Review Report

Alghuraybi et al., A Snapshot of the Earliest Stages of Normal Fault Growth, TEKTONIKA, 2023.

- Executive editor: Gwenn Peron-Pinvidic
- Handling associate Editor: Frank Zwaan

Review process summary:

The manuscript was submitted on 6 December 2022, was assigned to the handling editor on 8 December 2023, and went into review on 14 December 2023. Two reviewers (Lisa McNeill and Vincent Roche) agreed to assess the manuscript and both reviews were received on 10 February 2023. Based on these reviews, minor revisions were requested, and a revised version of the manuscript was submitted on 19 April 2023. The editors requested some additional revisions, after which the final version of the manuscript was submitted on 19 June 2023 and accepted for publication on 3 July 2023.

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1st Round of Revisions

Decision Letter

2 May 2023

Dear Authors,

Many thanks for resubmitting a new version of your manuscript, and for providing a detailed reply to the previous review comments.

We have evalutated your resubmiteed manuscript and although we like the overall paper and the reviews were positive, we identified two main issues that need attention before it can be considered for publication:

1) Structure: the current text mixes data, interpretation and discussion. It is important that these are strictly separated to avoid any confusion. This will mean that some text needs to be move from the results section to the discussion section of the manuscript. Note that also some parts of the introduction seem to be out of place.

2) Figure count. Both reviewers commented that the number of figures is too high, and we agree with them, even though we did not specify this in our previous email. The reviewers suggested to move some of the figures to the appendix. We propose another solution: it seems quite possible to simply merge some of the figures to reduce the figure count: 1+2, 4+5, 7+8, 9+10, 11+12 and 14+15. That could be a nice compromise.

NB: it would in general be nicest to fit figures in portrait mode pages, rather than landscape mode pages, if possiblem, in order to enhance readibility.

Please check the attached annotated PDF files (of the text and figures) for more detail on the main points, and for some additional points that require some attention.

If you have any questions, please let us know.

Kind regards,

Frank Zwaan (handling editor) & Gwenn Peron-Pinvidic (executive editor)

Comments by Reviewer 1

Lisa McNeill

This paper analyses the 3D pattern of fault slip and growth from a set of Jurassic-Cretaceous active, low slip rate faults from part of the N Atlantic margin/Barents Sea rift system, offshore Norway. The aim is to analyse how the fault grows laterally, how it compares with other fault datasets and how it compares with two competing fault growth models. The data are high quality and the analysis appears robust overall. The results suggest the faults grew laterally very rapidly and at much higher rates than their vertical slip rates. At first glance this seems unusual, and it is suggested to be a consequence of the faults being short lived/immature ie in their early stage of growth. The fault slip rates and aspect ratios are also low relative to others. As the authors point out, datasets like this are rare because most data lack the resolution to constrain growth rates well. The downside of this is that those that can be measured may be unusual (with fast growth rates) and we don't have many others to compare with, therefore there remain questions about how representative the results could be or what they mean. I have some comments on possible uncertainties in the results and the paper also needs to articulate why the results are significant. With some minor edits, it would be suitable for publication.

1. The paper is well written and easy to follow. There are just a couple of minor typos or missing words, but a read through should catch these. The figures are very nicely drafted. A large number of example faults (6?) are shown within the figures which I like. If the journal suggests the number of figures was too large, I think some of these could be moved into supplementary material without too much detriment to the paper. A suitable amount of supplementary material is included.
2. A very nice introduction and background to the problem is given. But something that's lacking here is a short section on why the results are important and relevant (the "who cares" part).
3. I found it interesting that the fault propagation/growth rates are so high for such low slip rate faults and low slip rates for relatively long faults (and for a fault set with very large aspect ratio). It's interpreted that this is because they are immature or rather not long lived (abandoned before reaching full maturity). But are these faults potentially unusual and therefore not typical of others for some other reason? And do low slip, low slip rate, long length faults, as studied here, behave in the same way as faster moving, shorter faults (or is that not the point)? Because it is not easy to quantify lateral propagation rates of faults, might you only find these results for a certain type of fault and therefore this could present problems for wider applicability? The authors do point out that faults active for short periods tend to have high lateral propagation rates. So are they typical and simply a dataset of early stage faulting (stated on line 287)? The exclusion of material properties limiting vertical propagation seems robust by the way, i.e., concluding the fault system is immature. In general it would just be good to

hear more in the paper about the wider relevance of the results.

4. The data are in time. How well known is velocity and to what extent might this be affecting the results? Where are the boreholes with the sonic (velocity) log data used for the time-depth conversion relative to the seismic profiles? An uncertainty of ±12% is mentioned for the two methods used, but is this between the two methods or some estimate of uncertainty relative to reality? I think it's the former (from looking at Appendix 3) but it should be clearer, plus the appendix spreadsheet file would benefit from some more explanation. Some comment on the veracity of the time-depth conversion is needed and its impact on the results. I think this is relevant because the offsets are small (e.g., as low as 10-20 ms) therefore small differences with depth in different units could make a difference (and some offsets are fairly close to the data resolution). In addition the small offsets may limit what can be resolved even before depth conversion. What is the error in simply measuring the offset?
5. The distribution of the palynological age information for the sequence is quite limited, ie mostly at the top and base of the sequence so horizon ages rely on interpolation. However for rate calculations only the section with ages are used (which is good). But this point only became clear when I reached section 4.2 of the paper, so I think you should explain this earlier in the paper, e.g., in the methods. In addition the age uncertainty for the palynological data is not mentioned. I do note that the authors acknowledge there's still uncertainty about timings of fault activity and hence rates within this period.
6. In lines 187-192, the wording should be clearer on how this indicates early establishment of fault length.
7. I wondered if the variable and quite complex vertical growth/propagation patterns of the faults (including potential vertical linkage) may introduce complications to the interpretations? It would be useful to include some statement about this.
8. Some parts of section 4.2 on fault growth rates could be more clearly written, i.e., the comparison with other fault datasets. Some parts were a bit confusing.

The compilation of data from a large number of fault datasets, for comparison, is useful and would be useful for future studies.

Comments by Reviewer 2

Vincent Roche

General comments:

The manuscript investigates fault growth based on detailed analyses of normal faults from the Barents Sea offshore Norway. The faults are imaged by high-quality 3D seismic reflection data, have low displacement, are Middle Jurassic-to-Early Cretaceous in age and are associated with Upper Jurassic growth strata. First, the authors present the overall geometry of the faults, discussing their length and throw, using time-structure maps, cross-sections, Dmax-L plots, throw-length profiles, throw-depth profiles and throw-strike projection. Then, they address the growth history refining the analysis of the syn-faulting strata based on isochron maps and expansion index. Finally, they investigate propagation and displacement rates and implications for growth models, i.e.' the fault propagation model' and the 'constant-length model'.

I think that the topic of this manuscript is relevant to the journal. In particular, the paper describes an interesting fault network using advanced methods and deals with the topical problem of fault development. Moreover, beyond the interpretation, the paper documents fault displacements, propagation, and displacement rates. All these make this study valuable for the journal and impactful for the structural geology community. Concerning the form, the paper is well-structured and well-illustrated, and although I am not native English, I think it is well-written. Nevertheless, I have a few major and minor comments (see below), and I think the paper should be considered for publication after a moderate/major revision.

