Response to Review #2

This contribution presents the use of geomorphic indices to assess fault activity in the Shanxi Rift (China). Fault orientations and activity are compared against pre-existing basement fabrics. The authors show that the overall geometry of the segmented Shanxi Rift, the geometries of the rift interaction zones (RIZs) between the main basins, and fault activity are influenced by pre-existing structures in the (upper) crust and anisotropies in the upper mantle; both of these types of pre-existing structures have been attributed to the amalgamation of the North China Craton and the formation and subsequent reworking of the Trans Northern China Orogen.

The manuscript fits the scope of the journal and special issue very well. The use of geomorphology to investigate the multi-faceted influence of structural inheritance is uncommon and therefore makes valuable addition to structural inheritance research. In general, the manuscript is well-structured. It would benefit from some thorough editing to enhance clarity and emphasize key messages. Below are some general and specific comments that I hope will contribute to the overall improvement of the manuscript. Congratulations to the authors for putting this interesting paper together.

> *We thank the reviewer for the positive and thorough review and their many constructive comments that will surely improve the overall quality of this contribution. Detailed responses to the general and individual comments are listed below (line references in brackets):*

General comments

This manuscript is missing a concise presentation of all the faults and their characteristics, including the lithology of the footwall, the main orientation of pre-existing basement fabrics, perhaps the strength of the geomorphic signal, and most importantly the inferred level/recentness of activity – this could be done as a summary table. The above information is all there already, but it is spread across several maps with different color schemes, which makes it difficult to follow the descriptions in the text and connect the different observations.

> *We agree that a summary of the faults and their geomorphological response, lithology and relation to inheritance would be helpful and make the argument of the manuscript stronger. We have added a table that summarises all this information (Table 1)*

A general comment that could apply to multiple parts of the manuscript: Sometimes I get lost in the details and explanations before understanding what the main statement of the paragraph/section is. It could help to flip the paragraph around, bringing the headline statement to the start of the paragraph, and then elaborating on the headline statement. One example of where this occurs is the first paragraph of the Conclusions.

> *We have done our best to implement this suggestion and overhauled some of the paragraphs to improve the overall readability and make the point of the paragraph clearer with a headline statement.*

Specific comments:

Lines 17-20: It would be more accurate to state that the tectonic geomorphological techniques were used evaluate fault activity. The interpretations of the role of inheritance comes later, but inheritance is not directly linked to geomorphological indices (at least not in this paper).

> *Yes, we agree that the wording in the manuscript suggesting a causative link between the inheritance and geomorphic analysis was imprecise and want to clarify we do not suggest a causative link between inheritance and geomorphology. We changed this part to "*Here we use tectonic geomorphological techniques, e.g., hypsometric integral (HI), channel steepness (k_{sn}) and local relief to study the evolution of the Shanxi Rift and identify areas of higher tectonic activity. We found that HI was less sensitive to lithology and more valuable in evaluating the tectonic signal and found that activity is concentrated in two rift interaction zones (RIZ) formed between the basins. We then evaluate the relationship between the active faults and mapped pre-existing structures and found that many faults formed parallel to inherited structures but faults in the RIZs often crosscut these structures.*" (17-22)*

Line 51: Line 60/61: Striking obliquely with respect to what? What is meant by "oblique striking"? Oblique with respect to what?

> *Oblique with respect to the main extension direction, we have modified the text to clarify that. Thanks for spotting that.*

Line 75: What did these previous studies reveal? Are their outcomes helpful in understanding the Shanxi Rift?

> *Changed to "that show active normal faults often follow the trends of inherited structures (Su et al. 2021) and possibly detach into low angle shear zones at depth (Pavlides et al. 1999) (81-83)*

Lines 92-98: This is a great summary of the presented work and a strong conclusion to the introduction! It would be good to apply this style and clarity in the other sections.

