Uncertainties in breakup markers along the Iberia-Newfoundland margins illustrated by new seismic data

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Response to reviews

Reviewer 1: Alexander Peace

In their paper "Uncertainties in breakup markers along the Iberia-Newfoundland margins illustrated by new seismic data" Causer et al. use seismic data from offshore Newfoundland to assess the suitability of commonly used break-up markers along the Newfoundland margin for plate kinematic reconstructions. According to their results, basement associated with the younger M-Series magnetic anomalies is comprised of exhumed mantle and magmatic additions, and therefore most likely represents transitional domains rather than true oceanic lithosphere. This seems reasonable although some aspects of this are hard to assess with the materials currently provided with the manuscript. This has implications for plate tectonic modelling which is well demonstrated in the paper.

The paper is on a worthwhile subject, and Solid Earth seems like an appropriate location for the results of this study. Plate reconstructions in the southern North Atlantic have been the focus of a number of recent publications, demonstrating that this is a very topical subject (Barnett-Moore et al., 2018; Nirrengarten et al., 2018; Peace et al., 2019). In addition, although the Newfoundland-Iberia margins are one of the most studied conjugate margin pairs in the world, there remains significant unknowns regarding the early aspects of separation (Eddy et al., 2017). Thus, the topic of the study addresses a very relevant subject.

Overall, the study seems to be generally well thought out and suitable for publication. However, there are several aspects that I think could be drastically improved, as outlined in detail below. I would therefore like to offer a largely supportive review on this paper, with a recommendation that this paper is published following major revisions.

No action: *We thank Alexander Peace for his fair and constructive review of our work. Below, we outline the changes we've made to our manuscript in light of his comments. References to line numbers are made with respect to the revised version of the manuscript.*

1) Applying results beyond the data coverage

It is reasonable to extrapolate the finding of the study somewhat beyond the area investigated. However, further consideration, and justification, of how feasible this is would substantially improve the manuscript. Specifically, limited 2D seismic reflection data is interpreted on the continental margins and this is used to derive implications for plate models of the entire region. Although I think the approach is probably valid, it could potentially be problematic because it is well established that passive continental margins are highly variable along strike, so observations made in a region are not necessarily applicable elsewhere without consideration of the processes involved. For example, breakup of the southern North Atlantic occurred via a propagating rift (e.g., Nirrengarten et al., 2018), so timing of rifting and breakup is not the same right along the margin, and also the margin is highly structurally variable, with local complexities such as magmatism and reactivation. As such, the interpretation of magnetic anomalies source using the limited seismic data may not be valid for the entire anomaly. The authors should consider this aspect further in their justification of the approach, and also in the subsequent discussion section.

Action: *We fully agree with the reviewer and have made this clearer in our revised manuscript (lines 97-99)*

2) Location and orientation of the lines

The location and orientation of Lines A-C is currently difficult to discern with the current figure setup and description in the manuscript. For example, although the complete seismic grid is shown (Fig. 4), none of the figures show which line within the grid is Line A-C. As such, it is problematic to fully assess the validity of the results and outcomes.

Action: *We have added Lines A-C to figures 1 and 4, and made reference to them in the text where appropriate.*

This links with the issue outlined above regarding the validity of the results over the entire region. This could in part be rectified by addressing the issues with the figures outlined below. In addition, although a sparse grid of 2D lines is shown on some of the figures only three lines are presented in detail in the paper. It would be beneficial if the authors could provide further description of what else is shown by the other lines in the grid of seismic data, and also describe why they have chosen lines A-C over others. Finally, the nature of the blue seismic grid shown on the Iberian margin is not well described in the manuscript.

Action: *The grids of lines have been removed from figure 4, and lines A-C are shown instead. We have maintained the grid on figure 8 as we believe this helps the reader better understand the implications of choosing conjugates on the basis of alternative plate models. The revised text includes a statement that we chose to present lines A-C because they cover the overall range of possible locations for the conjugate to IAM-5.*

3) Deformable models

The fundamental subject of the paper is about how current plate kinematic models of the Newfoundland-Iberia conjugate margins do not sufficiently describe the separation, and lead to problems when reconciled with regional observations. This aspect is well outlined in the paper. Recent work however, has sought a new solution to this issue through the use of deformable plate tectonic modelling, to reduce overlap in reconstructed conjugate margins and develop concepts of plate kinematics (Ady and Whittaker, 2018; Müller et al., 2019; Peace et al., 2019). These models are far from perfect but offer an alternative approach to the problem addressed in the paper. I think that discussion of the role of this new approach to plate modelling would also be beneficial in the manuscript.

Action: *We agree that deformable models do present an alternative approach to studying highly extended continental margins, and techniques such as these have been worked on in the past years (e.g. Ady and Whittaker, 2018; Müller et al., 2019; Peace et al., 2019). Deformable models such as these are founded on assumptions which integrate uncertainties investigated in this paper, for example the COB and M-Series. Recent work by Eagles et al., (2015) found that the choice of COB only has a modest effect on its planispatically-restored equivalent, as COB estimates are reduces by stretching factor. As a result statistical uncertainties are greater for deformable models than the more conventional methods of rotating points around a stage pole.*

We have included the suggested references, and added detail to the text regarding deformable models (Lines 51-65).

4) Figures

In my opinion the figures are currently one of the weakest aspects of the manuscript. Overall, I felt that they were: 1) underutilised in the text, 2) difficult to interpret, and 3) at times ambiguous.

Generally, on all figures making the text larger would substantially improve them.

Action: *Done*

As outlined in the points below, the figures need substantial work to be of publication quality. In addition, I think adding a new figure showing a magnetic anomaly map of the region as a new Figure 2 would substantially improve the manuscript. This would be very beneficial to those working outside of the present study area as it could be used to label feature such as the J-Anomaly and M-Series. Something like the EMAG model (Maus et al., 2009) would suffice here.

Action: *We feel that an extra gridded magnetic anomaly map would take up too much space to justify only for the purpose of locating anomaly J and the disputed M-series isochrons. Instead, we have added the location of the J and M-Series anomalies to figure 1 for reference.*

Figure 1**:** I felt that figure 1 could have been used much more extensively throughout the manuscript. In particular, I think it could be used to show the locations of the other figures, and the data, as well as providing a better description of the geological setting such as the key magnetic anomalies. Also, many aspects of this figure are very problematic to see and interpret. For example, the red dots indicating drill sites are nearly impossible to find. In addition, although many of these are referred to in the text (e.g., DSDP site 398) there appear to be some wells in the Bay of Biscay without labels leaving me wondering what is the relevance of these? The green dashed line is not defined in the caption, and the “white envelopes” are difficult to see. Moreover, the red dashed lines do not show all the oceanic fracture zones, so why have these ones been chosen specifically?