Main points:

1. Fault tip. Throughout the manuscript, the authors discuss fault length. However, some of the studied faults seem to reach the end of the data according to the maps provided, e.g. F1, F3, F5, F8, F19, or intersect oblique faults, e.g. F2, F8, F10, F11, F13, F17. In this case, the fault length may not be complete. Maybe it is worth discussing this aspect in the paper and providing more details on the nature of the fault tips.
1. Non-mapped faults. Some faults visible in the maps and sections are not mapped, e.g. Figs 4B and 5A, 8B and 9B. I understand that this may be for illustrative purposes, but some of those faults may be important as they may be part of the interacting fault systems and control local throw variation or fault arrest. Therefore, I think those faults should be discussed or mapped. Of more concern, the authors should discuss the criteria they used to select the studied faults rather than the others.
1. Relay zones. The authors state that the studied faults are not associated with clear fault bends, abandoned splays or relays (L.161 and 218). First, I am not sure the data supports this. For example, we can see large stepping zones between F2 and F3 (or F1 and F2), F5 and F6, and F10 and F11, which could

be intact relay zones. Also, F15 and F16 seem to be the segments of the same fault, while F17 may be in a conjugate relay zone system (see Childs et al. 2019). Again, not counting for such potential relay zones raises the general question of defining the fault tips (i.e. unrestricted or tip restricted, according to Nicol et al. 1996). Second, beyond prominent stepping geometries like the ones aforementioned, the authors also identify multiple throw maxima along the same stratigraphic level for some faults (L.217). Some of those variations may be related to deformation partitioning with nearby faults. For example, the abrupt decrease in displacement in the Eastern part of F8 correlates with the location of F9 and its magnitude. Since such interaction/partitioning can control the displacement, it may be important to discuss their potential impacts on displacement and propagation rates analysis.

1. Propagation rates and displacement rates. The methodology concerning propagation and displacement rates could be further detailed (i.e. L.136-147 and 241-255). For example, it is unclear from my reading on which faults those rates are calculated. How many rates are calculated? Where are the displacement rates calculated? Also, is there any assumption on the sedimentation rates? Finally, why not include L.241-255 in the methodology section?

1. Lateral propagation versus slip rate. I am slightly confused with the slip rate to propagation rate ratio discussed in Section 4.2 and Fig. 16c. First, in theory, if we do Length/Time divided by Displacement/Time on the same time interval, are we not just looking at Length/displacement, which is the inverse of the displacement gradient on a specific time interval? Then, if we average that over the fault lifespan, isn't it Dmax/L? Second, how is this ratio indicative of the growth model? I understand that the authors suggest that faults propagating laterally much faster than accumulating displacement (Ratio >1) are more in line with the 'constant-length model', whereas they expect a ratio close to 1 for 'the fault propagation model'. But since faults typically have Dmax/L << 1, doesn't that mean that no fault grows with a ratio close to 1 on average? My point is that the ratio's absolute value may be less relevant than its variation over time. But I don't think there is such data in the present study. In any case, I will suggest that the authors clarify their model.

1. Early stage of faulting. The authors suggest that the studied network captured faults during the earliest stage of development when they were growing by the 'constant-length model'. According to this model, the fault grew first in length and then accumulated displacement. From my understanding, the fault was active Middle Jurassic to Early Cretaceous, i.e. 163.5 – 132.6 Ma. But most displacement and length occur during the first 6 Myrs (or 3.1 Myrs). Then the fault becomes primarily inactive. So for the sake of argument, could we argue that the data indicate that the fault grows according to the 'propagation model' with a relatively low displacement gradient? Then become inactive.

1. Figures. The paper is well illustrated, but there are many figures (i.e. 16).

Maybe Figs. 7-12 are not all necessary for the manuscript, and some should be in supplementary materials, considering that most of the information is provided in other figures, like Figs. 4, 5 and 15. Also, the figures are very data-oriented. Maybe, after removing some figures, the authors could provide additional schematic diagrams on the fault growth and growth history, theoretically or specifically for the studied faults.

Minor points:

- 16,132. Please define layer-bounded. It is a bit ambiguous here, considering those are growth faults.
- 25, 42, 269, 292. Please define fault maturity, as seismologists use such terminology.
- 200. Remove the extra bracket after 2003.
- 228. See also Roche et al., 2021 for the effect of layering on fault geometry.
- 243. 'Upper limit in the duration of fault activity'. Isn't that contradicting the faults active from Middle Jurrasic to Upper Cretaceous (L.158)?
- 246-253. This part is difficult to follow without illustration. Does that mean that the methodology is different from that in Fig. 3?
- 256 to 266: I found the analysis of Fig. 16 challenging. I suggest the authors help the reader a little, for example, using sentences like "compare red circles with black crosses".
- 303. See Roche et al., 2021, for aspect ratio values going up to 14.
- L306-309. But the faults are synsedimentary, so they cannot be restricted upward.
- 3. There is no X0 in B
- Figs 4 and 5. What happened to F4, F6, F12 and F20?
- 6B: There is no aspect ratio of F21.
- 16: Please indicate the number of measurements.

I hope this will help to improve the manuscript.

Authors' Reply Letter

19 April 2023

Dear Editors,

We would like to thank you and the two reviewers for your time and effort to consider this submission. We are grateful for their constructive feedback and helpful suggestions, which have helped improve the overall quality of the paper, and for their support for eventual publication. We have carefully gone through all the reviewers' comments and, we hope, addressed all their concerns in a revised version of our manuscript.

The two reviewers noted the value of using high-quality data and robust methods to study the growth of normal faults and, more specifically, the rather understudied topic of the rate at which they propagate laterally and accumulate displacement. The main criticism raised by the reviewers relates to considering uncertainties regarding the different data and methods used in our study, in addition to considering alternative interpretations.

We here provide a detailed (i.e., itemised) response to all comments, even in cases where we disagree with the reviewers' suggestion or assessment. Reviewers' comments are indicated by blue text, and by the manuscript section and line number where they were provided. Our responses are provided in a black text following each comment.

Many thanks again to the handling editor, executive editor, the Tektonika Editorial Team, and the two reviewers for their help with our submission.

Kind regards,

Ahmed Alghuraybi – on behalf of all coauthors

Authors' Reply to Editors' Comments

Abstract

1. L84 – Unclear what is meant here

- See response to comment 9 to reviewer 2

Geological Setting

2. Please develop the Geological Setting section adding information on what is the Barents Sea. In 2-3 sentences, summarize the global extensional history for readers who are not familiar with the area.

- We have updated the text to include more information about the geological setting. This text now reads **(L.114-121)**:

"We have studied a system of low-displacement (< ~150m throw), Middle Jurassic-to-Early Cretaceous normal faults in the SW Barents Sea offshore northern Norway (Fig. 1). The SW Barents Sea is a passive margin that experienced multiple phases of rifting following collapse of the Caledonian orogenic belt in the Devonian and ending in the Eocene with the opening of the Norwegian and Greenland seas and the initiation of seafloor spreading (e.g., Faleide et al., 2008). These rift phases shaped the large-scale structure of the region (i.e., NNE-trending rift basins like the Hammerfest, Nordkapp and Sørvestsnaget basins, and basement highs like the Loppa, Stappen and Fedynsky highs), with the Middle Jurassic to Early Cretaceous phase forming the faults studied here (e.g., Faleide et al., 2008)."

