REPLY TO REVIEWER 2

In this document, we have replied to comments on our Solid Earth Discussion article 'A systems-based approach to parameterise seismic hazard in regions with little historical or instrumental seismicity: The South Malawi Active Fault Database' (SE-2020-104) by Reviewer 2 (Folarin Kolawole). In italics are the reviewer's comments, which have been copied from the original review, and in blue cambria text are our replies to them with how we would like to incorporate them into a revised manuscript to submit to Solid Earth.

Kind regards
Jack Williams (on behalf of all coauthors)

*This manuscript presents a new systematic approach useful for parametrizing seismic hazards in areas with limited instrumental seismicity. The study was carried out in the southern part of Malawi, and documents the large faults that are capable of accommodating medium-large magnitude earthquakes in the region, as well as the attributes of these faults that are relevant for the hazard analysis. Also, the study discusses both the seismic hazard and tectonic implications of the results, as well as the uncertainties in the estimates. I believe that this approach is great and useful in active plat boundary settings where there is poor earthquake monitoring infrastructure. Such settings abound in several continents, and seismic instrumentation is expensive; thus, necessitating a need for creative, less expensive approaches as presented in this study. The manuscript is well written and easy to read. I believe that this manuscript contains material fit for publication in EGU Solid Earth.*

*However, I believe this manuscript could appropriate for publication in the journal after moderate revisions to the paper. I'm recommending moderate revision because of the issues I consider to be major flaws in the interpretation of the tectonic domains and associated structural elements in the study area, which directly impact either the input data or specific features of the implementation of the analysis performed in the study. Here below, are the 7 major issues I have with the manuscript, and 2 comments/questions that I think the authors could consider incorporating into the discussion part of the manuscript. Also, I made comments in different parts of the text that are either minor corrections/comments, or are related to the major issues stated below (see attached an annotated pdf).*

*Regards, Folarin Kolawole*

***Major Issues***

*Major Issue 1: The interchanging use of "southern Malawi" and "southern Malawi Rift". These two terms should not be used interchangeably in this text as it can bring confusion. "Southern Malawi" refers to a geopolitical region that hosts rift segments of different tectonic affiliations; whereas, "Southern Malawi Rift" refers to the southernmost segment of the Malawi Rift which includes only the Makanjita Trough & Malombe Graben (bifurcation around the Shire Horst), and the Zomba Graben. This interchanging use occurs at too many parts of the manuscript, so I decided to just mention it here instead of commenting on it in the text (attached pdf). This issue also leads to and is related to my Major Issue 2…see below.*

We acknowledge our interchangeable use of 'southern Malawi' and 'the southern Malawi Rift' will be confusing to readers not familiar with the area, and further adds to the confusion in the various ways that the southern end of the Malawi Rift has been defined previously (Chapola and Kaphwiyo, 1992; Chorowicz and Sorlien, 1992; Ebinger et al., 1987; Laõ-Dávila et al., 2015). In our revised submission, we will carefully outline that the database covers the geopolitical region of southern Malawi, as opposed to the southern 'Malawi Rift' (albeit with the necessity that it will include some faults that extend into Mozambique). This choice also reflects that seismic hazard is typically considered at a national level, and so it makes sense that active fault databases are defined by national, and not geological, boundaries, with the necessary exception that faults that cross geopolitical boundaries are included.

*Major Issue 2: Definition of principal grabens of the southern Malawi Rift. The authors identified the graben "Lower Shire Graben" as a principal graben of southern Malawi Rift (pg 19 lines 458-459). I have issue with the characterization of this graben as a tectonic element of the Malawi Rift. This is very misleading as this Lower Shire Graben is a sub-basin in the Shire Rift, not the Malawi Rift (Castaing, 1991). I understand that this graben is located within the Malawi geopolitical boundary, whereas most of the other sections of the Shire Rift are located in Mozambique. However, geopolitical location does not automatically make this graben a part of the Malawi Rift. Moreover, the Shire Rift has a distinctly different structure, orientation, and tectonic history from those of the southern Malawi Rift. Shire Rift is a multiphase rift basin (Mesozoic-Cenozoic; Castaing, 1991), whereas, southern Malawi Rift is Late Cenozoic (e.g., Wedmore et al., 2019; Scholz et al., 2020). Infact, exposed basement highs separate the Zomba Graben (which is at the southernmost tip of the Malawi Rift) from this Lower Shire Graben and the other sections of the Shire Rift. Therefore, in order not to confuse a reader, I'll suggest that the authors use the term "southern Malawi" in the context of describing the location of the 'Lower Shire graben' (i.e. use geographical description), rather than the term "southern Malawi Rift".*

As discussed above with reference to Major Issue 1, by explicitly outlining that the South Malawi Active Fault Database (SMAFD) and the South Malawi Seismogenic Source Database (SMSSD) cover the political region of southern Malawi, not the southern 'Malawi Rift,' we will address this comment.

*Major Issue 3: The descriptions of the "Makanjira Graben" in the manuscript and the modelling done in Fig.A3a shows that the authors consider that term to incorporate both the Makanjira Trough and Malombe Graben. The Malawi Rift bifurcates around the Shire Horst into these two segments and further south, they link-up and transition into the Zomba Graben. The Makanjira Trough is bounded to the west by Chirobwe-Ncheu Fault, and to the East by Shire Horst, whereas the Malombe Graben is bounded to the west by the Malombe Fault and to the east by the Mwanjage Fault. The surface+subsurface structure of this section of the Malawi Rift (Lao-Davila et al., 2015) shows that the Malombe Graben has a greater hanging wall subsidence and thus, border fault offset than the Makanjira Trough. Here are the evidences:*

1.) *The floor of the Makanjira trough is mostly dominated by exposed basement, whereas, the Malombe Graben is relatively better developed graben structure with a wider-spread sediment accumulation and even a lake development at the foot of its border fault. The zone of sediment accumulation on the northern half of the Makanjira trough is associated with subsidence along the southern extension of the N-S trending eastern border fault of the Nkhotakota Segment of the Malawi Rift (for location of Nkhotakota Segment see Lao-Davila et al., 2015; for the described subsidence and fault location, see Fig.5b of Scholz et al., 2020).*