Action: *Done*

Figure 2: Text is again too small. In addition, what is the small circle within 'the maximum extent of the Continent-Ocean Transition Zone' at 83 Ma offshore Newfoundland (under the 'B' of 'Base').

Action: *We have increased text size and removed the small circle which was in this figure by error.*

Figure 3: It is not immediately clear to the reader where the magnetic profiles shown in parts b and c are located. In addition, the text is again too small. Finally, what are the black dots shown on a, they are not described in the legend.

Action: *We have increased text size and improved the figure's labelling. The black dots are the locations of picks on the younger (oceanward) edge of anomaly J made on magnetic profiles that are not included in the rest of the figure.*

Figure 4: This figure is integral to the study as it shows the location of the data. However, it is difficult to know which line presented in the paper (i.e. Lines A-C) corresponds which location shown on the figure. This information needs adding to the figure, otherwise the reader is unable to locate the data. Also the age of the isochrons quoted on the figure are according to which timescale?

Action: *We have modified the figure to show the position of lines A-C. We have also clarified the timescale used.*

Figure 5-7: Although the general interpretations shown look reasonable, there are several aspects of these figures that need substantial improvement. First, the labelling of subfigures (a-c) on these figures is a little strange as the seismic line and its interpretation are not given a subfigure letter. Another thing that struck me when I first saw the interpreted sections was that ages are provided for the sediment packages (e.g., Late Cretaceous), yet in the text it is stated that "sediments have been grouped into Synrift 1, Synrift 2, Breakup-sequence, and Post-Rift packages based on seismicstratigraphic observations". Given this, where have these ages come from? In addition, it would help if the scale bars for TWT and distance were also present on the seismic data. Also, on some of the figures sills are labelled, how are these differentiated from other high amplitude reflectors? Finally, the difference between the grey and the black lines (in the key) is impossible to determine on the figure, the L-reflector symbol is too similar to the fault symbol, and the text on all of these figures is too small.

Action: *Seismic lines have been updated and the ages of syn-rift 1 and syn-rift 2 have been removed (they were there from an early iteration of the manuscript). The source for the age of the U reflector has been referenced in the updated text. We have further improved figure quality by:*

- *Using colour-coded symbols: e.g. exhumation/detachment faults are now shown in red; seismic moho is now shown in blue.*
- *Adding scale bars to all.*
- *Increasing the size of distance bars.*

Our reasoning behind the interpretation of sills is made clear in the revised text (Lines 311-312)

Figure 8: I like the approach to showing reconstruction using different models, however the text on this figure is again too small, particularly the age in Ma.

Action: *done.*

Figure 9: I think the concept behind figure 9 is good, particularly the description in the text acknowledging the limitations in this approach. However, all of the text on this figure either needs to be made substantially larger or removed. If all of the interpretation has been shown previously perhaps the text can are provided below.

Action: *We have condensed the text down to the key points and increased size for readability.*

5) References

Throughout the manuscript there are multiple statements that require references. In. particular, when the 'literature' is referred to or a statement like 'broadly accepted' is used, I think it is necessary to add additional references. Specific examples are of this are provided below.

Action: *we have added references in light of the reviewer's detailed comments.*

In addition, a few references are cited in the paper that do not occur in the reference list. For example, Eagles et al. (2015) is not in the reference list.

Action: *done*

Furthermore, the citation of 'in prep' works seems unnecessary given that the statement being supported could be supported with other published works. For example, at line 235 the compilation model of Matthews et al. (2016) could be cited as this also includes independent plates for Newfoundland (as part of North America), Iberia, Eurasia and Africa, as do other models (e.g., Nirrengarten et al., 2018). In addition, in plate modelling one can keep adding more and more plates, building increasingly complex models so what would be different about the model cited as 'in prep'? For example, Nirrengarten et al. (2018) use independent plates (with separate poles) for Flemish Cap, Rockall-Hatton Bank, Orphan Knoll and also parts of Iberia. Perhaps, this aspect is worthy of discussion in the paper.

Action: *we have maintained the citation to our work in preparation and have clarified how this on-going work differs from those mentioned by the reviewer here (lines 249-252).*

By adding more and more small plates bounded by COBs or disputed M-series isochrons, as the reviewer describes and as has been done before, the interpretational uncertainty in breakup markers that is the subject of our manuscript is not only ignored, but potentially also magnified by propagation through rotations in neighbouring branches of the model. As we explain in the revised text, the aim of our work in preparation is not to increase model complexity in this way, but to reduce model uncertainty by interrogating the set of statistically-permissible combinations of a small number of uncontroversial large-plate *models with the aim of finding which of the wide range of Iberia-Newfoundland breakup marker interpretations are viable and, of these, which are most likely.*

5) Minor points:

Line 14: I suggest replacing ‘on the belief’ with another phrase such as ‘based on the concept’.

Action: *done*

Lines 14-15: What exactly differs between the models? The timing or the rotations? Inclusion of different plates? Essentially I found this statement a bit vague.

Action: *clarified (Line 16)*

Line 23: I suggest replacing ‘to’ with ‘with’ after ‘associated’.

Action: *done*

Lines 34-38 (opening paragraph of introduction): All the statements in this paragraph need referencing.

Action: *done*

Line 45: ‘computer generated plate reconstructions’ – I found this statement to be quite vague, surely most modern plate reconstructions are done on a computer?

Action: *changed to “modern”.*

Lines 48-49: ‘alternative scenarios proposed in the literature’ - Which alternative scenarios, and in what literature? This statement needs references and further description. I know this is described later on but I felt that without references here the statement feels out of place.

Action: *References have been added (Lines 53-54).*

Line 51: ‘overlaps’ – deformable plate modelling goes someway to address this, and I think it would be good to discuss this aspect of plate modelling (Ady and Whittaker, 2018; Müller et al., 2019; Peace et al., 2019).

Action*: done (Lines 58-65).*

Line 56: Why say ’West" here but nowhere else when referring to Iberia?

Action: *rectified.*

Line 66: ‘heavily debated’ – By who? This statement needs references, and explanation of what exactly is debatable about the aspects described in the sentence.

No action: *We discuss this statement in the same paragraph, immediately after making it (Line 76 onwards)*

Lines 56-75: I felt that this was a really good description of the history and problems associated with studying the Newfoundland Iberia conjugate margins.
No action

Lines 83-84: Slightly awkward phrasing.

Action: *Rewritten.*

Line 85: ‘said studies’ – which ‘said studies’? You should cite them here & Line 85: ‘published rotation schemes’. Again, I think you should say which rotation schemes by citing the appropriate literature.

Action: *done (Lines 101-105)*

Line 89: Awkward phrasing. I suggest modifying this.

Action: *done*

Line 90: Should the references be in chronological order in Solid Earth papers?

Action: *all references have been changed to chronological order.*

Line 94: Eagles et al. (2015) is not in the reference list.