3. L94 – you may try to be a bit more pedagogic with your reader explaining with 2-3 sentences (and reference) why the structures you present may be interpreted in terms if (non) gravitational deformation

- We have expanded the section by adding more information and references. The new text now reads (**L.121-129**):

"Three lines of evidence suggest that the studied fault system is tectonic (i.e., formed via upper crustal extension imposed by far-field stresses) rather than gravitational (i.e., formed by relatively local extension above a tilted, ductile intra-stratal detachment). First, the faults strike perpendicular to the NNW-SSE extension direction associated with Middle Jurassic to Early Cretaceous rifting. Second, in a gravity-driven deformation setting, one would expect the basal detachment to be tilted in the direction of fault dip and for these faults to be listric (e.g., Spathopoulos, 1996; Corredor et al., 2005; Robson et al., 2017), neither of which are the case here. Finally, extension within gravity-driven systems is typically associated with complimentary shortening in the form of folding and thrusting; again, this is not observed within the study area."

4. L102 – rather long link, perhaps add a citation (NDP 2023) or so and add the link in the reference list?

- We have moved the link to the references list as suggested and updated the text in **L.133-134** to now read:

"see also the formation evaluation and gamma-ray log, and lithology well-log in wellbore 7124/4-1S (NDP, 2023)).”

Results

5. L155 – If there are only 15 faults, why are there faults numbered up to 21, whereas some numbers are missing (e.g., F4)? –> I would suggest renumbering faults to avoid confusion

- We originally mapped 21 faults within this faults network, but some of these (e.g., F4, F20) were minor, antithetic or synthetic faults. That is why we have only included 15 out of the 21 faults here, given they represent the more major, laterally extensive faults that are particularly well-imaged by the data. However, we have renumbered the faults to avoid confusion.

6. L158 – General question: are there signs of underfilling that could affect the interpretation of fault activity and thus fault growth? (like in the North Sea). If so, this neds to be taken into account.

- There are no clear signs (such as absence of fault-scarp degradation; Jackson et al., 2017) of basin/hangingwall underfilling in the study area. Therefore, we do not anticipate this to have an impact on our interpretation of fault activity and fault growth.

7. L169-170 – Perhaps these should be highlighted in Fig. 6 and the fault numbers should be specified here I would say.

- We have updated Fig. 6 to highlight the faults in the aspect ratio plot (Fig. 6B) and also indicate the fault numbers in text. We are not highlighting the faults in the remaining panels as we feel it would take away from the fault network, fault subset, and average behaviours we wish to highlight. The text in **L.237-239** has been updated to explicitly state the fault numbers. The new text now reads:

“Here, we present a detailed geometric analysis of six faults (three from subset 1 (Faults 1, 6 and 8) and three from subset 2 (Faults 5, 9 and 14); we consider these are representative of the range of geometric characteristics observed within the fault network.”

8. L248 – not sure if this is clearly shown there?

- We think the GR log and lithology column help in showing the mechanical anisotropy encountered by the wellbore and expected in the region.

9. L276 – From here on, there are a number of comparisons to previous works, hinting that this assessment of results, should be put into the discussion instead

- We have restructured section 4.2 “Fault growth rates” by moving the below text to the Data and Method section In **L.187-203**

“We calculate the displacement and lateral propagation rates using the time between the two dated horizons at the base (H4) and middle (H2) of the syn-kinematic package (Fig. 2; sequence with best palynological age control). This results in a period of 6.2 Myrs, which we argue should be considered as an upper limit of the duration of what we refer to as early-stage fault activity. In fact, our detailed geometric analysis showed that the strike-parallel depocenters formed in the hangingwalls of the studied faults over a shorter period than the time between the two horizons defining the top and middle of the syn-kinematic package (<6.2 Myr), however we do not have age-control on horizons between H4 and H2. In the absence of higher resolution age constraints, we speculate that the similarity in seismic facies characteristics throughout the syn-kinematic interval indicates that the: (i) lithology; (ii) depositional style; and (ii) sediment accumulation rate, did not vary significantly during the syn-kinematic period (c. 7 m/Myr for the 6.2 Myr period, based on wellbore data). If the sediment accumulation rate was constant, then we might infer the duration of the earliest stage of fault development (i.e., the time duration between horizon H4 and H3) to be c. 3.1 Myrs instead of 6.2 Myr, based on the observation that the thickness of the earliest seismically resolvable depocenter is c. 50% of the total thickness of the 6.2 Myr syn-kinematic package (Figs. 2, 13 and 14). Therefore, the values we show should be regarded as lower estimates of displacement and lateral propagation rates of the studied fault network, given we show rates calculated using a duration of 6.2 Myr. Additional borehole-derived age data, derived from the hangingwall fill of one or more faults, would help further refine our calculations.”

- We moved the below text to the Discussion section in **L.328-346**

“Our studied fault network has displacement rates that are comparable to those measured over similar time scales (i.e., >107 years; dark blue crosses compared to light blue circles in Fig. 16A) in the North Sea (Nicol et al., 1997; Bell et al., 2014), the Timor Sea (Meyer et al., 2002), and the Basin & Range and Taranaki Rift (Mouslopoulou et al., 2009), or for faults with similar trace lengths (>104 km; Fig. 16B; Lathrop et al., 2021) averaged over longer time scales. However, for faults active for a comparable time period, our studied fault network shows higher lateral propagation rates (i.e., c. 0.38 – 3.4 mm/year and 0.76 – 6.9 mm/year based on fault ages of 6.2 and 3.1 Myr respectively), being approximately an order of magnitude faster (compare light green or yellow green circles to red crosses in Fig. 16A). Depending on the growth paths these faults took (i.e., constant length model vs. propagating fault model), a relationship should emerge between the rate of lateral propagation, fault displacement rate, and fault maturity. Specifically, if the faults grew in accordance with the propagating fault model, the ratio between lateral propagation and displacement rate will be closer to 1. However, if the faults established their lengths before accruing significant displacement, then the ratio between lateral propagation and displacement would be >1, especially during the early stages of fault development (i.e., initial 20 – 30% of fault lifespan; e.g., Walsh et al., 2002; Meyer et al., 2002; Nicol et al., 2005; Nicol et al., 2016; Childs et al., 2017; Rotevatn et al., 2019, Nicol et al., 2020; Lathrop et al., 2022). We observe that independent of fault length and whether the duration of faulting is estimated to be 6.2 or 3.1 Myr, the studied faults propagated laterally much more rapidly (i.e., c. 300 - 20 times faster) than they accumulated displacement (Fig. 16C). This value is 2-3 orders of magnitude higher than for other seismically imaged faults of similar length (Fig. 16C; e.g., Bell et al., 2009; Lathrop et al., 2021)."

- Here is the updated section 4.2 "Fault growth rates" in **L.310-324**:

"In addition to the geometric properties of the fault network, we also assess the kinematics of its constituent faults, with specific focus on their displacement and lateral propagation rates. We then compare and contextualise these with rates derived from 29 other locations (Fig. 16A). Spanning various tectonic and depositional settings, and derived from active and inactive faults, our compiled dataset is not intended to be exhaustive; it simply allows us to compare our faults with some global examples of rates determined across different observational periods.
Our studied faults show relatively low displacement rates compared to the global dataset (i.e., c. 0.0062 – 0.025 mm/year averaged over a 6.2 Myr period of fault activity and c. 0.012 – 0.050 mm/year averaged over a 3.1 Myr period; Fig. 16A). We can see this by comparing the light blue (cyan) circles to the dark blue (navy) circles in Fig. 16A. In contrast, for faults active for comparable periods, our studied fault network shows higher lateral propagation rates (i.e., c. 0.38 – 3.4 mm/year and 0.76 – 6.9 mm/year based on fault ages of 6.2 and 3.1 Myr respectively), being approximately an order of magnitude faster (compare light green or yellow green circles to red crosses in Fig. 16A). However, faults observed over shorter durations (i.e., 10^5 – 10^6 years) appear to have faster lateral propagation rates (i.e., approximately an order to magnitude higher) compared to our studied fault network (compare red circle and square data to light green circles in Fig. 16A)."