> *Thanks and noted!*

Line 94: Is it necessary to distinguish between basement heterogeneities and inherited structures? Please see the general comment about the need to clearly define basement structures, pre-existing structures, inherited structures, etc.

> *We have made clearer what we refer to when mentioning basement and inherited structures (I.e. Palaeoproterozoic structures) in the methods section. (181-183)*

Line 171: How is it determined that faults are active? What is your definition of an "active" fault?

Added the following definition and description to make clearer what we mean by active fault and how we identified them:

"We define active faults as linear, steep scarps (>20-30°) that offset Quaternary sediments, similar to the approach by Wedmore et al. (2022). Furthermore, we used topographic profiles across faults and geomorphological features such as steepened river channels and triangular facets along the fault scarp as features guiding our identification of active normal faults." (186-189)

Lines 179-181: Is there literature supporting the statement that the three chosen geomorphic indices are the most robust for evaluating tectonic signals?

This statement is mostly based on our observations of using various geomorphic indices and these proved to be the best. The three chosen indices were used successfully in other studies – Erbello et al. (2022) employed Relief, ksn and HI; Gao et al. (2016) and Pérez-Peña et al. (2009) showed that HI is a robust index to evaluate tectonics; Obaid and Allen (2019) and Groves et al. (2020) furthermore showed the effectiveness of HI and ksn in evaluating active tectonics. We've added these references to the manuscript. (195-196)

Lines 218-220: Does a high k_{sn} also indicate a high uplift rate? If so, please specify this as you have done for the other two geomorphic indices.

Yes, high k_{sn}, denotes steeper channel and therefore higher uplift rates. We've added this along with references to the end of the sentence. (244-246)

Lines 229-330: You refer to Fig. 3 here, but the faults are not labelled in Fig. 3.

We've added labels to the faults on this map.

Lines 234-235: This statement is vague. How is the "general" NE-SW trend distinguished from the "local" ENE-WSW orientation? Where can we see this on the map (e.g., in Fig. 3)?

*This change in trend is best observed on Fig.3 or on the stereonets on Fig. 5 which show the slight change in trend going northwards. We have reworded to: "*In the northern basement massifs (Hengshan and Wutai) there is a subtle change to WNW-ESE-trends *(Fig. 3). (264-265)*

Lines 279-281: Do you mean that the JC and TG faults have lower k_{sn} and R_i values compared to other faults in the region that are considered active? I think the sentence needs rewriting for clarity.

Yes, both faults generally have low R_l and k_{sn} values, we reworded this sentence to make this clearer. (328-330)

Section 4.5: Can this section be combined with the previous three sections? Otherwise, we are jumping back and forth between geomorphic indices.

We have combined sections 4.2/3/4 and 4.5 to improve readability.

Lines 307-308: I suggest moving this to the methods section.

We have added this part to the methods section.(196-200)

Line 347: Fig. 3 shows the ages of the units but not the lithologies.

We have fundamentally changed Figure 3 (in line with comments from other reviewers) to now include lithology as well.

Lines 348-351: Why not make it clear that the two groups you are referring to are crystalline rocks and low-grade metasediments? It would make the comparisons in the subsequent paragraphs easier to follow. Also, were the carbonates also subject to low-grade metamorphism? If so, wouldn't they technically also be considered metasediments?

We have changed this accordingly to reflect the two groups (crystalline rocks and low-grade metasediment) to improve readability. We include carbonates in the group of low-grade metasediments. (379-384)

Lines 357-363: What does HI tell us about tectonic activity? A short explanation of what HI means with respect to tectonics would be useful here.

Added two sentences to briefly highlight the tectonic implications of high HI values:

"High HI values are often correlated with high uplift rates, especially in regions with variable uplift rates; higher HI values are found in regions of higher uplift (Hurtrez et al. 1999). Therefore, the high HI values found in the footwalls of the Huoshan, Wutai, Xizhoushan and Shilingguan fault indicate that these footwalls have been uplifted the most rapidly." (395-397)

Lines 361-364: How do we reconcile this with the limitations of HI for tectonic interpretations (Section 4.4)?