2.) *The floor of the Makanjira half-graben is at a higher elevation compared to that of the Malombe Graben, indicating that subsidence is most-likely greater in the Malombe Graben. For reference see the across-rift profiles in Figs.4L-4M of Lao-Davila et al. (2015). I am guessing that the authors consider that because the Chirobwe-Nchue Fault has a higher footwall elevation/escarpment along the rift section, therefore, it must have the largest throw. If that is the consideration upon which the border fault definition and Fig.A3a model are based, I refer the authors to the Rukwa Rift where border fault footwall elevation/uplift is not representative of the subsurface fault throw (Morley et al., 1999). Thus, based on the observed geologic structure, I think the model in Fig.A3a is problematic because it ignores the presence of the fault with the larger offset and hanging wall subsidence at the so-called "Makanjira Graben". Also, the model assumes the Chirobwe-Ncheu to has the greatest offset/hanging wall subsidence along the profile which is not representative of the distribution*

> *of subsidence across this section of the rift (Figs. 4L-4M in Lao-Davila et al., 2015). Therefore, in my opinion, if possible, I think this model needs to be revised. If impossible due to modelling limitations, then it should be stated.*

Firstly, please note that the purpose of the profile in Figure A3a is not to construct a realistic across-rift cross-section. Instead, and as conducted by Shillington et al., (2020) for the northern Malawi Rift, it is to explore the range of flexural profiles across the rift that *may* have formed given the significant uncertainties in each variable that we must test. We recognise that this was not clearly indicated in the initial discussion paper, and we will clarify the purpose of this modelling in the revised manuscript.

We address the reviewer's concerns on how we define border faults and intrabasinal faults further below (Major Issue #4). In the context of the Malombe Fault, as the reviewer correctly points out, the Shire Horst divides the rift section that we term the Makanjira Graben. However, though this structure may have been important in the tectonic evolution of the rift (Laõ-Dávila et al., 2015), for the reasons outlined below we do not consider that it strongly influences the current distribution of extensional strain in the Makanjira Graben.

With respect to the reviewer's first set of concerns, we disagree that the 'Makanjira trough' is dominated by exposed basement with any sediment accumulation necessarily related to subsidence along the Nkhotakota rift segment: (1) geological maps and boreholes indicate that sediments have not just accumulated along the northern half of the Makanjira trough, but along its entire length (Dawson and Kirkpatrick, 1968; Walshaw, 1965; Figure 1b of our discussion paper) and including to the south of the Nkhotakota fault as mapped by Scholz et al., (2020), (2) there is geomorphic evidence of recent multiple earthquakes along the Bilila-Mtakataka Fault (BMF; Hodge et al., 2018, 2019, 2020; Jackson and Blenkinsop, 1997), indicating that this is a highly active part of the rift capable of creating accommodation space for sediment accumulation, (3) boreholes indicate that these sediments in this section of the rift thicken to the west against the BMF (Dawson and Kirkpatrick, 1968; Walshaw, 1965), indicating that it is the BMF not the Nkhotakota fault that is primarily generating accommodation space, and (4), where there is exposed basement in the hanging-wall of the Chirobwe-Ncheu fault, this can be related to footwall uplift of the interior BMF (Lines 263-267 of the discussion manuscript).

With respect to the reviewer's second concerns, the higher elevation of the Makanjira trough relative to the Malombe trough does not require that these should be separated as distinct basins. There are other (albeit smaller) horst structures and basement highs that the Malawi Rift bifurcates around in the Central and North Basins of Lake Malawi (Ebinger et al., 1987; Scholz et al., 2020; Shillington et al., 2020). These also result in complex across-rift topography; however, they have not necessitated the division of the rift across strike. We suggest too that the formation of Lake Malombe does not require that the Malombe Fault has accommodated considerable throw as: (1) it only extends across the northern section of the fault and (2) it has a maximum depth of 5 m (Weyl et al., 2004). Indeed, this part of the rift has very little variation in subsidence with the Shire River experiencing only a 1.5 m drop in elevation in the 85 km distance between Mangochi and Liwonde; (Dulanya, 2017).

We agree with the reviewer that ideally subsurface data should be used to characterise the structure of the Malawi Rift. However, south of Lake Malawi, such data are scarce, and in their absence, we prefer to use the data we *do* have from the rift's topography and basement-penetrating boreholes to characterise its structure (Figure 2b; Bloomfield, 1965; Bloomfield and Garson, 1965; Walshaw, 1965). Cumulatively, we suggest that these observations indicate that the Malombe Fault should be considered as an intrabasinal fault (see Major Issue #4), albeit it could be one with considerable displacement (>500 m). In this context, it could be considered similar to some of the high displacement horst-forming intrabasinal faults (up to 2.5 km throw) in Lake Malawi (Scholz et al., 2020; Shillington et al., 2020).

To further demonstrate how we have used topography and borehole data to characterise the rift's structure, we propose that in the revised manuscript we would include across-rift cross sections for each basin in southern Malawi. For the Makanjira Graben cross section, as highlighted by the reviewer, we will note the Shire Horst structure and the lower elevation in the eastern side of the graben, as these structures were not described in sufficient detail in the discussion paper. Also note that Figure 4L-M in Lao-Davila et al. 2015 would not be a good reference for such a figure, as although they suggest a ~500 m thick sequence of sediments in the Malombe Trough, it is not clear what evidence they have for this assertion.

*Major Issue 4: Age of the Thyolo Fault and modelling of strain in Lower Shire graben (Fig. A3c and pg 37 lines 895-896, pg 38 lines914-915). The authors suggest that the Thyolo Fault is Karoo age. There is no evidence suggesting that there exists karoo-agesedimentary or volcaniclastic deposits on the hanging wall of the Thyolo Fault (Habgood, 1963; Habgood et al., 1973). Mesozoic activity along the Thyolo Fault would require subsidence of its hanging wall and creation of accommodation space for the deposition of volcanic and sedimentary sequences. Both Habgood (1963) and Castaing (1991) suggested that the Mwanza-Namalmbo Fault system is the eastern border fault of the Mesozoic Shire Rift. Castaing (1991) suggested that the Thyolo Fault is Cenozoic, bounding the currently active eastern domain of the Shire Rift. Therefore, I think this idea of Thyolo Fault being a Karoo fault needs to be revised except the authors provide data showing the presence of Mesozoic deposits on the hanging wall of the Thyolo Fault.*

In the context of a paper on active fault databases, the timing of Thyolo Fault activation is not important (the important part is that it is currently active). Nevertheless, in the context of our hanging-wall flexural modelling, we accept that we cannot prove the Thyolo Fault was active during the Karoo. However, equally, it cannot be proved that it was inactive during the Karoo, as its hanging-wall stratigraphy is poorly constrained.