Authors' Reply to Reviewer 1

1. The paper is well written and easy to follow. There are just a couple of minor typos or missing words, but a read through should catch these. The figures are very nicely drafted. A large number of example faults (6?) are shown within the figures which I like. If the journal suggests the number of figures was too large, I think some of these could be moved into supplementary material without too much detriment to the paper. A suitable amount of supplementary material is included.

- We have revised the paper to correct all typographic errors. As the journal and editors did not comment on the number of figures, we have decided not to move any of the original figures into supplementary material.

2. A very nice introduction and background to the problem is given. But something that's lacking here is a short section on why the results are important and relevant (the "who cares" part).

- We have updated the introduction (**L. 99-110**) to now include:

"Normal faults are the key expression of extensional strain in the Earth's crust. They define the physiography of rifted landscapes and seascapes, and control the distribution and production of important energy resources (e.g., geothermal, hydrocarbons), and the location and safety of storage sites for hazardous waste (e.g., nuclear, CO_2). The growth of normal faults is also associated with hazardous earthquakes that threaten lives, livelihoods, and critical infrastructure. Documenting the rates at which normal faults grow is thus critical to understanding the timescales over which landscapes develop and in turn, how variable slip and lateral tip propagation rates, and fault geometry more generally, impacts sediment dispersal and the distribution of sedimentary facies. Fault geometry and related host rock strain also influences subsurface fluid flow and accumulation by controlling fault architecture and fault zone properties such as permeability. The rate of fault growth may dictate the recurrence interval of potentially hazardous earthquakes, meaning an improved understanding of related seismic hazard can be gained by studying both ancient (i.e., inactive) and active faults"

3. I found it interesting that the fault propagation/growth rates are so high for such low slip rate faults and low slip rates for relatively long faults (and for a fault set with very large aspect ratio). It's interpreted that this is because they are immature or rather not long lived (abandoned before reaching full maturity). But are these faults potentially unusual and therefore not typical of others for some other reason? And do low slip, low slip rate, long length faults, as studied here, behave in the same way as faster moving, shorter faults (or is that not the point)? Because it is not easy to quantify lateral propagation rates of faults, might you only find these results for a certain type

of fault and therefore this could present problems for wider applicability? The authors do point out that faults active for short periods tend to have high lateral propagation rates. So are they typical and simply a dataset of early stage faulting (stated on line 287)? The exclusion of material properties limiting vertical propagation seems robust by the way, i.e., concluding the fault system is immature. In general it would just be good to hear more in the paper about the wider relevance of the results.

- We do not think that these faults are atypical for tectonic normal faults in terms of their general structure and evolution. However, they are unusual in the sense that they: (i) became inactive relatively early in their histories, prior to accumulating significant displacement (see Walsh et al. 2002); and (ii) they are imaged in a high-quality, three-dimensional seismic reflection dataset. So we are indeed saying that “We do not think these faults are atypical….(stated on **L. 351**)” and simply a dataset of early-stage faulting.
- We suggest that the maximum displacement, final fault length and slip rate all depend on the temporal window of observation provided by a given dataset (see **L.63-69**) *and* the growth stage that a particular fault is at (i.e., early vs. late or immature vs. mature). The faults we study in this paper have comparable displacement rates (i.e., c. 0.0062 – 0.025 mm/year) to faults measured over similar time scales (i.e., >10^7 years), and have trace lengths (i.e. 10s km) that are similar to other seismically imaged normal faults. However, we argue that these faults capture the behaviour of early-stage fault growth, which will be harder or impossible to determine for more fully-developed or mature faults due to strain overprinting by subsequent phases of slip and propagation.

4. The data are in time. How well known is velocity and to what extent might this be affecting the results? Where are the boreholes with the sonic (velocity) log data used for the time-depth conversion relative to the seismic profiles? An uncertainty of ±12% is mentioned for the two methods used, but is this between the two methods or some estimate of uncertainty relative to reality? I think it’s the former (from looking at Appendix 3) but it should be clearer, plus the appendix spreadsheet file would benefit from some more explanation. Some comment on the veracity of the time-depth conversion is needed and its impact on the results. I think this is relevant because the offsets are small (e.g., as low as 10-20 ms) therefore small differences with depth in different units could make a difference (and some offsets are fairly close to the data resolution). In addition the small offsets may limit what can be resolved even before depth conversion. What is the error in simply measuring the offset?

- Rather than using two completely different approaches or methodologies, we in fact use a single, two-step approach. The first step was to create a time-depth-relationship since the wellbore did not have any checkshot data. For this we used velocities derived from a sonic log, which we later use in the second step as an input in our seismic-well tie. We now show the location of this well on Fig. 1B.

- We have also attempted to quantify the uncertainty in our time-depth conversion by comparing the Jurassic interval velocities we calculate from the single wellbore in our area with other studies in the literature that use regional wellbores and velocity modelling. The variation in interval velocities between our data and studies in the literature leads to an uncertainty in the depth conversion of around s ±12%. The updated text now reads (**L.165-171):**

"We use velocities derived directly from average sonic log responses from the wellbore that correspond with key seismic intervals (V1; Fig. 2) to create a time-depth relationship. We then apply the generated time-depth relationship to perform our seismic-well-tie (V.2; Fig. 2) and convert our time measurements from ms TWT (milliseconds two-way time) to depth (Fig. 2). The uncertainty in throw arising from using our depth-conversion approach is ±12%; this value arises by comparing the range of velocities we obtain for the Jurassic interval with regional velocity modelling and regional wellbore data presented by others (e.g., Clark et al., 2013; Rojo et al., 2019; see Appendix 3)".

- We note the difference between the limits of separability and visibility in seismic data as discussed in Osagiede et al. (2014). Essentially, one (limit of separability- or resolution) refers to the tuning thickness (1/4 of a wavelength) while the other (limit of visibility or detectability) is dependant on the signal-to-noise-ratio and acoustic impedance contrast and can be as low as 1/30 of a wavelength. In our study, we estimate the limit of visibility to be around 5 m (3-4 ms). We have updated the text now and added the following in **L.139-140**

"The survey has an approximate visibility (or detectability) limit of c. 5 m (see Osagiede et al., 2014 and references therein)."

5. The distribution of the palynological age information for the sequence is quite limited, ie mostly at the top and base of the sequence so horizon ages rely on interpolation. However for rate calculations only the section with ages are used (which is good). But this point only became clear when I reached section 4.2 of the paper, so I think you should explain this earlier in the paper, e.g., in the methods. In addition the age uncertainty for the palynological data is not mentioned. I do note that the authors acknowledge there's still uncertainty about timings of fault activity and hence rates within this period.