We added a discussion part on the Loess plateau (and moved it from the results section) (399 - 408) –We see high HI responses that are not related to active tectonics from 1) palaeorelief from previous tectonic events such as thrust faults and folds from the Mesozoic orogenies that shaped the Shanxi highlands prior to rifting. These are easily identified by comparing them to mapped structures. 2) The Loess plateau – just by the nature of how Loess forms and is shaped by surface processes it is prone to create ridges rather than sloping gentle landscapes. This is an impact of lithology on the HI response; however Loess is a rather extreme case and has very different properties to the main lithologies in the Shanxi Rift – Paleoproterozoic crystalline rocks and low-grade metasediments – therefore the main observation that HI is not as sensitive to differences in lithology still applies (apart from extreme cases such as Loess). However, this naturally has consequences for the interpretation as Loess needs to be accounted for when present.

Lines 366-367: What does "similar basement geology" mean? Would erodibility be influenced by factors other than lithology, e.g., the orientations and types of structures in these basement rocks?

We mean with similar basement geology the overall rock strength of that region, i.e. are these footwalls mainly composed of crystalline rocks or the low-grade metasediments which are the dominant groups in this study area.

Lines 368-373: These sentences seem to repeat what was already described in the previous paragraph.

> *We think, this short summary statement helps to highlight a key point, however we shortened it to:*
>
> *"This enables us to compare the landscape response of these footwall uplifts to tectonics. In the Shanxi Rift for example, the Huoshan fault on average has higher values for geomorphic indices than other faults with Paleoproterozoic crystalline rocks in the footwall." (412-414)*

Lines 375-377: It is difficult to follow which faults are being compared here.

> *Changed to:*
>
> *"Here the difference in geomorphic response between the Shilingguan RIZ and the other faults with low-grade sedimentary rocks in their footwalls is even more pronounced than comparing faults with Paleoproterozoic crystalline rocks in the footwall where the difference between the Huoshan fault and for example the Hengshan or Wutai faults is less stark." (416-419)*

Section 5.2: You could consider splitting up this section into two, with the second section focusing more on fault activity and implications for seismic hazard. Or you could include seismic hazard in the current heading.

> *Added seismic hazard to the current heading. (423)*

Lines 386-388: Edit sentence for clarity. I recommend splitting it into two sentences. Also, in Line 388, replace "metrics" with "observations".

> *Edited the sentence and changed "metrics" to "observations." (433-435)*

Lines 388-390: Do these two observations or categories only apply to breached RIZs? If so, please make this clearer. In Line 390, what does "They" refer to? Only breached RIZs or all RIZs? Perhaps it is worth summarizing how the temporal evolution of RIZs are assessed, and what observations are associated with unbreached, partially breached, recently breached, and breached RIZs (according to Kolawole et al., 2022).

> *We have changed this paragraph and have included a summary of the expected observations for the different evolution stages of RIZs:*
>
> *"Recently breached and breached RIZs have an established breaching fault and connect the drainage of two different rift segments, but breached RIZs show less topography due to increased subsidence during the longer time period since the RIZ was breached. Unbreached RIZs show no apparent structural connection and no drainage connection, while partially breached RIZs may have a breaching fault partially connecting the rift basins but the drainage integration has not occurred yet. The different RIZ stages come with distinct morphological responses and have relevance to the seismic hazard so in the following we classify the two RIZs based on the Kolawole et al. (2021) classification scheme and assess the response of the geomorphic indices." (435-441)*

Lines 402-406: Here small-scale faults are described, but they are not shown on the maps in Fig. 7. Hence, it is difficult to observe the "complexity and distribution of faulting" in the Lingshi RIZ.

We marked the small-scale faults on the map in Fig. 8 (previously Fig. 7)

Lines 410-411: Rewrite sentence for clarity.