Action: *done.*

Line 95: ‘gradual’ - Is it really gradual? I am just not sure that this is the best description. It is wide and structurally complex, but I don’t think we can describe a change in crustal affinity as gradual.

Action: *reworded.*

Line 98: ‘so-called’ - according to whom? Add appropriate references here.

Action: *references added.*

Line 99: I suggest inserting ‘the’ before ‘literature.

Action: *done.*

Line 100: Which ‘literature’ is being referred to in the sentence ending here. Add appropriate references.

Action: *done.*

Lines 101-112 (whole paragraph): I think this paragraph could be summarised to make it a bit simpler.

Action: *done.*

Line 108: ‘age of seafloor spreading’ - Eddy et al. (2017) discuss this. Also, this reference should probably be included generally as its quite recent and integral to the topic.
Action: *Reference added.*

Lines 114-115: Add appropriate references regarding the complexity of reconstructing the kinematics of the Iberian plate.

Action: *done.*

Line 120: ‘broadly accepted’ – By who? Add references.

Action: *done.*

Line 127: I don’t think the italics on the citation are necessary.

Action: *done.*

Lines 131-132: Cadenas et al. (2018) also conducted a recent study on compression along this boundary that might be of use. Also, the models in Peace et al. (2019) show this compression, and actually overestimate the extent and magnitude of thickening (based on published constraints) implying that the published models do not account well for Iberia’s kinematics.

Action: *done.*

Line 133: I am not sure the italics on the citation are necessary here (and elsewhere).

Action: *done.*

Line 155: ‘generally accepted’ – this needs references to show who it is accepted by.

Action: *done.*

Line 164: Why are these references not at the end of the sentence? As it stands, it is confusing which statement the references are referring to.

Action: *references moved.*

Line 167: ‘contradictory geological evidence’ – you should expand on what this evidence is and provide references.

Action: *done.*

Line 167: ‘Site 1070’ – This is very difficult to see on figure 1.

Action: *Figure 1 has been updated.*

Line 178: “old oceanic lithosphere’ – How old? If you can provide an age here it would be better.

Action: *done.*

Line 186: ‘The J-Anomaly’ – See notes in section above regarding a figure showing the magnetic anomaly locations.

Action: *Added to Figure 1.*

Line 196-200: Some references are in italics whilst others are not?

Action: *rectified.*

Line 201-208: Same as previous comment regarding italics.

Action: *references are now a consistent style.*

Line 219-225: I found the tense of this paragraph quite strange. Essentially you are describing what you will do so why write it like this?

No action: *The style the reviewer refers to conforms to the structure “X would achieve Y, but X is not available at present”. We don’t see the need to change verbal tense in this instance.*

Line 235: The citation of ‘in prep’ works seems unnecessary given that the statement being supported could be supported with other published works. This point is expanded on in the points above.

No Action: *see our response to the reviewer’s previous mention of this issue.*

Line 237: Remove ‘some’.

Action: *done.*

Line 252-253: ‘sediments have been grouped into Synrift 1, Synrift 2, Breakupsequence, and Post-Rift packages based on seismic stratigraphic observations’ - This statement appears to contradict what is shown on the figures as on the figures the sediments are also given ages? Also, where have these ages come from? I suggest providing the source of the information.

Action: *ages were removed from figures for consistency – they corresponded to tentative ages in an earlier version of the manuscript.*

Line 263: ‘DSDP, Site 298’ - This is very hard to see on Figure 1. I suggest making this larger, along with all the other wells shown on the figure.

Action*: Figure 1 has been changed.*

Line 274: ‘variable offsets’ – This is quite a vague phrase. Can these offsets be quantified on the data?

No action: *we don’t feel a change here is needed, the reader is referred to the figure.*

Line 275: ‘seismic Moho’ – refer to the figure showing this?

Action: *done.*
Line 289: ‘Fig 5c’ - This is good, I suggest referring to the subfigures more often when describing the interpretation.

Action: *done.*

Line 295: ‘distorted seismic imaging’ - This is quite vague terminology.

Action: *We have described the basis of our interpretation more precisely in the revised text.*

Line 299: Again, which line on the figure showing the seismic grid is line B?

Action: *Lines A-C are now shown on figures 1 and 4 for clarity.*

Line 320: As with previous comment but for Line C.

Action: *Lines A-C are now shown on figures 1 and 4 for clarity.*

Line 350 onwards (opening paragraph of the Discussion): I found the whole of this first paragraph of the discussion to be very vague, and question whether it is fully necessary as much of this information has already been provided in the introductory sections.

No Action: *We believe this paragraph summarises and reminds the reader of the points raised in the results section, and sets the scene for the discussion to follow.*

Line 350: ‘three seismic lines’ – why is a grid of seismic lines shown but only three are presented in the paper? Did you analyses the others, and how did you choose the ones presented?

Action: *We have added some clarification in the text (Lines 87-91). The three lines presented were chosen on the basis of them 1) being previously unpublished and 2) crossing regions associated with the J and M-series anomalies.*

We have maintained the grid on figure 8 as we believe that it illustrates how the choice of plate model influences the identification of conjugates.

Line 368: Yamasaki and Gernigon (2009) do not mention the origin of SDRs in their paper, so this citation does not make sense here.

Action*: Removed.*

Line 406-408: Opening statement on conjugate margins - This is good, I like that you state this.

No action

Reviewer 2: Frauke Klingelhoefer

The mansucript "Uncertainties in breakup markers along the Iberia-Newfoundland margins illustrated by new seismic data" by Annabel Causer, Lucía Pérez-Díaz, Jürgen Adam and Graeme Eagles present unpublished seismic data from the Southern Newfoundland Basin to study the impact of commonly used break-up markers for plate cinematic reconstructions of the initial ocean opening between the West Iberia and Newfoundland margins. The main conclusion is that in this region the "traditional" break-up markers do not allow to unequivocally discriminate the validity of the different plate tectonic rotational poles proposed in literature.

From this the authors propose:

1) **Major Comments:**

That new and better constrained reconstruction are needed to identify individual seismic profiles as parts of conjugate pairs. It is a bit unsatisfactorly that the main conclusion of this manuscript is that it is not possible to better constrain the opening using the data presented. A better constraint on the error of the different reconstructions could probably be done using the work of Hellinger, 1981 or Chang, Royer et al., 1991. A tool using these approaches is available in the free Gplates software (https://www.gplates.org/user-manual/HellingerTool.html).

