Response to Comments and Recommendations of the Editor (Mohamed Gouiza)

We thank Mohamed for his comments (in italics below). We have updated the text in response to his suggestions. A summary of our responses is given below.

Chris raised an interesting question regarding the effect of sedimentation on the modelling results. This was addressed in the revised manuscript (Lines 203-210 and Figure 4), which suggests that sedimentation has no effect on the structural evolution of the model. One would expect the opposite, but I presume that since the syn-kinematic sequences in these domains (i.e., hyperextended and exhumed mantle) are often thin, the effect of sedimentation would be negligible anyway.

Our updated text in lines 238 to 246 regarding sediment loading of the model

The model results of increasing sediment supply are shown in Figures 5b-c and compared with the model result with no sediment deposition shown in Figure 5a. Figure 5b shows a relatively small amount of sediment incrementally added to the model and is consistent with a relatively sediment starved scenario corresponding to the SW Galicia margin as imaged by the 3D seismic of Lymer et al (2019). The isostatic response to the small amount of sediment loading shown in Figure 5b is also small and the flexural isostatic fault rotation is therefore not significantly different from the model result with no sediments shown in Figure 5a. The increased isostatic response to increasing sediment supply (Figures 5c&d) results in a slight decrease in fault rotation resulting in slightly steeper faults for the same fault extension. Sediment supply and its isostatic loading are therefore expected to exert a control on when faults lock and new oceanward in-sequence faults develop.

However, I am wondering if this has to do with the numerical modelling approach as well? This is why, I think it is essential to address the limitation of the numerical model RIFTER. You do refer the reader to published literature where detailed description of the model formulation is provided, but I think you should address the impact of the assumptions and simplifications of the model formulation on this particular case study. For instance, the lack of a dynamic implementation of temperature and the assumed initial Te of 0.5km. This could be addressed either in the discussion or in a separate section just before the discussion.

Our updated text in lines 101 to 125 regarding the kinematic model

We use a numerical model (RIFTER) to replicate faulting and fault block geometry within the hyper-extended domain, and to investigate fault rotation, fault geometry interaction, the formation of crustal allochthon blocks and the transition between hyper-extended and exhumed mantle domains. RIFTER is a kinematic forward lithosphere deformation model that allows the production of flexural isostatically compensated as well as balanced cross-sections. Within RIFTER, lithosphere is deformed by faulting in the upper crust with underlying distributed pure-shear deformation in the lower crust and mantle. RIFTER can be used to model and predict the structural development in extensional tectonic settings as shown in Figure 2. The model is kinematically controlled with fault geometry, fault displacement and pure-shear distribution given as model inputs as a function of time.

The kinematic formulation of RIFTER represents an advantage over dynamic modelling because the input data given to RIFTER can be constrained by observed geology. Specifically fault position, extension magnitude and sequence order with respect to other faults can be taken directly from the interpretation of seismic reflection images and used to drive the kinematic model. This is in contrast to dynamic models where fault location, extension magnitude and sequence order are predicted by the model and may bare little relationship to an observed structural and stratigraphic cross-section. In a kinematic model, while the lithosphere deformation is specified as an input, the thermal and isostatic consequences may be dynamically determined to predict thermal uplift and subsidence (e.g. Gómez-Romeu et al. 2019). Because model outputs are geological cross-sections which are flexural isostatically compensated as well as structurally balanced, RIFTER provides for the isostatic testing of palinspastic cross-sections and can also be used to explore different kinematic scenarios. A more detailed description of the model formulation (originally called OROGENY) is given by Toth et al., (1996), Ford et al., (1999) and Jácome et al., (2003). These studies show the model formulation applied to compressional tectonics however similar physical principles apply for an extensional tectonics scenario. Gómez-Romeu et al., (2019) show how RIFTER can be used to reproduce both extensional and compressional tectonics using the Western Pyrenees as a case-study.

Our updated text in lines 141 to 147 regarding choice and sensitivity to Te

We use a Te value of 0.5 km in our modelling of extensional faulting during the formation of the hyperextended domain and mantle exhumation (Figure 3). This value is consistent with those determined at slow-spreading ocean ridges ranging between 0.5 and 1 km (e.g. Buck, 1988; Smith et al., 2008; Schouten et al., 2010) where a similar lithosphere flexural strength to that of the distal rifted margins is expected. The sensitivity of model predictions to Te is shown in Figure 4; increasing Te increases the bathymetric relief.resulting from extensional faulting but otherwise the structural architecture remains similar.

I also believe that there is an important point that was raised by Tony that was not considered in the revised manuscript: How does your contribution differ from the models already published? and I would add: How does you modelling results compare to what is already published? There is at least one published work that I can think of that also addressed the process of hyperextension and mantle exhumation in rifted margins, but using geodynamic modelling, by Peron-Pinvidic & Naliboff (2020, https://doi.org/10.1130/G47174.1).

Our updated text in lines 72 to 93 regarding relation of our work to previous studies

Dynamic thermo-rheological finite element models of continental lithosphere stretching and thinning (e.g. Lavier & Manatschal, 2006; Brune et al. 2014; Naliboff et al. 2017) leading to continental breakup and rifted margin formation have been successful in simulating the progression from necking to hyper-extension to mantle exhumation. at magma-poor rifted margins. However these dynamic models do not replicate the extensional fault and detachment structures observed on 2D and 3D seismic reflection data. The dynamic model of Peron-Pinvidic & Naliboff (2020), specifically investigating extensional detachment development, predicts extensional fault structures that penetrate to depths much greater than the seismically observed S-type reflector; additionally their predicted fault geometries remain steep failing to match the lower fault angles imaged on seismic reflection data. The kinematic model presented by Ranero & Perez-Gussinye (2010) using extensional fault block rotation much better replicates extensional fault and detachment structures imaged by 2D seismic within the hyper-extended magma-poor margin domain. Their work however preceded the 3D seismic observations by Lymer et al (2019) of the S-type detachment and its corrugations.

Lymer et al. (2019) propose that their observations strongly support the development of the S seismic reflector by a rolling-hinge process (Buck 1988) in which a sub-horizonal detachment is created by the incremental addition of the soles of basement extensional faults. The kinematic rolling-hinge model of Buck (1988) has been successfully used at slow spreading ocean ridges to replicate and analyse extensional faulting leading to footwall exhumation, detachment faulting and core complex formation (Smith et al. 2008; Schouten et al, 2010). In this paper, we use a recursive adaptation of the rolling hinge model of Buck (1988) to examine how both active and inactive fault geometries are modified by flexural isostatic rotation during sequential faulting to form the sub-horizonal structure imaged on seismic reflection data.

One last minor suggestion regarding the caption of Figure 1c, which could be improved as follow: 3D view extracted from a 3D seismic reflection cube in hyper-extended domain of the Porcupine Basin, showing a seismic line and the interpreted "S" reflector surface in two-way travel time (adapted from Figure 2b of Lymer et al, 2022). It illustrates the horizontal detachment corrugations and their relationship with the extensional basement faults above.

We have updated the caption for Figure 1b with the text above.

Julia Gomez Romeu and Nick Kusznir