- We have updated the manuscript to discuss the distribution of the palynological age information and related uncertainties in the Methods (**L.186-189**). The added section now reads:

"We calculate the displacement and lateral propagation rates using the time between the two dated horizons at the base (H4) and middle (H2) of the syn-kinematic package (Fig. 2; sequence with best palynological age control). This results in a period of 6.2 Myrs, which we argue should be considered as an upper limit of the duration of what we refer to as early-stage fault activity."

6. In lines 187-192, the wording should be clearer on how this indicates early establishment of fault length.

- We do not see any mention of early establishment of fault length in lines 187-192. The text in lines 187-192 from the submitted manuscript states:

"Both F11 and F19 have aspect ratios of c. 19, whereas F6 has an aspect ratio of c. 11 (Fig. 6B).

The Upper Jurassic strata thicken across all faults within the studied network with EI values >1 for all faults (up to 2.2 and 1.7 for F8 and F11 respectively), defining strike-parallel and elongate depocenters (Fig. 5A). We make two key observations here regarding the fault network. The first is that the lowermost reflections in Upper Jurassic package onlap onto the base syn-kinematic horizon immediately adjacent to the fault tips (H4) (Fig. 13)."

- However, we have checked the rest of the manuscript to make sure the wording is as clear as possible. We mention the term early establishment in **L.252-254**, which reads:

"This interpretation of thinning and onlapping towards the lateral tips of normal faults is supported by field examples from Gulf of Suez, Egypt (see Fig. 4 in Gawthorpe et al.,2003), where this stratigraphic architecture is interpreted to reflect early establishment of the fault length, consistent with the constant-length model."

- We have updated this text to now state in **L.267-273**:

"Thinning and onlapping of earliest syn-rift immediately adjacent to the lateral tips of large normal faults is observed in the Gulf of Suez, Egypt (see Fig. 4 in Gawthorpe et al.,2003) and the East African Rift (Morley, 1999), where this stratigraphic architecture is interpreted to reflect early establishment of the near-final fault length, consistent with the constant-length model. In contrast, if the faults grew by simultaneously accumulating length and displacement (i.e., 'propagating fault model'), then we would expect to observe progressive onlapping of the syn-kinematic strata towards the lateral tips of the faults (see Fig. 3 in Morley, 1999)."

7. I wondered if the variable and quite complex vertical growth/propagation patterns of the faults (including potential vertical linkage) may introduce complications to the interpretations? It would be useful to include some statement about this.

- We propose that their complex vertical growth patterns and spatial (i.e., mechanical) interactions might explain the internal variability between faults in terms of their aspect ratio and lateral propagation and displacement rates. We have updated the paper to include new text to reflect that (**L.377-380**):

“The variability in the geometric and kinematic properties of the studied fault network might be explained by the variable and complex vertical growth history of individual structures, which likely reflects the role of the marked lithological and likely strong mechanical anisotropy observed in wellbore data (Fig. 2).”

8. Some parts of section 4.2 on fault growth rates could be more clearly written, i.e., the comparison with other fault datasets. Some parts were a bit confusing.

- We have now updated this section based on the other reviewer and editor comments. The updated text in **L.308-322** now read:

“In addition to the geometric properties of the fault network, we also assess the kinematics of its constituent faults, with specific focus on their displacement and lateral propagation rates. We then compare and contextualise these with rates derived from 29 other locations (Fig. 16A). Spanning various tectonic and depositional settings, and derived from active and inactive faults, our compiled dataset is not intended to be exhaustive; it simply allows us to compare our faults with some global examples of rates determined across different observational periods.

Our studied faults show relatively low displacement rates compared to the global dataset (i.e., c. 0.0062 – 0.025 mm/year averaged over a 6.2 Myr period of fault activity and c. 0.012 – 0.050 mm/year averaged over a 3.1 Myr period; Fig. 16A). We can see this by comparing the light blue (cyan) circles to the dark blue (navy) circles in Fig. 16A. In contrast, for faults active for comparable periods, our studied fault network shows higher lateral propagation rates (i.e., c. 0.38 – 3.4 mm/year and 0.76 – 6.9 mm/year based on fault ages of 6.2 and 3.1 Myr respectively), being approximately an order of magnitude faster (compare light green or yellow green circles to red crosses in Fig. 16A). However, faults observed over shorter durations (i.e., 10^5 – 10^6 years) appear to have faster lateral propagation rates (i.e., approximately an order to magnitude higher) compared to our studied fault network (compare red circle and square data to light green circles in Fig. 16A).”

Authors' Reply to Reviewer 2

Major points

1. **Fault tip**. Throughout the manuscript, the authors discuss fault length. However, some of the studied faults seem to reach the end of the data according to the maps provided, e.g. F1, F3, F5, F8, F19, or intersect oblique faults, e.g. F2, F8, F10, F11, F13, F17. In this case, the fault length may not be complete. Maybe it is worth discussing this aspect in the paper and providing more details on the nature of the fault tips.

- Some of the studied faults are tip-restricted (e.g., F2, F6, F8, F9, F10, F13) as they intersect oblique faults; tip restriction is indicted by the former having higher throw gradients near their branchpoints (and presumably branchlines) with the latter (e.g., Nicol et al., 1996). This means that the tip-restricted faults would likely have propagated further and thus have been longer in the absence of the oblique faults, meaning our reported lengths are conservative estimates. Nevertheless, this does not detract from our conclusion, given these faults are *already long for their displacement*. There is undoubted uncertainty in constraining fault lengths for faults that likely extend outside of the seismic survey (e.g., F1, F3, F4, F6, F14). However, by incorporating other observations (such as throw measurements and throw-length profiles), we argue that in the case of faults F1, F3, and F6, throw approaches zero near the edge of the seismic survey. Therefore, based on the broad bell-curve shape of the throw-length profile and the decreasing throw values, we suggest that the fault tip lies a short distance outside of the survey, and that the observed length is only a little less than the overall fault length. We have updated text in **L.225-236** to discuss these possible uncertainties.

"Some of the studied faults are tip-restricted (e.g., F2, F6, F8, F9, F10, F13) as they intersect oblique faults; tip restriction is indicted by the former having higher throw gradients near their branchpoints (and presumably branchlines) with the latter (e.g., Nicol et al., 1996). This means that the tip-restricted faults would likely have propagated further and thus have been longer in the absence of the oblique faults, meaning our reported lengths are conservative estimates. Nevertheless, this does not detract from our conclusion, given these faults are *already long for their displacement*. There is undoubted uncertainty in constraining fault lengths for faults that likely extend outside of the seismic survey (e.g., F1, F3, F4, F6, F14). However, by incorporating other observations (such as throw measurements and throw-length profiles), we argue that in the case of faults F1, F3, and F6, throw approaches zero near the edge of the seismic survey. Therefore, based on the broad bell-curve shape of the throw-length profile and the decreasing throw values, we suggest that the fault tip lies a short distance outside of the survey, and that the observed length is only a little less than the overall fault length."

2. **Non-mapped faults**. Some faults visible in the maps and sections are not mapped, e.g. Figs 4B and 5A, 8B and 9B. I understand that this may be for illustrative purposes, but some of those faults may be important as they may be part of the interacting fault systems and control local throw variation or fault arrest. Therefore, I think those faults should be discussed or mapped. Of more concern, the authors should discuss the criteria they used to select the studied faults rather than the others.