Rewrote sentence and combined with previous sentence:
"Li et al. (1998) proposed that during the early evolution of the Shanxi Rift in the Miocene and Pliocene, the basins were filled by isolated lakes and later, during the mid-Pleistocene, a fluvial connection was established." (461-463)

Lines 413-414: Why is the Lingshi RIZ classified as "recently" breached? Because breaching is thought to have occurred in the Late Pleistocene? See previous suggestion about clarifying how RIZs are classified.

The RIZ has been classified as recently breached due to the presence of 1) a breaching fault that connects the two basins and 2) a physical connection of the depositional systems of the Taiyuan and Linfen basin in the form of the Fen River. This is apparent both in the topographical Swath profile (Fig. 8) and the longitudinal river profile that we added to Figure 8, which agrees with the classification scheme of Kolawole et al. (2021). Adding the timing of the breaching to have occurred in the Pleistocene is speculative based on literature on this area. However, the classification as "recently breached" is purely based on its morphology.

Line 416: Is the Shilingguan Fault the breaching fault? If so, please make this clear. Also, the Jiaocheng Fault needs to be labelled on the map (Fig. 8a).

Yes, the Shilingguan Fault is the breaching fault of the Shilingguan RIZ – we have added this to the text (471-472) and have labelled the Jiaocheng Fault on Fig.9a

Lines 421-422: "Recent uplift" was already mentioned earlier in the same paragraph. Combine the two for conciseness.

Rewrote this part to avoid using recent uplift twice in this proximity. (474-477)

Lines 422-424: Refer to Fig. 2 here?]

Yes, good idea, included the reference to the figure here (477-479)

Lines 441-442: What is the general extension direction? Or is this a general statement about oblique faults (not limited to the Shanxi Rift)?

In the case of the Shanxi Rift the general extension direction is NW-SE (151° - Middleton et al. 2016) so the N-S fault are forming oblique to it but the statement was intended to be more general to highlight other areas where similar observations were made.

Lines 454-455: Could you please rewrite this sentence for clarity?

Done. Reworded to: "RIZs often experience increased seismic activity due to increased strain along the tips of established basin bounding faults that progressively link across the RIZs." (521-522)

Line 461-465: Specify the length of the Huoshan Piedmont Fault here for comparison to the shorter faults in the Shilingguan RIZ. Also, this is a long sentence that should be split into at least 2 sentences.

Split the sentence into three and added the length of the Huoshan fault: "The faults in the Shilingguan RIZ are comparatively short and segmented (10-20km), this might limit their ability to generate large magnitude earthquakes. However, the Huoshan Piedmont Fault, the breaching fault of the Lingshi RIZ) is equally segmented (Fig. 7a) with segments 20-30km in length and has shown to be the site of major historic earthquakes. The historic Hongdong Earthquake (Mw 7.2-7.6) in 1303 CE was caused by slip on the Huoshan Piedmont fault (Xu et al. 2018) and had an estimated rupture length of 98km, which shows that multiple segments can link up during seismic slip to generate larger magnitude events." (531-537)

Lines 466-468: This sentence feels a bit out of place and could be connected to a previous statement about shorter RIZ faults.

Moved this sentence to an earlier position in the paragraph for a more logical progression. (523-526)

Line 473: Samsu et al. (2023) is now published.

Fixed that and included the correct reference.

Lines 478-480: Rewrite this sentence for clarity.

Reworded the sentence for clarity: "Some of the rift faults do not contain Precambrian crystalline rocks in the footwall, but for example the Jiaocheng and Taigu faults in the direct vicinity of the crystalline Lüliangshan and Taihangshan massif (about 50km distance)." (552-554)

Lines 486-487: This headline statement could be moved further up to make the discussion easier to follow, e.g., to Line 477.

Moved this line to the start of the paragraph. (545-546)

Line 496: Upon observing Fig. 9, Hengshan Fault does not appear to follow the basement trend (at least not along its entire length), contrary to what is written in the text.