We therefore suggest that in our revised hanging-wall flexure strain modelling, we will now also consider a scenario where the Thyolo Fault has only been active during East African Rifting and so has a hanging-wall sedimentary thickness equivalent to the maximum proven thickness of EAR sediments in its hanging-wall (64 m; Habgood, 1963). In this case, the flexural strain in its hanging-wall will be even less than previously modelled, and so if anything, will further support this analysis main finding; that hanging-wall flexural strain in southern Malawi is negligible.

*Major Issue 5: Definition of "border fault" in southern Malawi (Fig. 2a). The Lisungwe Fault, Malombe Fault, and Mwanza Faults are excluded from the 'border fault' definition and I am not particularly sure why. This is an issue for me, particularly because the structure of the basins point directly to the essence of these faults. For example, the Malombe Fault is the principal border fault of the Malombe Graben, not the Mwanjage Fault which you've assigned as the main border fault. Even the distribution of the amplitudes and wavelengths of the magnetic fabrics beneath the Malombe Graben in Fig.2c (Laõ-Dávila et al., 2015) clearly shows that the hanging wall of the Malombe Fault has significantly larger subsidence than that of the Mwanjage Fault. Also, the Mwanza Fault is a major border fault of the NW half of the Shire Rift (as shown in the maps in Figure 2). There is also evidence that the exposed segment of the Mwanza fault has been reactivated in the Cenozoic given by accumulation of Quaternary sediments on its hanging-wall (Habgood 1963).*

We thank the reviewer for bringing these points to our attention, and for demonstrating that the classification of border faults and intrabasinal faults is not always as clear-cut as the manuscript suggests in its current form. In the resubmitted manuscript, we will include a section where we more explicitly define the difference in border and intrabasinal faults, and how this was applied to southern Malawi (including the use of geological cross sections as outlined for Major Comment #3). We define border faults using the simplest geometric criteria: the fault at the edge of the rift's surface expression. In other words, this definition is purely based on the geometry and distribution of brittle deformation across the rift. This definition is not inconsistent with differences between border and intrabasinal faults noted in previous studies (e.g. cumulative offset, slip rate, length; Agostini et al., 2011; Ebinger, 1989; Gawthorpe and Leeder, 2000; Muirhead et al., 2019; Wedmore et al., 2020b), but equally this definition is not dependent on these factors.

To specifically reply to the reviewer's comments on individual faults: the justification for not including the Malombe Fault as a border fault is discussed in Major Comment #3. With regards to the Mwanza Fault, we agree that it has been active during the East African Rifting, hence its inclusion in the SMAFD. Nevertheless, on the basis of the reviewer's comments and more recent mapping by Daly et al.,( 2020) that suggests this part of the rift may extend further into Mozambique and the Lower Zambezi Rift where it forms a different microplate boundary (Angoni-San), we will consider the Mwanza Fault as the border fault of a different rift section to the Lower Shire Graben. Unfortunately, in this case there are no geodetic constraints on the extension rate across the Zambezi Rift. In this case, we will calculate fault slip rates using values of between 0.2-1 mm/yr, where the lower estimate represents the minimum strain accrual measurable by geodesy (Calais et al., 2016) and the upper estimate represents that extension rates in the Zambezi Rift are unlikely to be higher than in the Lower Shire Graben given that the Mwanza Fault has only accumulated EAR sediments along its south-eastern most extent (Habgood, 1963).

The topography at the western edge of the Zomba Graben, where it grades into the Kirk Plateau, is very complex and so it is difficult to fit the Zomba Graben into conventional half-graben/graben models (Wedmore et al., 2020a). In particular, there are a number of N-S trending deeply incised valleys that lie to the west of the Lisungwe Fault and which have been previously interpreted as 'rift valley faults' (Bloomfield and Garson, 1965, see Figure 1 below). In addition, there are a number ENE-WSW trending valleys that are interpreted as 'cross faults' (i.e. strike-slip) faults (Bloomfield and Garson, 1965). Though only one of these faults (the Wamkurumadzi Fault) meet our definition of being active and is included in the SMAFD (section 3.1 of the discussion paper), inclusion of this fault, and the generally complex topography, requires that the Lisungwe Fault does not meet the definition of the border fault as outlined above. In the revised manuscript, we will more carefully outline how we have come to this decision and hope that this study will stimulate further studies into the question of fault activity at the western edge of the Zomba Graben.

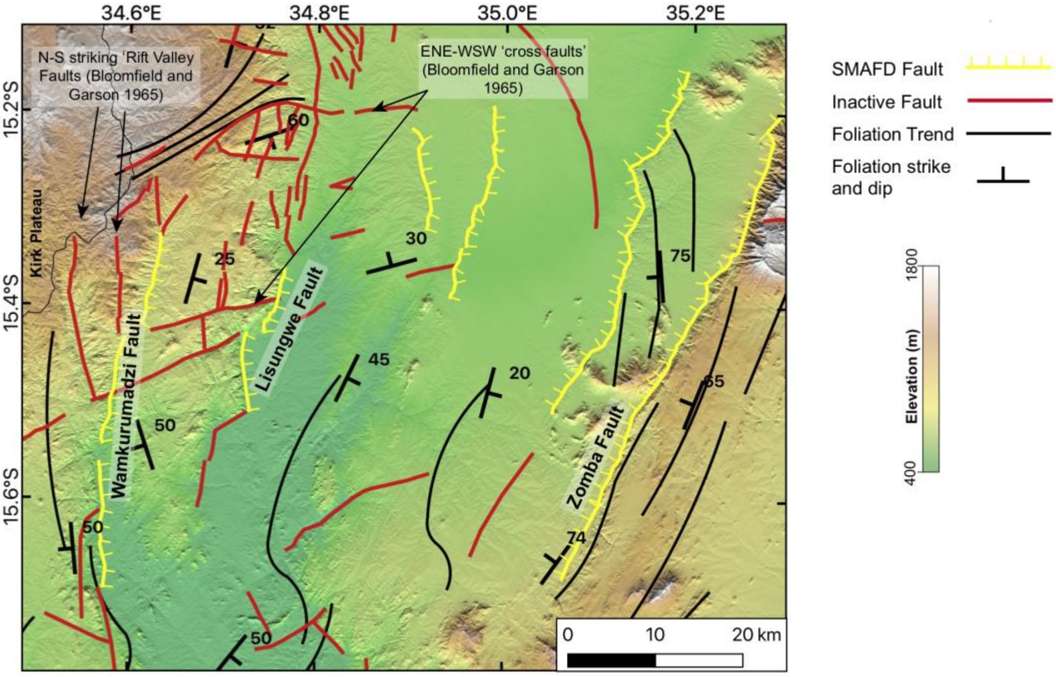

Figure 1: Fault map for Zomba Graben underlain by TanDEM-X 12 m resolution digital elevation model. 'Inactive faults' as mapped by Bloomfield and Garson, (1965). TanDEM-X data was obtained via DLR proposal DEM_GEOL0686.