No Action: *the reviewer has not appreciated the main aim of our manuscript, which is to use new data to highlight the large degree of uncertainty involved in interpreting breakup features of the kind that are often used to lead quantitative plate reconstructions. These aims are clearly outlined in section 1 (lines 87-105). Unfortunately, Chang's statistical tools are only applicable with Hellinger's fit criterion for seafloor spreading data. Regardless of how available these tools are in GPlates, they would only be applicable for a small subset of the cited plate reconstructions (those that only use seafloor spreading data). These tools are useless for assessing the uncertainty in geological markers like COBs off Iberia and Newfoundland, or transtensional basins in the Pyrenees. We do aim to take a quantitative statistical approach to understanding the study region in future work, based on a suite of purpose-built two-plate models for Africa, North America, Eurasia, Greenland and Iberia using a more modern and robust inversion scheme. This work is still in progress, and well beyond the scope of this manuscript.*

In my opinion, the manuscript is missing some information. It would be nice to know which software has been used for the plate cinematic reconstructions and for data processing. A short description of the seismic data processing, even if done by TGS would be of interest.

Action: *We have added detail on seismic processing to the revised manuscript (lines 254-265). The caption of figure 4 acknowledges plate modelling method used. Given that plate kinematic modelling is not the principal aim of our manuscript we don't see a need to include further details in the text.*

The discussion should be extended to give at least an impression of comparable margins. Is this uncertainty a general problem or only in this specific region, which has nonetheless been very extensively investigated? If only here, than why, for example are the magnetic anomalies especially unclear and uninterpretable or is this due to the large extend of serpentinised mantle material?

No Action*: we refer the reviewer back to our introduction section, in which the difficulties of interpretation at divergent continental margins in general are introduced by citing a previous global study in which some of us were involved. More specifically, as our study region is the type region for mantle exhumation in wide transition zones, we feel there is little to be gained from a detailed examination of comparable margins where the difficulties of interpretation are likely to be understood with reference to Iberia-Newfoundland.*

The manuscript has no acknowledgement section, but probably some free software ("Generic mapping tools" or other) were used and should be acknowledged.

Action: *GMT will be acknowledged in the final manuscript.*

Figures:

Figure 1: it would be nice to add the magnetc anomaly positions.

Action: *Done.*

Figs 5, 6, 7: all panels should be annotted a,b,c,d,e and explained in the legend. I think a classical offset and time annotation would be helpful, rather than just having a scale for one second and 10km. Middle panel have no indication for 0 s.

Action: *figures have been improved and re-labelled in response to the comments here and those of Reviewer 1.*

Figure 9: strictly spreaking there are no data shown in this figure, but mentioned in the caption.

Action: *this figure and its caption have been modified.*

Minor corrections:

L. 82 Furthermore -> Furthermore we

Action: *done.*

L. 94 missing ")"

Action: *done.*

L. 104 "(" too much

Action: *done.*

L. 169 Isn’t M25 125 Ma age?

No Action: *M25 dates to ~155 Ma in the timescale of Gradstein et al., 2012, which we have used throughout.*

L. 177 "(" too much

Action: *done.*

L. 219-228 This is more "objectivs" than "Data and methods"

Action: *section has been refined.*

L. 229 allows -> allow

Action: *done.*

L. 239 Would be C2 nice to have more detail, seize of the airgun array, length of the streamer...

Action: *More detail has been added (Lines 254-265).*

L. 390 suggested -> suggest Gurnis, M., M. Turner, S. Zahirovic, L. DiCaprio, S. Spasojevic, R. D. Müller, J. Boyden, M. Seton, V. C. Manea, and D. J. Bower, Plate tectonic reconstructions with continuously closing plates, Computers & Geosciences, 38, 35-42, 2012. Hellinger, S. J. (1981). The uncertainties of finite rotations in plate tectonics. Journal of Geophysical Research: Solid Earth, 86(B10), 9312-9318. Chang, T., Ko, D., Royer, J. Y., & Lu, J. (2000). Regression techniques in plate tectonics. Statistical Science, 342-356.

No Action: *These references describe specific tools (Gurnis et al for GPlates, and Hellinger and Chang for one approach to statistical modelling of plate motions from seafloor spreading data) that we have not used at any point for this manuscript and have zero relevance to the discussion of Anomaly J at line 390.*

Anonymous Referee #3

The aim of the manuscript submitted by Causer et al. is to discuss breakup markers along the Iberia-Newfoundland margins based on new seismic data. The theme of the manuscript is of major scientific interest, since neither the nature, not the timing and location of breakup are well constrained along the Iberia-Newfoundland margins. Many papers, some of which are very recent, have been dedicated to this problem. I have to admit that I did not find new ideas, or new, well constrained observations that add something new to the subject. Indeed, the interpretation of the new seismic data lack a rigorous interpretation and observations and interpretations are mixed and difficult to follow (for some further comments see comments below). The manuscript reads more like a report referring to old studies and only very few new observations are added. Most disturbing is that some of the latest studies, that come to almost the same conclusions, are only marginally referred or partly not discussed. This omission weighs heavily and discredit the authors. Apart from these points, there are several other points (see comments below) that makes that this manuscript can not be accepted in its present version.

Specific comments:

l.30: here and elsewhere in the paper the authors make statements that are similar to the papers of Nirrengarten et al, without citing their work. Actually, most of the conclusions reached in this paper are similar to those by Nirrengarten et al. 2017 and 2018, thus, referring to these results is necessary. I would propose that the authors should discuss how their results are different from those of Nirrengarten et al. 2017 and 2018. I do not really see a big difference. Moreover, the papers of Stanton et al. 2015 and Nirrengarten et al. 2018 that deal with the same subject are not referred to.

***Action:** We disagree with the reviewer's statement that our work lacks referencing to that of Nirrengarten on the J-anomaly, although acknowledge our oversight of Nirrengarten et al. 2018, and have now included it.*

Regarding similarity – both our work and that of Nirrengarten focus on a similar study area and discuss the J-anomaly and its significance for kinematic modelling. However, our work differs from previous studies in that 1) presents and discusses previously unpublished seismic data and 2) illustrates and discusses in detail the impact of "breakup markers" as the basis for plate kinematic modelling.

l. 25: the SDR packages need to be better described; what is the origin (magmatic) and the significance of the SDR package? I can not find them in the figures

***Action:** SDR packages are labelled in figure 5 and described in the text (Section 4).*

l.130 to 150: the tectonic setting part is completely outdated. A lot of work has been done in the last years that need to be referred to.

***No Action:** Were this comment to have been more detailed, it would have been difficult to weigh against reviewer 1's suggestion to reduce the level of detail in lines 130-150. As it stands, however, we cannot act on this comment because it lacks any citations to work completed over 'the last few years' that the reviewer thinks we might have missed. With the* *help of the more detailed and helpful comments made by reviewers 1 and 2, we are confident that this section of the manuscript is both up to date and fit for its purpose.*

l.218 Dataset and methods section need to be rewritten and more details about the data presented in the paper need to be presented.

