that the seismogenic faults—the MFT and MT—extend their influence well beyond the ZLL (Fig. 1b).

We have added the relocated aftershock distribution of the 1950 Assam earthquake from Coudurier-Curveur et al. (2020) in Fig. 1b.

Other changes by the author

1. Owing to the reorganization of the institute, the original first affiliation "Key Laboratory of Mountain Hazards and Earth Surface Processes, Chinese Academy of Sciences, Chengdu, 610041, China" has been removed. In addition, as the institute has relocated, the postal code has been updated to "610213."

2. Figures 4 and 5 have been merged into a single figure.

3. In addition to the language expression problems pointed out by the reviewers, we further checked and proofread the possible language errors.

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