- We mapped a total of 87 faults including some secondary faults (synthetic and antithetic), oblique faults (i.e., those striking oblique to the dominant ENE-WSW trend), and the major, basin-bounding faults (i.e, the TFFC, which is located in the SW of the study area). However, we decided to focus on the 15 largest, E-W-striking faults within the network, given they are particularly well-imaged. We have updated the text in **L.207-211** to discuss our criteria and highlighted some of the oblique faults that are interacting and/or controlling local throw variations.

"We mapped a total of 87 faults including some secondary faults (synthetic and antithetic), oblique faults, and the major, basin-bounding faults (i.e, the TFFC, which is located in the SW of the study area; see Alghuraybi et al., 2021 for more details on the fault networks in the area). However, we decided to focus on the 15 largest, E-W-striking faults within the network, given they are particularly well-imaged in our seismic data , thus allowing us to undertake a detailed kinematic analysis. (Alghuraybi et al., 2021)."

3. **Relay zones**. The authors state that the studied faults are not associated with clear fault bends, abandoned splays or relays (L.161 and 218). First, I am not sure the data supports this. For example, we can see large stepping zones between F2 and F3 (or F1 and F2), F5 and F6, and F10 and F11, which could be intact relay zones. Also, F15 and F16 seem to be the segments of the same fault, while F17 may be in a conjugate relay zone system (see Childs et al. 2019). Again, not counting for such potential relay zones raises the general question of defining the fault tips (i.e. unrestricted or tip restricted, according to Nicol et al. 1996).

- We acknowledge the presence of these relays between some of the faults. However, what we refer to in text in **L.217** and **L.289** is the general lack of clear fault bends, abandoned splays or breached relays **along and within** individual faults. For example, even though a large unbreached relay exists between F2, F3 (or F1 and F2), F5 and F6, and F10 and F11, we do not see evidence of similar breached relays **within** the individual faults. As shown in the newly added schematic diagram (Fig. 17), it is possible for the fault network to grow and develop intact, unbreached relay zones between some of the faults. The presence and formation of these intact relays does not impact our interpretation or proposed fault growth model for the studied network. We now clarify the difference between these intact inter-fault relay zones and the lack of evidence of breached relay zones along individual faults.

4. Second, beyond prominent stepping geometries like the ones aforementioned, the authors also identify multiple throw maxima along the same stratigraphic level for some faults (L.217). Some of those variations may be related to deformation partitioning with nearby faults. For example, the abrupt decrease in displacement in the Eastern part of F8 correlates with the location of F9 and its magnitude. Since such interaction/partitioning can control the displacement, it may be important to discuss their potential impacts on displacement and propagation rates analysis.

- We state in **L.286-296** that “The presence of multiple throw maxima along the same stratigraphic level on some of the subset 1 faults (e.g., F1 and F6; Figs. 7, 8) may provide geometric evidence that they grew by lateral segment linkage (e.g., Cartwright et al., 1995). However, the lack of obvious bends, breached relays, or abandoned splays suggests that the precursor segments did not overlap, and may have formed as part of a single, kinematically linked structure from their inception (e.g., Childs et al., 2017). Instead, these throw maxima might relate to across-strike throw partitioning between adjacent faults. For example, where F6 decreases in throw towards its eastern tip, throw on the adjacent F7 increases near its western tip(Figs. 4B, 8). The interpretation that geometrically segmented faults formed part of a kinematically coherent system from their inception is supported by the fact that the across-fault thickening we observe occurs along almost the entire strike-length of the faults and is associated with onlap of the lowermost syn-kinematic onto pre-kinematic strata immediately inboard of the lateral fault tips (Fig. 13).”
- We do discuss the potential impact of strain localisation on to the TFFC on why the faults became inactive (**L. 361-363**). However, we have also updated the text to discuss the potential impact of deformation partitioning with nearby faults in **L.291-293**. The new text now reads:

“Instead, these throw maxima might relate to across-strike throw partitioning between adjacent faults. For example, where F6 decreases in throw towards its eastern tip, throw on the adjacent F7 increases near its western tip(Figs. 4B, 8).”

5. **Propagation rates and displacement rates**. The methodology concerning propagation and displacement rates could be further detailed (i.e. L.136-147 and 241-255). For example, it is unclear from my reading on which faults those rates are calculated. How many rates are calculated? Where are the displacement rates calculated? Also, is there any assumption on the sedimentation rates? Finally, why not include L.241-255 in the methodology section?

- As suggested, we moved some text (previously numbered **L.241-255**) from the Results section to the Data and Method section. We believe our methodology, in terms of how we calculated lateral propagation and displacement rates, is now adequately explained by this text and Fig. 3.

- We also added further details on how many rates were calculated and where the displacement rates were calculated. This added text in **L.180-183** reads:

"We calculate displacement rate at every along-strike location where we made a complimentary throw measurement (i.e., at 250 m intervals for a total of c. 1100 measurement point). Then, we take the minimum and maximum displacement rates for each fault to capture their full range of behaviour. This results in two displacement rate measurements for each of the 15 studied faults"

- In terms of assumptions regarding sedimentation rates, we state in **L193-203**

"In the absence of higher resolution age constraints, we speculate that the similarity in seismic facies characteristics throughout the syn-kinematic interval indicates that the: (i) lithology; (ii) depositional style; and (ii) sediment accumulation rate, did not vary significantly during the syn-kinematic period (c. 7 m/Myr for the 6.2 Myr period, based on wellbore data). If the sediment accumulation rate was constant, then we might infer the duration of the earliest stage of fault development (i.e., the time duration between horizon H4 and H3) to be c. 3.1 Myrs instead of 6.2 Myr, based on the observation that the thickness of the earliest seismically resolvable depocenter is c. 50% of the total thickness of the 6.2 Myr syn-kinematic package (Figs. 2, 13 and 14). Therefore, the values we show should be regarded as lower estimates of displacement and lateral propagation rates of the studied fault network, given we show rates calculated using a duration of 6.2 Myr. Additional borehole-derived age data, derived from the hangingwall fill of one or more faults, would help further refine our calculations".

- We also note that Reviewer 1 thought this was a reasonable approach

6. **Lateral propagation versus slip rate**. I am slightly confused with the slip rate to propagation rate ratio discussed in Section 4.2 and Fig. 16c. First, in theory, if we do Length/Time divided by Displacement/Time on the same time interval, are we not just looking at Length/displacement, which is the inverse of the displacement gradient on a specific time interval? Then, if we average that over the fault lifespan, isn't it Dmax/L? Second, how is this ratio indicative of the growth model? I understand that the authors suggest that faults propagating laterally much faster than accumulating displacement (Ratio >1) are more in line with the 'constant-length model', whereas they expect a ratio close to 1 for 'the fault propagation model'. But since faults typically have Dmax/L << 1, doesn't that mean that no fault grows with a ratio close to 1 on average? My point is that the ratio's absolute value may be less relevant than its variation over time. But I don't think there is such data in the present study. In any case, I will suggest that the authors clarify their model.