Agreed, it appears that the Hengshan fault only sometimes exploits the shallow basement fabrics, while other times cutting across it. We included two sentences to discuss this behavior which is similar to observations of the Bilila-Mtakataka Fault from Malawi (Hodge et al. 2018b) (565-568)

Lines 505-507: This is another headline statement that could be moved to the start of the paragraph.

Done. (560-561)

Lines 513-515: Zig-zag faults have been described in other studies (e.g., Lezzar et al., 2002; Corti, 2009; Hodge et al., 2018).

Added these further references to the paragraph, thanks for highlighting these. (587-588)

Lines 517-520: Here it would be good to mention the orientation of the regional strain (and cite the work that supports this, e.g., Middleton et al., 2017?). Also, have you considered whether (a) the geometry and relative timing of faults is influenced by the mechanical contrasts or weaknesses in the basement rocks, (b) rift-related faults that are still active and perturbing the stress or strain field as the RIZ faults form and grow, (c) we have a combination of a and b? Is there existing evidence of the main basin-bounding rift faults forming before the RIZ faults?

We propose that it is a combination of factors (c) – The main rift faults surrounding the RIZs perturbate the regional strain field in the RIZs, but the inherited structures of the basement rocks also influence the fault pattern, so instead of a regional strainfield that is orientated NW-SE (151 – Middleton et al. 2017) the local strain field (in the RIZs) is broadly E-W orientated. Some faults will follow the NE-SW trending basement structures, others will form perpendicular to the local strain field (N-S) – leading to the aforementioned zig-zag faults. The assumption that the main basin bounding faults formed before the RIZ faults is based purely on their morphology as they are larger, have accommodated more slip and often show more eroded fault scarps. Based on the work conducted in this study it is unfortunately not possible to make more concrete statements on the ages of these faults. It would also follow the pattern of RIZs in East Africa, where the basin bounding faults establish first and the breaching of the RIZs follows. We have edited the segment slightly to make this relationship clearer. (590-594)

Line 548: Molnar et al. (2020) presents analogue models, not numerical models.

Thanks for spotting the mistake, changed it to analogue models.

Lines 554-556: I appreciate that this is beyond the scope of this contribution, but I think it is useful to discuss in a bit more detail why the pre-existing lithospheric and crustal scale structures are not parallel, especially as you mention that this "could have either occurred during transpressional accretion of the Trans-North China Orogen or during later reworking by the polyorogenic event that formed the Trans-North China Orogen" (Lines 550-551) but do not explain this in more detail.

We tried not to go too far into this as at this point the paper already became quite lengthy, however we have added a bit more detail to this of one possibility. Kusky et al. (2007) propose one possible evolutionary model in which the TNCO (named Central Orogenic Belt (COB), the two are not technically the same as Kusky's evolutionary model has different implications for timing of the orogenic events) formed initially as an Archean Orogen at about 2.5 Ga, later the NCC collided with Columbia (~1.8 Ga) which reworked the Archean COB, which may have contributed to the oblique relation of crustal and mantle structures of the Archean-Palaeoproterozoic rocks in Shanxi. Similarly, Santosh et al. (2010) proposes a double-sided subduction to be responsible for the amalgamation of the NCC, with the TNCO being formed primarily along a (present-day) N-S trend with later subduction of the Columbia supercontinent from the North, which may have reworked some of the crustal *fabrics we see today. Li et al. (2010) show a protracted evolutionary history of the TNCO from 2.5-1.8 Ga where closure of the ocean separating started along a broadly N-S trend and then later from about 1.85 Ga onwards the collision of the Eastern and Western block culminated in formation of NE-SW structures, this could also explain the obliquity of a N-S trending relict subduction zone in the upper mantle and NE-SW trending crustal structures that formed during later collision. These are just three possible scenarios, and this is by no way complete. The formation of the NCC and TNCO is still very contested, and we prefer to not get involved into reconstructions of the various subduction zones active at different times that may have formed the NCC/TNCO. (623-629)*

We have added a bit more detail about these possible scenarios and the appropriate references.

