Reviews comments

Response to reviews comments

Hi, this comment is a bit of a cop-out I'm afraid. Having read the paper, and realised that is 95% computer modelling-based, I feel I am probably not the right person to see this one through the whole review process. I've worked with computer tectonic modellers, but never done it myself. Therefore you need someone who can properly examine the input variables, boundary conditions, iterations, etc. May I suggest John Naliboff if you haven't already asked him? I worked with him on a recent paper and he is excellent at this stuff. He's at New Mexico Tech, john.naliboff@nmt.edu.

However, as this is an open review anyway, a few general comments:

1) Most importantly, you need to describe why this is an important (or at least useful) contribution to the discussion on the structure of highly extended margins. How does it differ from the models already published, or does it just confirm and add weight to them via lithospheric modelling?

2) It would be useful to define in simple terms, up front, what "in sequence" and "out of sequence" faulting mean. Not everyone reading this will have been as deeply immersed in the debate as you are, so some definition of terms would help the general reader.

3) In my opinion, there isn't enough actual seismic in this paper. It's almost all computer output, with nothing to tie it to. Apart from Fig. 6 (which actually describes a special case) it's just assumed that the reader has seen the seismic elsewhere. For completeness - and real-world grounding, please consider at least one more general seismic line over the margin.

All general comments, I know. You need an expert modeller for the rest.

Best wishes and good luck with the process,

Tony Doré

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We thank Tony Dore for his 3 comments. We understand and agree with them – they are constructive and appropriate.

The aim of our paper is to investigate whether the rolling hinge fault model of Buck, used very successfully to explain fault processes at magma-poor slow-spreading ocean ridges, can reproduce the evolution of extensional faulting interpreted from the 3D seismic imaging of the hyper-extended domain of the Iberian magma-poor rifted margin. The 3D seismic analysis by Lymer et al. (2019), following earlier 2D seismic work (e.g. by Reston, Ranero, Pérez-Gussinyé), has, we believe, answered long standing questions concerning the relationship between high-angle extensional faulting and the "S" sub-horizontal reflector.

As well as making the aims of our paper clearer, we need to summarise better the extensional faulting process proposed by Lymer at al. from their 3D seismic analysis, perhaps by showing an example of their seismic sections in our figure 1. We also need to explain what is meant by in-sequence extensional faulting as used in the papers we cite as well as our own paper.

The paper by Gomez-Romeu and Kusznir presents modelled fault geometries, whose sequential restoration includes the effects of flexural isostacy. The main aim is to demonstrate how different starting fault geometries (listric vs planar faults, fault angle) evolve with time, and respond to isostatic effects, and consequently, what criteria might be identified to discriminate the different starting geometries on seismic reflection data. The paper is well written and referenced, and the illustrations are good. The examples presented usefully illustrate the basic range of geometries that can be expected for large displacement faults on hyper extended margins, and how the sequence of deformation is important. I only have minor comments – below.

Lines 111-113 Perhaps could be more specific about the starting configuration. Fig. 3 – was a) and b) modelled by pure shear and the conjugate faults are just schematically illustrated?

While Fig. 1 is a useful summary, it would be good to have at least one regional seismic line that illustrates the full regional picture of what you are modelling. Because Iberia is referred to numerous times in the text, it got me wondering if you were actually trying to model a particular part of the margin. I think it would be helpful to more clearly state somewhere around lines 52-59 that you are not modelling a specific margin or seismic line, but you have created generic models to address the types of feature found along the Iberia margin (and perhaps cite other examples too).

Model formulation – although the model can include sedimentation, it does not appear that sedimentation has been built into the modeling, and I did not see in section 2 any mention about why this has been omitted. I presume it is because the syn-kinematic sediments are likely to be thin, and not much denser than the water column. But I think this simplification of the model should be addressed. It also provides the opportunity to address your assumptions about how rapidly you think the extension would proceed (slow extension would acquire more syn-kinematic sediment).

I accept that these margins can largely evolve from normal faults that dip at typical normal fault angles (i.e. 45-60 degrees), so have no issue with the scenarios presented here. There is an implication that variations in starting fault angle do not need to be considered. However, I think it would be interesting to look at normal faults with lower starting angles (20-30 degrees) as well, just to see what differences may arise, and are features produced that are incompatible with the seismic data. Reactivation of low-angled zones of weakness, such as thrusts, may sometimes produce initially low-angle normal faults.

One simple way to estimate the initial angle of a fault is to assume bedding was initially horizontal, and use the bedding-fault cutoff angle to determine the initial fault angle. It would be useful if you could comment on whether there are significant changes in cutoff angle as your model increases displacement, and what magnitude of variations occur.

Summary, perhaps being more specific about the nature of the S reflection and how your modelling of planar and listric faults differ would be useful.

I enjoyed reading the manuscript.

Chris Morley

We thank Chris Morley for his comments and suggestions.

We agree that adding a regional seismic reflection section to figure 1 would improve the accessibility of the paper to readers and also illustrate our review and summary of what has been learnt by seismic reflection analysis in the hyper-extended domain of the Iberia continental margin. We also agree that we should make clear that we are not modelling a particular seismic line but rather that we are modelling the generic processes operating during the formation of an hyper-extended rifted magma-poor margin.

The model that we use can incorporate sediment deposition during the incremental tectonic development of a magma-poor rifted margin. We did not include sedimentation in order to focus on the tectonics and fault evolution – however we should perhaps reconsider this. We can include an additional figure showing this which would illustrate the diachronous nature of fault extension and the distinction between syn- and post-tectonic sedimentation.

We note your comment that we only consider normal faults with steep initial angles (~60^{o}). We believe that this starting angle is appropriate to the Iberian margin and many others. We agree however, that where extensional faulting reactivates thrust faults, that the starting angle is much lower (30^{o} or less). A good example of this is on the SW margin of the South China Sea where thrusts are reactivated as extensional fault. Preliminary modelling of reactivated low angle thrusts shows that the flexural response to extensional faulting successfully reproduces observations and is sensitive to fault angle. This is work in progress and beyond the scope of this paper which focuses on fault geometry evolution during the hyper-extension of magma-poor rifted margins.

We believe that the question of whether the bedding-fault angle can be used to determine the initial fault angle has also already been addressed in papers summarising seismic reflection observations at hyper-extended rifted margins. We will add text and references to summarise this.

Regarding listric versus planar fault geometry, we believe that the shallower parts of extensional fault during hyper-extension are planar but become listric as they sole into the S reflector. This is an important point and we will make it clearer in the revised text.