*Major Issue 6: Related to "Issue 4" above, the authors classified Namalambo Fault as an active Fault (e.g., Figs. 1b & 2). Namalambo Fault cannot be classified as an East African Rift System Fault because there is no evidence supporting its Cenozoic reactivation (see Bloomfield, 1958; Habgood, 1963; Castaing, 1991). The mentioned geological reports specifically stated that there is no Quaternary sediment deposition on top of the karoo sedimentary units at the base of its scarp, suggesting it has not been reactivated in the Cenozoic. Also, this fault does not satisfy the criteria stated by the author in Pg11 lines 260-267. Are the authors including it because they're assuming that it could be reactivated sometime in the future? If yes, I think this should be stated in the relevant figure captions and in the manuscript (particularly because this fault is a prominent fault in the area, and could be confusing to a reader without this additional information).*

Although we noted in the database that the Namlambo Fault formed during Karoo-age rifting, we accept the reviewers comments that there is very little evidence for its reactivation during East African Rifting, and so in the resubmitted manuscript we will remove this fault from the SMAFD and include it in the 'Malawi Rift Inactive Fault' database instead.

*Major Issue 7 (minor): A 'declaration' that I think is not clearly made in the set-up of the premise of the manuscript is that the parameterization approach focuses on tectonically active continental settings. I do not think that the authors imply that the approach is applicable to relatively more stable intraplate settings where much lower strain rates generally abound and potentially dangerous faults are buried, although some of those areas could be seismically active (e.g., intraplate induced seismicity). Therefore, I'll suggest that the authors state this clearly, at least in the abstract and introduction sections of the paper. I noticed that in different parts of the text, it is subtly implied with phrases relating to plate boundary, interplate setting etc., however, I think it will be beneficial to the reader if this is stated clearer from the onset.*

The reviewer is correct that the approach outlined for characterising seismic hazard is most applicable to low strain rate regions (plate boundary slip rates 0.1-10 mm/yr; Scholz et al 1986), which are distinct from both high strain rate regions (plate boundary slip rates >10 mm/yr) *and* stable cratons (plate boundary slip rates <0.1 mm/yr). We will correct for this in the revised manuscript.

*Question/Comment 1: Pg29 lines 703-707. The authors highlighted the anomalously large seismogenic thickness of the southern Malawi area, with continuous 30-60 km long fault sections. Crustal thickness map of southern Malawi (Njinju et al., 2019a) shows that an unusually thick crust dominates the area. In addition, heat flow map of the same area (Njinju et al., 2019b) shows an anomalous thermal gap in the area. Both of these have been associated it with an eastern extension of the Niassa Craton. Do you think that there is a possibility that these have an impact on the observed seismogenic thickness?*

The contribution of low heat flow to the anomalously thick seismogenic crust in southern Malawi is acknowledged (Lines 183-186), however, we thank the reviewer for the suggested reference, which we will include in the revised manuscript. It is also worth noting that Fagereng, (2013) demonstrated that an anomalously low heat flow alone (63 mW/m$^{-2}$) is not sufficient to explain the thick seismogenic crust in this region, with other factors such as strain rate and crustal composition also important. Furthermore, the seismogenic crust is unusually thick throughout Malawi (>30 km), even in places where the heat flow is higher (e.g. 65-70 mW/m$^{-2}$ in Karonga; Ebinger et al 2019).

*Question/Comment 2: It is well-known that the patterns of seismogenic fault reactivation are influenced by the frictional stability of faults. Asides from strain rate and lithology/mineralogical composition, another important factor that influence the frictional stability is geothermal gradient/heat flow. Well-constrained heat flow & geothermal gradient maps of southern Malawi (Njinju et al., 2019b) show interesting thermal anomalies within the areas analyzed in this study. I am curious as to how the heat flow distribution in the area may affect the results/conclusions of this study.*

Although the reviewer raises an interesting point, as noted above there are other factors beyond heat flow that will control fault reactivation in this region. We consider that to discuss them all will go beyond the scope of this study, which is focussed on active faulting, not crustal rheology. Furthermore, classic Mohr-Coulomb theory suggests that brittle fault reactivation is temperature independent (Sibson 1985), although it will partially influence thickness of the seismogenic crust (as discussed above).

## *Comments on Reviewer Supplement*

*Line 31: This sentence, as it is written here, implies circular logic. This is because measurements of fault length is one of the inputs into your model estimates of EQ magnitude. How about "These potentially high magnitudes for continental normal faults are compartible with the observed 11-140 km-long faults and thick (30-35 km) seismogenic crust of southern Malawi."*

We will revise this sentence as the reviewer suggests

*Line 61: The repetition of "estimate" sound awkward...could reword as "fault slip rates can be estimated using geodetic constraints"?*

We will correct this in the revised manuscript as advised

*Line 87: I suggest a rewording of this text. Southern Malawi lies NEAR the southern incipient end of the EARS, not "AT" the end.*
*Rather, it is Central/Southern Mozambique that lies AT the southern incipient end of the EARS and has all those characteristics you've mentioned...see papers on the MOZART project (e.g., Fonseca et*

*al. (2014), Urema Graben, Mazenga Graben, Chissenga-Urema Graben System, and the Changani Graben System (Mueller & Jokat, 2019).*

We will correct this in the revised manuscript and outline that the Malawi Rift lies *near* the southern end of the EARS