- We agree with the reviewer regarding the fact that faults typically have D_{max}/L << 1, which is something we state in **L.35-37** for example, : "…that faults grow by simultaneously accumulating length and displacement (where D_{max}/L_{max} typically ranges between 1 – 0.01; e.g., Watterson, 1986; Walsh and Watterson, 1988; Cowie and Scholz, 1992; Schlische et al., 1996; Walsh et al., 2003)."
- We also agree with the reviewer that the **absolute** value of total displacement/length may be less relevant than its variation over time.
- However, what we present here is in fact data that show variation of D/L over time. We use a value of D (calculated between horizon H4 and H3) that represents the initial displacement during early fault growth rather than D_{max} (the final, total maximum displacement) that the reviewer is referring to in their comment. Therefore, we propose that if the faults grew in accordance with the propagating fault model, the ratio between lateral propagation and displacement rate for our early-stage D/L would be closer to 1. We observe a ratio of early D/L of << 1, supporting our conclusion of faults growing laterally much faster than they accrue displacement during the early stage of faulting.

7. **Early stage of faulting**. The authors suggest that the studied network captured faults during the earliest stage of development when they were growing by the 'constant-length model'. According to this model, the fault grew first in length and then accumulated displacement. From my understanding, the fault was active Middle Jurassic to Early Cretaceous, i.e. 163.5 – 132.6 Ma. But most displacement and length occur during the first 6 Myrs (or 3.1 Myrs). Then the fault becomes primarily inactive. So for the sake of argument, could we argue that the data indicate that the fault grows according to the 'propagation model' with a relatively low displacement gradient? Then become inactive.

- We have found that our studied faults have grown in length much faster than they accrued displacement in the first 6 Myrs of their activity, before then becoming inactive. We are less concerned with the semantics of whether this is called the "constant-length model" or the "propagation model with low-displacement gradient". We note that faults growing according to the "propagating fault model", but with a relatively low displacement gradient, is essentially the same as the "constant-length model" we describe here in our study, and that we highlight in Fig. 17. We note that the "constant-length model" does not preclude individual faults or fault segments undergoing tip propagation and ultimately linking via relay ramp breaching. What matters is the partitioning, in time between lengthening and displacement accumulation.

8. **Figures**. The paper is well illustrated, but there are many figures (i.e. 16). Maybe Figs. 7-12 are not all necessary for the manuscript, and some should be in supplementary materials, considering that most of the information is provided in other figures, like Figs. 4, 5 and 15. Also, the figures are very data-oriented. Maybe, after removing some figures, the authors could provide additional schematic diagrams on the fault growth and growth history, theoretically or specifically for the studied faults.

- We have added a schematic diagram in Fig. 17 to help explain the growth history of the studied fault network. We have chosen to retain the figures to show as much data as possible to support our conclusions. Also, as the journal and editors did not comment on the number of figures, we have decided not to move any of the original figures into supplementary material.

Minor points

We have gone through the manuscript and figures and updated the minor comments highlighted by the reviewer. We are also included more detailed response below where needed.

9. **16,132**. Please define layer-bounded. It is a bit ambiguous here, considering those are growth faults.

- We have removed the term from the manuscript and replaced it with "basal tip-restricted syn-kinematic faults". We also updated the text in **L.94-97** to now read: "basal tip-restricted syn-kinematic faults (i.e., faults that are bound by a base mudstone layer that inhibits downward propagation whereas their upward propagation is restricted by the free-surface)"

10. **25, 42, 269, 292**. Please define fault maturity, as seismologists use such terminology.

- We have provided a new definition in **L.45-54**. This new text reads:

“Different definitions of fault maturity exist in the literature. For example, Manighetti et al. (2007) defines fault maturity based on a combination of four criteria (trace length ≥ 1000km and/or Initiation Age ≥ 10Ma and/or Slip Rate c. few cm/yr and/or Total Displacement ≥ 100km. In contrast, other studies focused on normal fault growth characterised mature fault systems as those that experienced multiple phases of change in their lengths and location of fault activity (Morley, 1999), while immature fault systems as having many relatively short <4km interacting fault traces (e.g., Nicol et al., 2010). However, we propose that an immature normal fault as being one that is still on its trajectory of increasing in length with minimal displacement (i.e., rapid tip propagation and segment linkage) and a mature fault is where its displacement increases with a little increase in fault length (i.e., dominant displacement accrual and constant length) (modified after Rotevatn et al., 2019).”

11. **243.** 'Upper limit in the duration of fault activity'. Isn't that contradicting the faults active from Middle Jurassic to Upper Cretaceous (L.158)?

- We have changed the text to clarify that this 6.2 Myr upper limit refers to what we define as the early period of fault activity; it does *not* mean that the faults stopped being active after that. We note that most of the faults in the studied network offset Lower Cretaceous strata, meaning that they experienced post-Early Cretaceous slip. However, the time of 6.2 Myr refers to when the faults reached their near-final lengths and accrued most of their displacement.
- The updated text now reads **(L.189-190**):

“This results in a period of 6.2 Myrs, which we argue should be considered as an upper limit of the duration of what we refer to as early-stage fault activity”

12. **246-253**. This part is difficult to follow without illustration. Does that mean that the methodology is different from that in Fig. 3?

- It is the same method as described in Fig. 3. We have now added more details on our method and moved the related section to the Data and Method section (**L.187-203**).

13. **256 to 266**: I found the analysis of Fig. 16 challenging. I suggest the authors help the reader a little, for example, using sentences like "compare red circles with black crosses".

- We have updated the text in **L.316-324** to now read:

“Our studied faults show relatively low displacement rates compared to the global dataset (i.e., c. 0.0062 – 0.025 mm/year averaged over a 6.2 Myr period of fault activity and c. 0.012 – 0.050 mm/year averaged over a 3.1 Myr period; Fig. 16A). We can see this by comparing the light blue (cyan) circles to the dark blue (navy) circles in Fig. 16A. In contrast, for faults active for comparable periods, our studied fault network shows higher lateral propagation rates (i.e., c. 0.38 – 3.4 mm/year and 0.76 – 6.9 mm/year based on fault ages of 6.2 and 3.1 Myr respectively), being approximately an order of magnitude faster (compare light green or yellow green circles to red crosses in Fig. 16A). However, faults observed over shorter durations (i.e., 10^5 – 10^6 years) appear to have faster lateral propagation rates (i.e., approximately an order to magnitude higher) compared to our studied fault network (compare red circle and square data to light green circles in Fig. 16A)."

14. **303.** See Roche et al., 2021, for aspect ratio values going up to 14.

- We have updated the text accordingly with the addition of this reference in **L.371-372**.

15. **L306-309.** But the faults are synsedimentary, so they cannot be restricted upward.

See response to comment 9 above

2nd Round of Revisions

Decision Letter

Dear Authors,

Many thanks for resubmitting a new version of your manuscript, and for providing a detailed reply to the previous review comments.

We have evalutated your resubmiteed manuscript and although we like the overall paper and the reviews were positive, we identified two main issues that need attention before it can be considered for publication:

1) Structure: the current text mixes data, interpretation and discussion. It is important that these are strictly separated to avoid any confusion. This will mean that some text needs to be move from the results section to the discussion section of the manuscript. Note that also some parts of the introduction seem to be out of place.

2) Figure count. Both reviewers commented that the number of figures is too high, and we agree with them, even though we did not specify this in our previous email. The reviewers suggested to move some of the figures to the appendix. We propose another solution: it seems quite possible to simply merge some of the figures to reduce the figure count: 1+2, 4+5, 7+8, 9+10, 11+12 and 14+15. That could be a nice compromise.

NB: it would in general be nicest to fit figures in portrait mode pages, rather than landscape mode pages, if possiblem, in order to enhance readibility.

Please check the attached annotated PDF files (of the text and figures) for more detail on the main points, and for some additional points that require some attention.