No Action: *this comment is also too vague as a basis for us to improve our manuscript. The reviewer should have supported their statements with examples and concrete suggestions or advice.*

l.265 to 345 The description of the seismic lines mixes observations with interpretations. Many questions remain open, such as how syn-rift 1 and 2 have been defined, where are possible limits, how were different types of basement defined and what are the evidence for magmatic additions (there are many more questions that arise by looking the seismic interpretations).

No Action: *As no examples are given by the reviewer (and neither of the other two reviewers have highlighted this issue) we are unsure as to where, in the text, the reviewer finds we are mixing observations and interpretations.*

The rationale for our identification of syn-rift packages, basement and magmatic additions is given in sections 3 and 4.

The presentation of the data needs to include the presentation of the seismic section (without interpretation), a line drawing and the presentation. As presented here, I cannot follow the interpretations and many of the assumption are not back up by observations. The presentation of the seismic data is insufficient and does not corresponds to the standard of scientific papers.

No Action: *This comment is simply baffling. What figures was the reviewer looking at? Our figures 5 to 7 do in fact include, on separate panels, the seismic section (without interpretation), a line drawing and detail panels, exactly as the reviewer complains they don't.*

l.360 to 400: this section does not really discuss new ideas and does not built on the observations neither. Most of what is said here is old and outdated (the authors seem to have missed the research on the Iberia-Newfoundland margins of the last 5 years??)

No Action: *This section puts our findings (previously presented in section 4) in the context of previously published research. This is the definition of a scientific manuscript's discussion. Regarding referencing, we are unsure as to what research the reviewer is referring to as missing, or out-dated, as yet again no examples are given.*

We have made changes to this section in response to concrete comments from reviewers 1 and 2.

l.405 to 460: This section reads more as a report than a discussion chapter.

No Action: *Yet again, a comment that is too vague on its own and too weakly supported by any of the other reviewers' comments to form any no basis on which we can make justifiable changes.*

Uncertainties in breakup markers along the Iberia-Newfoundland margins illustrated by new seismic data

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Abstract.

Plate tectonic modellers often rely on the identification of "break-up" markers to reconstruct the early stages of continental separation. Along the Iberian-Newfoundland margin, so-called "break-up markers" include interpretations of old magnetic anomalies from the M-series, as well as the "J-anomaly". These have been used as the basis for plate tectonic reconstructions ~~on the belief~~are based on the concept that these anomalies pinpoint the location of first oceanic lithosphere. However, uncertainties in the location and interpretation of break-up markers, as well as the difficulty in dating them precisely, has led to plate models that differ in both the timing and relative palaeopositions ~~their depiction of the separation~~ of Iberia and Newfoundland during ~~stages of~~ seperation.

We use newly available seismic data from the Southern Newfoundland Basin (SNB) to assess the suitability of commonly used break-up markers along the Newfoundland margin for plate kinematic reconstructions. Our data shows that basement associated with the younger M-Series magnetic anomalies is comprised of exhumed mantle and magmatic additions, and most likely represents transitional domains and not true oceanic lithosphere. Because rifting propagated northward, we argue that M-series anomaly identifications further north, although in a region not imaged by our seismic, are also unlikely to be diagnostic of true oceanic crust beneath the SNB. Similarly, our data also allows us to show that the high amplitude of the J Anomaly is associated with~~to~~ a zone of exhumed mantle punctuated by significant volcanic additions, and at times characterised by interbedded volcanics and sediments. Magmatic activity in the SNB at a time coinciding with M4 (128 Ma), and the presence of SDR packages onlapping onto a basement fault suggest that, at this time, plate divergence was still being accommodated by tectonic faulting.

We illustrate the differences in the relative positions of Iberia and Newfoundland across published plate reconstructions and discuss how these are a direct consequence of the uncertainties introduced into the modelling procedure by the use of extended continental margin data (dubious magnetic anomaly identifications, breakup unconformity

interpretations). We conclude that a different approach is needed for constraining plate kinematics of the Iberian plate pre M0 times.

1 Introduction

Over the past decade, plate tectonic modellers working on divergent settings have focused their efforts on better-constraining the early stages of continental separation, partly driven by the oil and gas industry's move to more distal and deeper exploration targets (Péron-Pinvidic and Manatschal, 2009; Skogseid, 2010; Nirrengarten et al., 2017; Sandoval et al., 2019). As of today, bridging the gap between the onshore and offshore geological evolution of rifted continental margins still presents a challenge, due to the difficulty in unequivocally interpreting the complex geology of extended continental margins (Alves and Cunha, 2018; Keen et al., 2018).

When studying divergent settings, the onset of seafloor spreading is often based on so-called "breakup markers" that originate in tectonic interpretations made along the extended continental margins. Identified and mapped from geophysical data, these features include depositional unconformities (e.g. Pereira et al., 2011; Soares et al., 2012; Decarlis et al., 2015), packages of landward dipping reflectors (e.g. Keen and Voogd, 1988), and seismic amplitude changes in the top-of-basement surface (e.g. Tucholke et al., 2007), interpreted to mark the change from continental to oceanic crust. These interpretations are utilised as the basis for many computer-generated plate reconstructions, which are in turn highly susceptible to uncertainties associated with the interpretation and mapping of said breakup markers. A recent global census and detailed analysis of these markers highlighted the very large average locational (167 km) and temporal (>5 Myr) uncertainties associated with defining them (Eagles et al., 2015).

Uncertainties of this kind, and their impact on tectonic reconstructions, have been illustrated by, for example, the alternative scenarios proposed in the literature for the movements of the Iberian plate between the Late Jurassic to Early Cretaceous (Srivastava et al., 1990, 2000; Sibuet and Collette, 1992; Sibuet et al., 2007; Greiner and Neugebauer, 2013; Barnett-Moore et al., 2016). Rotational poles derived from interpretations of the location of the continent-ocean boundary (COB), for example, have often resulted in overlaps of known continental crust along the Iberia-Africa plate boundary (e.g. Srivastava and Verhoef, 1992). Such overlaps are not present in kinematic models built on the basis of magnetic anomalies, which assume Iberia moves together with Africa for much of this time period ~~(~~e.g. (Sibuet et al., 2012)~~, or and is~~. They are greatly reduced in so-called "deformable" plate models ~~which assume deformable plate boundaries~~that account for continental margin deformation during continental breakup (Ady and Whittaker, 2018; Müller et al., 2019; Peace et al., 2019).~~.~~ Because these models undo stretching deformation, the large uncertainty in COB location estimates reduces to a much smaller uncertainty envelope of ~~Models such as these are founded on assumptions which integrate uncertainties investigated in this~~