*Line 112: I think the authors should include the Salambidwe Igneous structure (Cooper, 1961) and the flood basalts associated with the Lupata Volcanic Complex (footwall and hanging wall of the Panga Fault; Habgood, 1963).*

We thank the reviewer for noting these omissions and will include them in the revised manuscript

*Line 123: By definition, can a graben can be bounded by 1 border fault? I suggest need rewording*

We will replace 'graben' with 'basin' in the revised manuscript

*Lines 136-144: This paragraph is written with a mixed context that could create confusion...i.e. written with a context of a political territory (i.e. southern Malawi) and a rift basin (Malawi Rift). I will say this is very 'dangerous' as it propogates a very common problem with the way geology has been carried out in Africa for a very long time. Therefore, I will suggest that the authors stick to "Malawi Rift" since this study and this particular paragraph focuses more on tectonic history.*

*On the aspect of the evolution of the Malawi Rift, I will refer the author to Scholz et al. (2020) which demonstrates clearly the southward episodic propagation of the Malawi Rift. In addition, studies have showed that Karoo sandstones outcrop along the Karonga border fault of the Karonga Basin, and Accardo et al. 2018 observed an anomalous velocity interval that suggests highly lithified Karoo sedimentary rocks directly overlying the basement beneath the Karonga and Usisya Basin fill.*

As outlined for Major Issue #1 we will more carefully define the term 'Malawi Rift' in our revised manuscript, and note that the databases cover the political region of southern Malawi, not the Malawi Rift. We will incorporate the Scholz et al (2020) reference into the revised manuscript.

*Lines 146-150: The inferences made in this section, as written, sounds highly speculative, and since it is placed in the "geologic setting" section, I will suggest rewording. First, the text totally ignores the Malombe Graben as the primary hydrologic linkage between the Lake Malawi and the Zomba Graben (i.e. hosts the axial stream). Second, the text implies that sedimentation in the grabens referred to are only associated with flooding episodes. This is very strange to me. The area described is defined by the southward bifurcation of the Malawi Rift into two narrower branches: a graben in the east (Malombe Graben), another graben to the west (Makanjira Graben). The Malombe Graben has a well-developed lake from which the axial stream Shire River flows southwards. South of the bifurcation, the two branches merge back into a weakly-extended graben (Zomba Graben) south of which the basement is exposed and faulting is diffused. The point here is than the bifurcation troughs are actively subsiding, fault-bounded tectonic elements with structurally-controlled axial (Shire River) and transverse streams (from the rift flanks) channelling sediments into the subsiding basins. Thus, it is more likely that both faulting and climate control sedimentation within these basins, and not 'only climate' (as it is described here). For general reference on interactions between faulting and climate in humid rift settings, I refer the authors to Gawthorpe & Leeder (2000).*

In the revised manuscript we will note that faulting in the rift will have influenced sedimentation. Nevertheless, it should be noted that base level changes in Lake Malawi are thought to be primarily driven by climatic forcing (e.g. Scholz et al 2007; Lyons et al 2015).

*Lines 151-152: What does this sentence mean? ...you mean the steep gradient of the rift floor does not correspond to a fault escarpment? As this sentence is written, it precludes every form of structural control on the gradient...and I am highlighting this because this particular zone is a transfer zone between the Malawi Rift and the currently active part of the Shire Rift. Transfer zones in areas of incipient rifting are typically characterized by elevated/exposed basement...for reference, see Heilman et al. (2019) and Gawthorpe & Leeder (2000).*

This sentence refers to the point that no active faults were identified in the region between the Zomba and Lower Shire Graben from fieldwork and analysis of high resolution digital elevation models (although we of course cannot exclusively prove that there are no active faults in this region). We will clarify this in the resubmitted manuscript.

*Lines 157-158: First, I think it should also be added that the Castaing (1991) mapping was infact, only limited to the Shire Rift part of southern Malawi...the mapped faults in the paper did not extend into Southern Malawi Rift.*

*Second, I have seen a lot of these faults mapped previously in the Malawi Geological Survey reports (e.g., Bloomfield, 1958; Habgood, 1963; Habgood et al., 1973)... some of which were cited in this manuscript. I could see that the authors mentioned some of these faults on pg 12, however, I think the contributions should also be acknowledged here.*

We will make it clearer in the revised manuscript that Castiang (1991) only considered EARS faults in the Lower Shire. With respect to the second point, we are discussing the mapping of *active* faults. The previous Malawi Geological Survey reports, although an excellent resource, made few attempts to differentiate active and inactive faults (as described at Lines 284-291).

*Line 161: The mapping in the Geological Survey reports looks pretty fine-scale to me because they were done on the field. I think the detailed info on slip rates and recent faulting are the parts that are missing which this current study provide.*

We are referring here specifically to the Global Earthquake Model active fault database here (Christophersen et al., 2015; Styron and Pagani, 2020), which do not incorporate the faults mapped by the Malawi Geological Survey, but those mapped by Macgregor, (2015). We will clarify this in the revised manuscript

*Line 178-179: This sentence sounds weird with the "to 1965". Pls check*

We will revise this sentence in the resubmitted manuscript as requested.

*Lines 181-188: Wondering if it will also be worth mentioning the crustal thickness in southern Malawi (Njinju et al., 2019a; Tectonics), and heat flow distribution in southern Malawi (Njinju et al., 2019b; J. Volc. & Geoth. Res.)*

*Njinju, E.A., Atekwana, E.A., Stamps, D.S., Abdelsalam, M.G., Atekwana, E.A., Mickus, K.L., Fishwick, S., Kolawole, F., Rajaonarison, T.A. and Nyalugwe, V.N. (2019a). Lithospheric structure of the Malawi Rift: Implications for magma-poor rifting processes. Tectonics, 38(11), pp.3835-3853.*

*Njinju, E.A., Kolawole, F., Atekwana, E.A., Stamps, D.S., Atekwana, E.A., Abdelsalam, M.G. and Mickus, K.L. (2019b). Terrestrial heat flow in the Malawi Rifted Zone, East Africa: Implications for tectono-thermal inheritance in continental rift basins. Journal of Volcanology and Geothermal Research, 387, p.106656.*

As outlined for Question/Comment 1 we will incorporate these references into the revised manuscript.