If you have any questions, please let us know.

Kind regards,

Frank Zwaan (handling editor) & Gwenn Peron-Pinvidic (executive editor)

Authors’ Reply to Editors’ Comments

Dear Editors,

Thank you for evaluating our resubmitted manuscript, and we apologise for the delayed response. We are grateful for your suggestions and constructive feedback. We have carefully gone through all your comments and, we hope, addressed all concerns in a revised version of our manuscript.

We here provide a detailed (i.e., itemised) response to all comments. We indicate the comments by blue text, and by the manuscript line number where they were provided. Our responses are provided in black text following each comment.

Many thanks again to the handling editor, executive editor, the Tektonika Editorial Team, and the two reviewers for their help with our submission.

Kind regards,

Ahmed Alghuraybi – on behalf of all coauthors

Structure:

General comment:

The current text mixes data, interpretation and discussion. It is important that these are strictly separated to avoid any confusion. This will mean that some text needs to be move from the results section to the discussion section of the manuscript. Note that also some parts of the introduction seem to be out of place.

Detailed comments:

1. L25: how is this unusual? —> there is little other data on early fault development?

We have rephrased this sentence and removed the word unusually.

“We suggest that the high ratio between lateral propagation rate and displacement rate is likely due to relative immaturity of the studied fault system, an interpretation that supports the ‘constant-length’ fault growth model.” [L.24-27]

2. L34 & L43: there should also a sentence with “the latter” to introduce the contrasting model —> see later comment

We have updated this sentence so that it now reads: “An alternative interpretation is that this variability results from fault maturity, related to the fact that some faults may attain their near-final lengths before accumulating significant displacement (i.e., the latter, constant-length fault model…" [L.50-52]..

3. L89: the East African Rift is sub-areal though, as is Iceland —> are these no good places for normal fault development analysis?

Although the East African Rift system is subaerial it has associated lakes like Lake Malawi and Lake Tanganyika that each contain >5 km of syn-rift sediments (e.g., Scholz et al., 1998). These syn-rift deposits enable the study of intra- and early-rift processes (e.g., Shillington et al., 2020). However, these deposits are covered by only 2D seismic reflection profiles and lack the necessary age constraints needed for a detailed analysis of the earliest stages of normal fault growth.

Similarly, in the Icelandic Rift Zone, data from Thingvallavatn were used to study the fault and magmatic interaction over a 9 kyr period (Bull et al., 2003). However, due to the relatively limited data quality (single-fold seismic) and reliance on a single age constraint (provided by dating a lava flow), the kinematic analysis of normal fault growth was rather limited.

In other active rifts like the Red Sea or Gulf of Suez, where the syn-rift deposits are exposed, the stratigraphic architecture of syn-rift strata (e.g., Gawthorpe et al., 1997) can be used to infer lateral propagation rates. However, such studies are often limited in that they demand areally extensive, high-quality exposures of dateable material.

We have incorporated this text into the introduction in [L.103-113].

4. L99-110: all this is general motivation to study normal faulting, and should be moved to the start of the introduction. The last sentence (Line 107-110) would be a very nice end of the first paragraph, making a clear link to the start of the current first paragraph that starts explaining the fault development models. Here, it strongly distracts the reader from the aim of the paper itself. Lines 97-99 is a very nice sentence to close the introduction.

We have restructured the introduction by moving text in [L99-107] to the start of the introduction in the first paragraph. We have also moved text in [L107-110] to the end of the first paragraph of the introduction.

5. L223-226: the use of i, ii, iii to list the subsets in the text does not align with the use if i, ii, iii in Fig. 6D, so that it becomes a bit confusing. It would be good to label the subsets in Fig. 6D itself, and to choose another manner to list the subsets in the text, e.g, a, b, c (or simply 1, 2, 3).

We are now using a & b to list the subsets in the text and have updated Fig. 4D to label the subsets explicitly in the figure.

6. L228-231: this reads like discussion, especially the last part that mentions the conclusion… —> the results section serves to present the data, not to discuss their implications

We have now moved this text from the results section to the end of the second paragraph in the Discussion [L379-384].

7. L268-274: reads like discussion

We have moved this text to the second paragraph in the Discussion [L367-374].

8. L285: reads like discussion

We think this section is aptly named interpretation and serves to offer our interpretation of the presented data without mention of any of its wider implications. The use of the Cartwright et al. (1995) reference here is essential when presenting our interpretation, given we are arguing for the integration of all observations to determine the mode of growth for these faults. So it is not really a discussion item, but rather a way to help us present a coherent argument for our preferred interpretation, which is consistent with the model in Childs et al. (2017), but *not* the one advanced by Cartwright et al. (1995).

As for text in [L301-303] in this section, we have moved that to the Discussion section [L395-399].

References:

Bull, J. M., Minshull, T. A., Mitchell, N. C., Thors, K., Dix, J. K., & Best, A. I. (2003). Fault and magmatic interaction within Iceland's western rift over the last 9 kyr. *Geophysical Journal International*, *154*(1), F1-F8. https://doi.org/10.1046/j.1365-246X.2003.01990.x

Scholz, C. A., Moore Jr, T. C., Hutchinson, D. R., Golmshtok, A. J., Klitgord, K. D., & Kurotchkin, A. G. (1998). Comparative sequence stratigraphy of low-latitude versus high-latitude lacustrine rift basins: seismic data examples from the East African and Baikal rifts. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *140*(1-4), 401-420. https://doi.org/10.1016/S0031-0182(98)00022-4

Shillington, D. J., Scholz, C. A., Chindandali, P. R., Gaherty, J. B., Accardo, N. J., Onyango, E., Edinger, C., & Nyblade, A. A. (2020). Controls on rift faulting in the north basin of the Malawi (Nyasa) Rift, East Africa. *Tectonics*, *39*(3), e2019TC005633. https://doi.org/10.1029/2019TC005633

Figure count

General comment:

Both reviewers commented that the number of figures is too high, and we agree with them, even though we did not specify this in our previous email. The reviewers suggested to move some of the figures to the appendix. We propose another solution: it seems quite possible to simply merge some of the figures to reduce the figure count: 1+2, 4+5, 7+8, 9+10, 11+12 and 14+15. That could be a nice compromise.

Detailed comments:

NB: it would in general be nicest to fit figures in portrait mode pages, rather than landscape mode pages, if possible, in order to enhance readability.

We have updated the figures based on the editors' suggestion and managed to reduce the number of figures from 17 to 11. The table below shows the old figure numbers and how they were updated.

In addition, we have corrected the orientation of the north arrow in all relevant figures and used consistent time steps in the conceptual model in Fig. 1.

Old Figure number	**Updated Figure number**
Fig 1	Fig 1
Fig 2	Fig 1.C
Fig 3	Fig 2
Fig 4	Fig 3.A
Fig 5	Fig 3.B
Fig 6	Fig 4
Fig 7	Fig 5.A
Fig 8	Fig 5.B
Fig 9	Fig 6.A
Fig 10	Fig 6.B
Fig 11	Fig 7.A
Fig 12	Fig 7.B
Fig 13	Fig 8
Fig 14	Fig 9. A
Fig 15	Fig 9.B
Fig 16	Fig 10
Fig 17	Fig 11

Acceptance Letter

We have reached a decision regarding your submission to Tektonika, A Snapshot of the Earliest Stages of Normal Fault Growth.

Our decision is to: Accept Submission