Lines 558-559: Agostini et al. (2009) demonstrated this en-echelon arrangement of faults above a weak zone.

Added this to the sentence. (637-639)

Line 576: The last sentence is not a complete sentence.

Changed the sentence to make it into a complete sentence. (659)

Lines 584: Why is it a problem that lithology has a strong influence on the geomorphic signal? I think you could be more explicit that one of the aims is to see which geomorphic index is most useful for understanding the interaction between tectonics and landscapes – then this sentence would have a clearer meaning. I think you could also explicate this aim in the Discussion (Section 5.1).

If the differences between the faults were solely down to lithology that would severely affect the usefulness of geomorphic indices to evaluate the tectonic signal in the Shanxi Rift. If only faults with Palaeoproterozoic crystalline basement in the footwall would have high HI values while all faults with low grade metasediments in the footwall have low HI values the differences would probably be down to lithology. Yet, the fact that we have considerable spread within the two lithology groups (see Fig. 6) shows that tectonics most likely influenced the geomorphic signal of the various faults. This is best observed in HI on Fig. 6. While we think our results show that HI is the most robust of the three geomorphic indices, more detailed work would be needed to make a more concrete statement on this to eliminate other factors that might influence the geomorphic indices. We think this would be beyond the scope of this paper.

Figure 588-589: I don't recall where it was explained that linkage of sub-basins progressed towards the north.

Discussion on this has now been added following input from the third review by Folarin Kolawole. The evolution stages of the RIZs is less breached towards the North (Lingshi – recently breached; SLG – partially breached; Hengshan – unbreached) This may be related *to their geometrical arrangement. Discussion on this has now been added to Section 4.2 (486-494; 675-677)*

Lines 589-591: This sentence should directly follow the first sentence of the paragraph.

Done (673-674)

Figure 3: Label faults on this map. It would be good it the colors of the geological units here more closely matched the ones on Fig. 6.

Added labels to the faults and changed this figure significantly in response to comments from other reviewers

Figure 6: The colors of the different faults are a bit distracting, as they appear arbitrary here and do not correspond with colors on any of the maps. On the other hand, the background colors that indicate Mesozoic-Paleozoic sedimentary rocks vs. Proterozoic basement is quite useful.

Agreed, changed the colour scheme of the figure.

Figure 7: Label Taiyuan and Linfen basins and Fen River on map (e.g., Fig. 7a).

Done. (Fig.8a)

Figure 8: Label basins in Fig. 8a and 8d. What are the blue arrows in Fig. 8a showing?

Blue arrows show the approximate drainage direction of the Fen river and the Hutuo river, added labels to make this clearer and labeled the basins on 9a/d

Figure 9: Why does this figure appear so late in the text? I think this figure could really aid earlier explanations, including Section 5.1. Also, what do "high", "medium", and "low" geomorphic signals mean? Can these signals be quantified? Definitions of the abbreviations of fault names are missing in the caption.

High, medium and low geomorphic signals are based on the responses of the faults to the three analysed geomorphic indices. As a general principle we assume faults that are characterized by low responses to all three indices to have a "low" geomorphic signal, while high responses to all of these being "high". We are aware that this classification is somewhat arbitrary, but we think it is helpful in this figure to give an overall overview. Details of this are now presented in Table 1.

Figure S3 (incorrectly labelled as S2): Why is this map in the supplementary information? It nicely shows the spatial relationship between earthquakes and faults (especially in the RIZs), which would be a useful visual aid for setting up the research problem (Introduction) and the discussion in Section 5.2. Is there a way to elegantly combine this map with Fig. 2?

Based on this being brought up by this and another review, we have decided to combine this with Figure 2, to show the recorded seismicity earlier in the text.