*Lines 202-203: True. However, another possibility that could be mentioned here is local stress rotations (see Morley, 2010...case study on the Rukwa Rift).*

As discussed in Williams et al., (2019) stress rotations do not explain the discrepancy in extension direction when inferred from geodesy or earthquake focal mechanisms in southern Malawi, as the orientation of recent joint sets in the region is uniform across the rift suggesting that the regional stress field is uniform. Furthermore, the hypothesis of Morley, (2010) is that that stress rotations reflect changes in foliation orientation, in which case it would not account faults locally cross cutting the foliation in southern Malawi.

*Line 237: also depth of medium-large magnitude EQ ruptures?*

We will include focal depth as a factor of whether an earthquake ruptures to the surface in the revised manuscript

*Line 250: "little" sounds awkward here, because how little is "little"? I'll suggest "limited" instead*

We will clarify this in the revised manuscript, and note that there is some limited dating from <10 ka sediments around Lake Malombe (Van Bocxlaer et al., 2012) and <50 Ka sediments 20-30 km east of the rift around Lake Chilwa (Thomas et al., 2009).

*Lines 458-459: See comments in 'major issues'.*

See reply to comment on Major Issue 3

*Lines 464-464: Isn't this graben is known as the Urema Graben/Rift (Castaing, 1991; Fonseca etal. 2014; Lloyed et al., 2019). Why give it a different name?*

*Castaing, C. (1991), Post-Pan-African tectonic evolution of South Malawi in relation to the Karroo and recent East African rift systems. Tectonophysics, 191(1-2), pp.55-73.*

*Fonseca, J.F.B.D., Chamussa, J., Domingues, A., Helffrich, G., Antunes, E., van Aswegen, G., Pinto, L.V., Custódio, S. and Manhiça, V.J., 2014. MOZART: A seismological investigation of the East African Rift in central Mozambique. Seismological Research Letters, 85(1), pp.108-116.*

*Lloyd, R., Biggs, J. and Copley, A., 2019. The decade-long Machaze–Zinave aftershock sequence in the slowly straining Mozambique Rift. Geophysical Journal International, 217(1), pp.504-531.*

As for the Malawi Rift, there is little consensus on the extent of the Urema Graben (see also, Steinbruch, (2010) which suggest it refers to mainly the basins around the river Urema 150 km along strike to the south). Our preference here is to avoid using this term as it may imply that our fault mapping covers the full extent of the Urema Graben, and this will be clarified in the revised manuscript.

*Lines 473-474: Does this estimate include subsurface measurement of the total throw at the hanging wall cut-off of the faults? Please, provide reference. Also, based on the wording, does this refer to southern Malawi Rift (excluding the 'Lower Shire Graben') or does it refer to all the faults in southern Malawi geopolitical boundary?*

Yes, this estimate includes the limited subsurface data that does exist in southern Malawi (i.e. groundwater boreholes; Bloomfield, 1965; Bloomfield and Garson, 1965; King and Dawson, 1976; Walshaw, 1965), and we will clarify this in the revised manuscript.

*Lines 687-689: For the sake of the reader, I think the hazard part should be stated before implications for continental rift as seismic hazard is the primary focus of this study. Thus, I'll suggest a rewording to: "In the following section, we examine some key results of the SMAFD in terms of its implications for seismic hazard in southern Malawi, its contribution to our understanding of fault growth in continental rifts, and future strategies to...".*

As discussed with respect to the comments for Lines 690-711 from Reviewer #1, we will be removing this section on 'controls on fault growth in southern Malawi' in the revised manuscript.

*Line691: This relates to my comment above... While this section is important and relevant, for the reader, it seems like a sudden digression from the seismic hazard story to bring it in at this early part of the discussion. Pls consider swaping it with '6.2 Implications for seismic hazard in southern Malawi'.*

See our reply to the previous comment.

*Line 694: Could also include Scholz et al. (2020)*

*Scholz, C.A., Shillington, D.J., Wright, L.J., Accardo, N., Gaherty, J.B. and Chindandali, P., 2020. Intrarift fault fabric, segmentation, and basin evolution of the Lake Malawi (Nyasa) Rift, East Africa. Geosphere.*

We thank the reviewer for bringing this article to our attention, and will incorporate it into the revised manuscript.

*Line 843: growth,*

We will correct this grammatical error in the revised manuscript

*Line 895-896: This statement, as written, is misleading. Please revise. Castaing (1991) argued that the Thyolo Fault is Cenozoic and along with the reactivated Mwanza Fault, is accommodating strike-slip in present day. He suggested that the Mwanza Fault was the primary eastern Karoo and Cretaceous border fault of the Shire Rift. See pages 65-66 and figs. 7,9,&10 of Castaing et al. (1999).*

In the revised manuscript, we will correct the Castaing, (1991) reference to state that he did not consider the Thyolo Fault to have been active during the Karoo.

*Lines 897-899: This statement, as written, is speculative. As I explained in my "Major issues 1 & 2", the Shire Rift is a multiphase rift of which the Lower Shire graben is the easternmost sub-basin. The Malawi Rift and Shire Rift have different tectonic histories and structure, and only linked up at the current location of southern Zomba Graben. Although the development of the Lower Shire graben could be syn-tectonic with the southward propagation of the Malawi Rift, the pre-rift and early-phase structures in the Shire Rift (which are absent in the Zomba and Makanjira grabens) could greatly impact the strain in the Lower-Shire Graben...e.g., consider the influence of the mechanical load of the thick sequences of volcanic flows in the hanging wall of the Panga Fault and buried Mwanza Fault (all beneath a part of the Lower-Shire graben), which could impact the throw on the Thyolo Fault. Thus, in the absence of actual subsurface data on Thyolo fault throw, I think it is speculative to make a statement like this. I understand that there is a need to assume a maximum throw limit for the* *modelling, thus, I'll suggest that the authors revise this sentence by stating that the estimate is an assumption.*

We will correct the revised manuscript to state that these are assumptions that we have made about the throw of the Thyolo Fault, which though speculative do not invalidate the results of our modelling. See also our reply to Major Issue #4.

*Lines 900-901: See my comments in "Major Issue 3" related to the structure of this rift segment as implemented in the model.*

See our reply to Major Issue #3

*Line 909: The lower Shire graben is no more than 38-40 km wide (at its widest). I'm curious to know how the extent of this basin is estimated?*

This was estimated from the combined width of the Karoo and EARS sections of the Lower Shire Graben (i.e. it incorporates the Karoo deposits in the footwall of the Panga Fault). We will correct this in the revised flexural modelling, so that for the modelling where the Thyolo Fault is assumed to be an EARS-only fault (see Major Issue #4), we only considers the extensional strain over a 40 km wide rift, which is the width of EARS sediments in the Lower Shire Graben.