~~paper (for example those related to COB and M-Series interpretations). Recent work by Eagles et al. (2015) found that the choice of COB only has a modest effect on its~~ palinspastically-restored equivalents (Eagles et al., 2015). This reduction is unlikely to be useful because, as those authors note, the restoration is achieved using rotations about a stage pole that is determined using an arbitrary choice of post-stretching COB estimate, and whose formal statistical uncertainty is of a similar size to, or larger than, the restored envelope~~. As a result, although seemingly resulting in a preferred continental margin fit, statistical uncertainties are greater for deformable models than the more conventional methods of rotating points around a stage pole~~. Hence, the shape of the pre-stretching COB estimate is sensitive to post-stretching COB estimates to an extent that is likely to be larger than the uncertainty that the palinspastic reconstruction technique generates for it. ~~A further study, constituting a combination of magnetic seafloor anomalies and on-land palaeomagnetic data, shows the Iberia-Africa boundary to be more complex (Neres et al., 2013).~~

The West Iberia and Newfoundland margins are considered by many as the type-example for magma-poor passive rifted margins (Boillot et al., 1995; Whitmarsh and Wallace, 2001; Reston, 2007; Tucholke and Sibuet, 2007; Péron-Pinvidic and Manatschal, 2009). The continental margins are the result of Late Triassic to Early Cretaceous rifting and separation of the North American and Eurasian plates. This pair of conjugate margins has been the focus of more than 40 years of intense research, including extensive geophysical surveying and drilling campaigns as part of the Ocean Drilling Programme (ODP) and Deep Sea Drilling Project (DSDP) (e.g. Whitmarsh and Sawyer, 1996; Wilson et al., 1996). Research has revealed the margins' tectonic asymmetry and the gradual proximal to distal transition from regions of highly extended continental crust to zones of exhumed mantle ~~at times~~locally intruded by pre or post-breakup magmatic intrusions. Despite this, the detailed plate kinematics, the age of distinct rift episodes, the timing of final breakup, and the significance of pre-existing structures and lithological heterogeneity are still heavily debated. The difficulty in identifying, mapping and dating the COB along this pair of conjugate margins is evident in the wide range of candidate COBs suggested in the literature (Fig. 1) (i.e. Eagles et al., 2015 and refs. therein). The age of final break-up and formation of first oceanic crust is particularly uncertain. Drilling results and breakup unconformity identifications date the onset of seafloor spreading at the Aptian-Albian transition (113 Ma) (Tucholke and Sibuet, 2007; Boillot et al., 1989). This is significantly younger than the age of the oldest isochrons interpreted from magnetic reversal anomalies (M20-145 Ma to M0-120 Ma) offshore Iberia (Srivastava et al., 2000) (Fig. 1). The discrepancy means that interpretation of these anomalies in terms of M-series isochrons is disputed. Although interpreted by some studies as markers of first oceanic lithosphere (e.g. Vissers and Meijer, 2012; Sibuet, et al., 2004), others have shown that they may instead be associated with igneous bodies located within zones of exhumed mantle (e.g. Sibuet et al., 2007; Sibuet et al., 2012).

Here we describe and interpret ~~a number of~~three ~~previously~~ previously-unpublished 2D seismic profiles imaging the regional tectonic structure and crustal architecture of the Southern Newfoundland margin from the shelf to the deepwater oceanic basin. The three profiles are chosen from among a large regional grid of data as the three most likely candidates for a conjugate to the IAM-5 deep seismic profile on the Iberian margin, and thus suitable for a detailed assessment of the possible effects of across-axis asymmetry on uncertainties in breakup markers (see Pinheiro et al., 1992; Afilhado et al., 2008; Neves et al., 2009). Our interpretations underline and add to knowledge of the structural and kinematic complexity of the transitions between continental and oceanic crust at the Iberia-Newfoundland conjugate margins, specifically the Southern Newfoundland Basin (SNB) that contribute to the challenges faced by plate modellers when reconstructing this pair of conjugate margins. Our new seismic data shows that, within the SNB, neither M-series magnetic anomalies nor the commonly used J-anomaly are diagnostic of true oceanic crust. Extrapolating these regional observations beyond the extent of the SNB is challenging due to the high along-strike structural variability of the margin (e.g. Nirrengarten et al., 2018). ~~However~~As we will show, ~~they~~our extrapolations are consistent with the growing literature questioning the validity of these anomalies as kinematic markers for Iberia-Newfoundland kinematic modelling (e.g. Bronner et al., 2011; Stanton et al., 2016; Nirrengarten et al., 2017).

Furthermore, we review a number of published studies in order to examine the uncertainties of available plate kinematic reconstructions of the Iberia-Newfoundland conjugate margin (Srivastava et al., 1990; Seton et al., 2012; Greiner and Neugebauer, 2013). We do this by (a) examining the locations, within our new seismic data, of "breakup markers" commonly used by ~~said~~ those studies and (b) utilising these published rotation schemes to reconstruct conjugate margin transects into their pre-drift positions, examining the consequences of choosing alternative rotation parameters.

~~Although we demonstrate the differences which occur from alternative schemes, we do not see it deafible to exptapolate our findings from seismic data further afield than the SNB. Findings are nor extrapolated on the ground of the Iberian – Newfoundland margins' representing a highly geologically and structurally complex along strike variability (e.g. Nirrengarten et al., 2018).~~

2 Study area – tectonic evolution and controversies

The formation of the Iberian - Newfoundland conjugate margins are primarily a result of a series of northward propagating Late Triassic to Early Cretaceous ~~rifting episodes~~episodes of rifting (Manatschal and Bernoulli, 1999; Wilson et al., 2001; Alves, et al., 2009). Progressive ~~extension,~~extension and final localization of the divergent plate boundary at a mid-ocean ridge led to the separation of the North American and the Iberian plates. Unlike the classic textbook examples of passive margin architecture, continental and oceanic crust are not juxtaposed along these margins, but separated by a very wide continent-ocean transition zone (150-180 km, (Eagles et al., 2015) (Fig. 1). Geophysical research into the Iberian - Newfoundland margins has, to an extent, illustrated ~~the gradualby a wide and structurally complex~~the gradu~~d~~al change from continental crust through structurally complex regions of exhumed continental mantle and into purely oceanic crust (e.g. Dean et al., 2015). Although transition zones like this have been widely studied over the past decade (e.g. Whitmarsh and

Wallace, 2001; Manatschal et al., 2001; Pérez-Gussinyé and Reston, 2001; Péron-Pinvidic and Manatschal, 2009; Mohn et al., 2012), the identification so-called break-up features, which cannot be confidently attributed to either crustal type, renders kinematic reconstructions based on them difficult and susceptible to large uncertainties. In the literature, this transition is often referred to as continent-ocean transition zone (COTZ) (Minshull et al., 1998; Dean et al., 2000; Davy et al., 2016).