*Line 914-915: This statement assumes that the Thyolo Fault is a Karoo-age border fault, which I think is problematic considering the observations in Castaing (1991). See "Major Issue 4".*

See our reply to Major Issue #4

*Line 1620/Figure 1b: For figure 1b: It will be very helpful if you can add symbols or number the colored polygons of the different terranes shown. The colored polygons are faded into the grey scale hillshade map which makes the color slightly different from the ones shown in the legend....by adding symbols or numbering, it makes it easier for the reader to identify where what terrane is.*

We will add text labels for the terranes in the revised manuscript

*Line 1621/Figure 1a: I'll suggest that you include the Aswa Shear Zone to this map as it is one of the most well-known lithospheric-scale shear zones in East Africa (see Daly et al., 1989; Ruotoistenmäki et al., 2014; Katumwehe et al., 2016; Saalmann et al., 2016). Other ones you could also include are the Lurio Shear Zone and the Sanangoe Shear Zone.*

We included the Aswa Shear Zone, as mapped by Fritz et al., (2013) in Figure 1a, but will revise the extent in the resubmitted manuscript as per the updated references the reviewer suggests. We will also include the other shear zones noted by the reviewer.

*Line 1639/Figure 2c: You might want to check the N-striking (80deg-dip) foliation anotated on the Namalambo Fault in Fig2c. The foliation trends in the Nsanje horst are NE-trending. The Namalambo Fault cuts the foliation. For reference, see "Structual Map of the Northern PortHerald Hills" in Bloomfield (1958).*

As suggested by the reviewer, we will remove this strike and dip measurements to reflect the regional NE-striking fabrics in the Nsanje Horst (albeit with local variations).

*Line 1732/Figure A3: The orientation of the Zomba and Lower Shire profiles should also be stated in this caption.*

We will include the orientation of these profiles in the revised manuscript.

*Line 1736/Figure A3: You mean WSW-ENE?*

Yes, this will be corrected in the revised manuscript

## References

- Agostini, A., Bonini, M., Corti, G., Sani, F. and Manetti, P.: Distribution of Quaternary deformation in the central Main Ethiopian Rift, East Africa, Tectonics, 30(4), doi:10.1029/2010TC002833, 2011.
- Bloomfield, K.: The Geology of the Zomba Area, Bull. Geol. Surv. Malawi, 16, 1965.
- Bloomfield, K. and Garson, M. S.: The Geology of the Kirk Range-Lisungwe Valley Area, Bull. Geol. Surv. Malawi, 17, 1965.
- Van Bocxlaer, B., Salenbien, W., Praet, N. and Verniers, J.: Stratigraphy and paleoenvironments of the early to middle Holocene Chipalamawamba Beds (Malawi Basin, Africa), Biogeosciences, 9(11), 4497–4512, doi:10.5194/bg-9-4497-2012, 2012.
- Calais, E., Camelbeeck, T., Stein, S., Liu, M. and Craig, T. J.: A new paradigm for large earthquakes in stable continental plate interiors, Geophys. Res. Lett., 43(20), 10,621-10,637, doi:10.1002/2016GL070815, 2016.
- Castaing, C.: Post-Pan-African tectonic evolution of South Malawi in relation to the Karroo and recent East African rift systems, Tectonophysics, 191(1–2), 55–73, doi:10.1016/0040-1951(91)90232-H, 1991.
- Chapola, L. S. and Kaphwiyo, C. E.: The Malawi rift: Geology, tectonics and seismicity, Tectonophysics, 209(1–4), 159–164, doi:10.1016/0040-1951(92)90017-Z, 1992.
- Chorowicz, J. and Sorlien, C.: Oblique extensional tectonics in the Malawi Rift, Africa, Geol. Soc. Am. Bull., 104(8), 1015–1023, doi:10.1130/0016-7606(1992)104<1015:OETITM>2.3.CO;2, 1992.
- Christophersen, A., Litchfield, N., Berryman, K., Thomas, R., Basili, R., Wallace, L., Ries, W., Hayes, G. P., Haller, K. M., Yoshioka, T., Koehler, R. D., Clark, D., Wolfson-Schwehr, M., Boettcher, M. S., Villamor, P., Horspool, N., Ornthammarath, T., Zuñiga, R., Langridge, R. M., Stirling, M. W., Goded, T., Costa, C. and Yeats, R.: Development of the Global Earthquake Model's neotectonic fault database, Nat. Hazards, 79(1), 111–135, doi:10.1007/s11069-015-1831-6, 2015.
- Daly, M. C., Green, P., Watts, A. B., Davies, O., Chibesakunda, F. and Walker, R.: Tectonics and Landscape of the Central African Plateau and their Implications for a Propagating Southwestern Rift in Africa, Geochemistry, Geophys. Geosystems, 21(6), doi:10.1029/2019GC008746, 2020.
- Dawson, A. L. and Kirkpatrick, I. M.: The geology of the Cape Maclear peninsula and Lower Bwanje valley, Bull. Geol. Surv. Malawi, 28, 1968.
- Dulanya, Z.: A review of the geomorphotectonic evolution of the south Malawi rift, J. African Earth Sci., 129, 728–738, doi:10.1016/j.jafrearsci.2017.02.016, 2017.
- Ebinger, C. J.: Tectonic development of the western branch of the East African rift system, Geol. Soc. Am. Bull., 101(7), 885–903, doi:10.1130/0016-7606(1989)101<0885:TDOTWB>2.3.CO;2, 1989.
- Ebinger, C. J., Rosendahl, B. R. and Reynolds, D. J.: Tectonic model of the Malaŵi rift, Africa, Tectonophysics, 141(1–3), 215–235, doi:10.1016/0040-1951(87)90187-9, 1987.
- Fagereng, Å.: Fault segmentation, deep rift earthquakes and crustal rheology: Insights from the 2009 Karonga sequence and seismicity in the Rukwa-Malawi rift zone, Tectonophysics, 601, 216–225, doi:10.1016/j.tecto.2013.05.012, 2013.
- Fritz, H., Abdelsalam, M., Ali, K. A., Bingen, B., Collins, A. S., Fowler, A. R., Ghebreab, W., Hauzenberger, C. A., Johnson, P. R., Kusky, T. M., Macey, P., Muhongo, S., Stern, R. J. and Viola, G.: Orogen styles in the East African Orogen: A review of the Neoproterozoic to Cambrian tectonic evolution, J. African Earth Sci., 86, 65–106, doi:10.1016/j.jafrearsci.2013.06.004, 2013.