The complex architecture of the Iberian - Newfoundland margins is the result of a sequence of extensional deformation episodes beginning with an initial “wide-rift” phase during late Triassic-earliest Jurassic times (Manspeizer, 1988; (Manatschal and Bernoulli, 1998; Tucholke et al., 2007; Péron-Pinvidic et al., 2007),. This was fFfollowed by the localisation of extension and related crustal thinning along the distal part of the future margins. This, which resulted in the exhumation of subcontinental mantle rocks within the transition zones, which formed prior to leading up to seafloor spreading sometime in the Early Cretaceous (Malod and Mauffret, 1990; Manatschal and Bernoulli, 1999; Dean et al., 2000; Péron-Pinvidic et al., 2007; Tucholke et al., 2007). The exact age of the onset of seafloor spreading is controversial and has been inferred on the basis of regional correlations, magnetic anomaly interpretations, and drilling results to . Some suggest initiation in thedate from as early as Valanginian (Wilson et al., 2001) or Barremian (Whitmarsh and Miles, 1995; Russell and Whitmarsh, 2003), and others the Valanginian (Wilson et al., 2001) or perhaps asto as late as around the Aptian – Albian boundary (Tucholke et al., 2007b) based on interpretation of a breakup unconformity marking the onset of seafloor spreading (Tucholke et al., 2007b; Péron-Pinvidic et al., 2007; Mauffret and Montadert, 1987; Boillot et al., 1989; Eddy at al., 2017). Or even still, perhaps seafloor spreading wasmay have coincidedental with the formation of the J Anomaly (115Ma), as suggested by drill results from ODP Site 1277 along the Newfoundland margin (Eddy et al., 2017).

One of the difficulties in reconstructing the separation of the Iberian - Newfoundland margins is presented by the complex kinematic history of the Iberian plate (Barnett-Moore et al., 2016; Nirrengarten et al., 2017; Ady and Whittaker, 2018; Peace et al., 2019). Although currently part of the Eurasian plate, the Iberian plate moved independently between the Late Jurassic and sometime in the Paleogene (Fig. 2). During the Late Jurassic to Early Cretaceous, the Iberian plate was separated from the African, North American and European plates by divergent plate boundaries (Le Pichon and Sibuet, 1971) (Fig. 2, a-c). During Aptian time, relative motions between the African, Iberian and Eurasian plates underwent a period of re-organisation (Roest and Srivastava, 1991; Pinheiro et al., 1996; Rosenbaum et al., 2002; Seton et al., 2012; Tavani et al., 2018). It is broadly accepted that the Iberian plate undertook an anticlockwise rotation of around 35° with respect to the Eurasian plate, resulting in the opening of the Bay of Biscay along its northern margin (Fig. 2, b-c) (Van der Voo, 1969; Choukroune, 1992; Sibuet et al., 2004; Gong et al., 2008). Considerable controversy still exists as to the exact nature, timing and consequences of this rotation, with conflicting scenarios having been proposed by authors based on interpretations of geological and geophysical observations (Olivet et al., 1984; Srivastava et al., 2000; Gong et al., 2008; Vissers and Meijer, 2011). Kinematic reconstructions can be split into two end member groups. In one, the Bay of Biscay is depicted as having opened in a scissor-like fashion, with the hinge of the scissors located in south-eastern corner of the Bay of Biscay (Srivastava et al., 2000) (as shown in Fig. 2d). In the other, opening happens in a left lateral manner (Olivet, 1996). The anticlockwise rotation of Iberia as recorded in paleomagnetic data (e.g. Gong et al., 2008) is most closely replicated by models depicting a scissor-type opening (Srivastava et al., 2000). However, models like these imply significant compression further east along the IB-EUR plate boundary– (e.g. Schoeffler, 1965; Matthews and Williams, 1968; Masson and Miles, 1984; Roest and Srivastava, 1991; Sibuet and Collette, 1991; Sibuet, and Srivastava, 1994; Srivastava et al., 1990, 2000; Cadenas et al., 2018; Peace et al., 2019), which is not supported by field geology (Lagabrielle et al., 2010; Tugend et al., 2014). TIn contrast to the modelled major crustal thickening, the presence of numerous bodies of sub-continental mantle rocks exposed along the North Pyrenean Zone suggests the formation of extensional basins during the Cretaceous (Bodinier et al., 1988; Lagabrielle et al., 2010; Vauchez et al., 2013; Tugend et al., 2014, 2015; Teixell et al., 2018) instead suggest the formation of extensional basins during the Cretaceous. The importance of constraining the evolution of these extensional basins has been highlighted by Peace et al., (2018), who suggest compression between Iberian and Eurasia is an overestimate, and consequently results in plate models which do not do a poor job of accounting for the kinematics of the Iberian plate well. Although S some authors have interpreted these basins as having formed in a back-arc setting resulting from the subduction of older oceanic lithosphere from north of Iberia beneath Europe (Sibuet et al., 2004; Vissers and Meijer, 2012). Alternatively, they can also be understood together with the opening of the Bay of Biscay can be also interpreted as the results of strike-slipoblique-divergent motion between Iberia and Europe, along the North Pyrenean Fault (e.g. Olivet et al., 1996; Lagabrielle and Bodinier, 2008). Although in this model the fit of Iberia and Eurasia, derived by fitting the prominent regional magnetic J Anomaly, deteriorates to the north, it is favoured by many (Stampfli et al., 2002; Jammes et al., 2009; Handy et al., 2010).

Partial closure of the Bay of Biscay between Late Cretaceous and Oligocene times led to the formation of the Pyrenees (Bullard et al., 1965; Van der Voo, 1969; Muñoz, 2002; Sibuet et al., 2004; McClay et al., 2004; Gong et al., 2008) (Fig. 2, e-f). In the early Miocene, the plate boundary between Iberia and Eurasia became inactive and the Iberian plate was incorporated into the Eurasian plate (Van der Voo and Boessenkool, 1973; Grimaud et al., 1982; Sibuet et al., 2004; Roest and Srivastava, 1991; Vissers and Meijer, 2012) so that the boundary between Eurasia and Africa ran south of Iberia and into the North Atlantic along the Azores-Gibraltar Fracture Zone (AGFZ) (Le Pichon and Sibuet, 1971; Sclater et al., 1977; Grimaud et al., 1982; Olivet et al., 1984; Roest and Srivastava, 1991; Zitellini et al., 2009). The present-day AGFZ (Fig. 1) is a complex plate boundary that accommodates relatively small differences between Eurasian-North American and African-North American seafloor spreading rates and directions along the Mid-Atlantic Ridge in the forms of minor extension at its western end (Searle, 1980), right-lateral strike-slip along its middle reach, and transpression in the east (e.g. Grimison and Chen, 1986; Srivastava et al., 1990; Jiménez-Munt and Negredo, 2003).