- Gawthorpe, R. L. and Leeder, M. R.: Tectono-sedimentary evolution of active extensional basins, Basin Res., 12(3–4), 195–218, doi:10.1111/j.1365-2117.2000.00121.x, 2000.
- Habgood, F.: The geology of the country west of the Shire River between Chikwawa and Chiromo, Bull. Geol. Surv. Malawi, 14, 1963.
- Hodge, M., Fagereng, A., Biggs, J. and Mdala, H.: Controls on Early-Rift Geometry: New Perspectives From the Bilila-Mtakataka Fault, Malawi, Geophys. Res. Lett., 45(9), 3896–3905, doi:10.1029/2018GL077343, 2018.
- Hodge, M., Biggs, J., Fagereng, A., Elliott, A., Mdala, H. and Mphepo, F.: A semi-automated algorithm to quantify scarp morphology (SPARTA): Application to normal faults in southern Malawi, Solid Earth, 10(1), 27–57, doi:10.5194/se-10-27-2019, 2019.
- Hodge, M., Biggs, J., Fagereng, Mdala, H., Wedmore, L. N. J. and Williams, J. N.: Evidence From High-Resolution Topography for Multiple Earthquakes on High Slip-to-Length Fault Scarps: The Bilila-Mtakataka Fault, Malawi, Tectonics, 39(2), e2019TC005933, doi:10.1029/2019TC005933, 2020.
- Jackson, J. and Blenkinsop, T.: The Bilila-Mtakataka fault in Malawi: an active, 100-km long, normal fault segment in thick seismogenic crust, Tectonics, 16(1), 137–150, doi:10.1029/96TC02494, 1997.
- King, A. W. and Dawson, A. L.: The Geology of the Mangochi-Makanjila Area, Bull. Geol. Surv. Malawi, 35, 1976.
- Laõ-Dávila, D. A., Al-Salmi, H. S., Abdelsalam, M. G. and Atekwana, E. A.: Hierarchical segmentation of the Malawi Rift: The influence of inherited lithospheric heterogeneity and kinematics in the evolution of continental rifts, Tectonics, 34(12), 2399–2417, doi:10.1002/2015TC003953, 2015.
- Macgregor, D.: History of the development of the East African Rift System: A series of interpreted maps through time, J. African Earth Sci., 101, 232–252, doi:10.1016/j.jafrearsci.2014.09.016, 2015.
- Morley, C. K.: Stress re-orientation along zones of weak fabrics in rifts: An explanation for pure extension in “oblique” rift segments?, Earth Planet. Sci. Lett., 297(3–4), 667–673, doi:10.1016/j.epsl.2010.07.022, 2010.
- Muirhead, J. D., Wright, L. J. M. and Scholz, C. A.: Rift evolution in regions of low magma input in East Africa, Earth Planet. Sci. Lett., 506, 332–346, doi:10.1016/j.epsl.2018.11.004, 2019.
- Scholz, C., Shillington, D., Wright, L., Accardo, N., Gaherty, J. and Chindandali, P.: Intrarift fault fabric, segmentation, and basin evolution of the Lake Malawi (Nyasa) Rift, East Africa, Geosphere, doi:10.1130/GES02228.1, 2020.
- Shillington, D. J., Scholz, C. A., Chindandali, P. R. N., Gaherty, J. B., Accardo, N. J., Onyango, E., Ebinger, C. J. and Nyblade, A. A.: Controls on Rift Faulting in the North Basin of the Malawi (Nyasa) Rift, East Africa, Tectonics, 39(3), e2019TC005633, doi:10.1029/2019TC005633, 2020.
- Steinbruch, F.: Geology and geomorphology of the Urema Graben with emphasis on the evolution of Lake Urema, J. African Earth Sci., 58(2), 272–284, doi:10.1016/j.jafrearsci.2010.03.007, 2010.
- Styron, R. and Pagani, M.: The GEM Global Active Faults Database, Earthq. Spectra, 1–21, doi:10.1177/8755293020944182, 2020.
- Thomas, D. S. G., Bailey, R., Shaw, P. A., Durcan, J. A. and Singarayer, J. S.: Late Quaternary highstands at Lake Chilwa, Malawi: Frequency, timing and possible forcing mechanisms in the last 44 ka, Quat. Sci. Rev., 28(5–6), 526–539, doi:10.1016/j.quascirev.2008.10.023, 2009.
- Walshaw, R. D.: The Geology of the Nchue-Balaka Area, Bull. Geol. Surv. Malawi, 19, 1965.
- Wedmore, L. N. J., Biggs, J., Williams, J. N., Fagereng, Dulanya, Z., Mphepo, F. and Mdala, H.: Active Fault Scarps in Southern Malawi and Their Implications for the Distribution of Strain in Incipient Continental Rifts, Tectonics, 39(3), e2019TC005834, doi:10.1029/2019TC005834, 2020a.

- Wedmore, L. N. J., Williams, J. N., Biggs, J., Fagereng, Å., Mphepo, F., Dulanya, Z., Willoughby, J., Mdala, H. and Adams, B. A.: Structural inheritance and border fault reactivation during active early-stage rifting along the Thyolo fault, Malawi, J. Struct. Geol., 139, 104097, doi:10.1016/j.jsg.2020.104097, 2020b.
- Weyl, O. L. F., Mwakiyongo, K. R. and Mandere, D. S.: An assessment of the nkacha net fishery of Lake Malombe, Malawi, African J. Aquat. Sci., 29(1), 47–55, doi:10.2989/16085910409503791, 2004.
- Williams, J. N., Fagereng, Å., Wedmore, L. N. J., Biggs, J., Mphepo, F., Dulanya, Z., Mdala, H. and Blenkinsop, T.: How Do Variably Striking Faults Reactivate During Rifting? Insights From Southern Malawi, Geochemistry, Geophys. Geosystems, 20(7), 3588–3607, doi:10.1029/2019GC008219, 2019.