2.1 Break-up markers along the Iberian – Newfoundland margins

It is generally agreed that statistical fitting of fracture zone trends and oceanic isochrons determined from magnetic anomalies is the most accurate method of modelling the relative motions of plates for the last 200 Ma (Müller et al., 1997; Seton et al., 2012). This is a consequence of the relatively small locational error and relatively high interpretational confidence compared to other geological and geophysical markers (Müller et al., 2008; Seton et al., 2012; Eagles et al., 2015). However, the presence of magnetic reversal anomalies is not of itself diagnostic of crustal type, particularly along passive margins with wide transitional zones, such as the Iberian – Newfoundland margins. Within COTZs, it is possible that magnetic anomalies resulting from the presence of intrusive igneous bodies within the upper crust or exhumed sub-continental mantle can be erroneously attributed to basaltic oceanic crust (e.g. Cannat et al., 2008). Similarly, oceanic crust formed at mid-ocean ridges that are overlain by a significant thickness of sediment (Levi and Riddihough, 1986) or formed at ultra-slow spreading centres may not give rise to strong magnetic signatures (Roest and Srivastava, 1991; Jokat and Schmidt-Aursch, 2007).

Accordingly, whilst some researchers have interpreted magnetic anomalies as isochrons dating back to Late Jurassic (Chron M20, 146 Ma) to model relative motions of the Iberian and North American plates (Srivastava et al., 2000), their utility can be disputed by contradictory geological evidence from drill core data. At Site 1070 on the Iberian margin (Fig. 1), for instance, serpentinised peridotite was drilled from the location of a magnetic anomaly that had been previously defined in terms of seafloor spreading at the time of chron M1 (~125 Ma; Whitmarsh et al., 1996; Tucholke and Sibuet, 2007). ~~Or the conjugate~~Similarly, at ODP Site 1277~~, where~~ basement associated with M1 ~~is considered~~has recently be interpreted as~~ to be~~ asthenospheric melts emplaced prior or coeval to mantle exhumation at 115Ma (Eddy et al., 2017). Numerous seismic surveys off both the Iberian and Newfoundland margins interpret the presence of transitional crust oceanwards of M0 (120 Ma), the youngest of the M-Series isochrons (Shillington et al., 2006; Dean et al., 2015b; Davy et al., 2016).

Several other M-Series isochrons have been interpreted along the North Atlantic margins from magnetic anomalies that are often characterised by a somewhat subdued (<100 nT amplitude; Fig. 3b) magnetic signature. Although their sources too are debated, and sometimes suggested to lie within domains of exhumed mantle and thinned continental crust (Russell and Whitmarsh, 2003; Sibuet, et al., 2004) their apparent symmetry across the rift and parallel trend with respect to the continental margins has led many researchers to interpret them as indicators of the presence of old, pre--Albain in age, oceanic lithosphere. The uncertainties in the origin and interpretation of these anomalies also contribute to the generally large set of discrepancies between plate kinematic reconstructions of Iberia, and in understanding the development of the Bay of Biscay in Late Jurassic to Early Cretaceous times (e.g. Srivastava et al., 1990; Whitmarsh and Miles, 1995; Srivastava et al., 2000; Barnett-Moore et al., 2016). For example, tectonic models using the M0 anomaly (125 Ma) result in a gap between eastern Iberia and Europe, the closure of which is difficult to reconcile with geological and geophysical data from the Pyrenees (Van der Voo, 1969; Gong et al., 2008; Lagabrielle et al., 2010; Tugend et al., 2014).

2.1.1 The "J" Anomaly

In addition to the interpretations of M-Series isochrons, a number of researchers have used a further regional magnetic lineation, known as the J anomaly, as a kinematic marker of the onset of seafloor spreading.

First acknowledged by Pitman and Talwani, (1972), the J anomaly is a high-amplitude anomaly identifiable on each side of the Southern North Atlantic Ocean south of the Galicia Bank and Flemish Cap regions (Fig. 3a). Based on its high amplitude and apparent symmetry across the rift, many have favoured the use of the J Anomaly over the M-Series as a kinematic marker. As a result, the J Anomaly has formed a basis for many plate kinematic reconstructions of the Iberia-Newfoundland conjugates (e.g. Srivastava et al., 1990, 2000; Sibuet, et al., 2004).

The amplitude, from trough to peak, of the J Anomaly is generally 500 – 600 nT in the South Newfoundland Basin (SNB) and conjugate Tagus Abyssal Plain (TAP) (Tucholke et al., 1989), reaching maxima of around 1000 nT over the southeast Newfoundland Ridge and conjugate Madeira Tore Rise (Fig 3b-c). The J Anomaly coincides with a structural step in the basement in the TAP (Tucholke and Ludwig, 1982) and with discontinuous basement ridges in the SNB (Tucholke et al., 1989).

The origin and subsequent significance of the J anomaly has been interpreted in two ways in published literature. The first of these interpretations suggests that the J anomaly is the oldest magnetic isochron of true oceanic origin formed by seafloor spreading and representative of the beginning of the M-series magnetic anomalies (Keen et al., 1977; Sullivan, 1983; Klitgord and Schouten, 1986). It may be interpreted as a superposition anomaly formed by spreading during the periods of isochrons M0 - M1 (Rabinowitz et al., 1978; Tucholke and Ludwig, 1982) or M0 – M4 (Whitmarsh and Miles, 1995), (Fig. 3b-c). In both cases, the J anomaly is seen as the boundary between first formed oceanic crust and exhumed mantle (Reston and Morgan, 2004).

The alternative interpretation of the J anomaly (Bronner et al., 2011), suggests that it expresses magmatic basement ridges dating from the Late Aptian (120 – 113Ma) during the time immediately preceding steady-state seafloor spreading. Both the unusually high amplitude and variable width of the J anomaly are explained by Bronner et al., (2011) as being the result of the interplay between excess surface magmatism and the locations of underplated bodies at depth. The apparent northward decrease in J anomaly amplitude and distance to chron C34 are interpreted as evidence for a northward propagating breakup. Agreeing with this line of interpretation, Nirrengarten et al., (2017) go on to question its validity as an indicator of first seafloor spreading processes~~.~~, suggesting the J Anomaly is a result of multiple magmatic events which occurred both during and after the formation of oceanic crust. ~~But, other researchers such as~~Conversely, Gillard et al., (2016) interpret the high amplitude ~~of the~~ J Anomaly ~~is simply~~as a relic of syn-rift magmatism which occurred during mantle exhumation pre-dating the onset of seafloor spreading.

3 Dataset and Methods

~~A high-resolution plate kinematic model generated using seafloor spreading data (unequivocal oceanic magnetic anomalies and fracture zone traces) would provide the ideal framework within which to investigate the evolution of the Iberia-Newfoundland passive margins.~~ A well-constrained plate rotation scheme for the separation of the Iberian and Newfoundland margins could be used to ~~rotate~~ align regional seismic transects and generate a virtual rift-spanning seismic transect ~~across both conjugate margin segments back into their paleopositions~~at the point of breakup ~~at the time of breakup to generate a virtual rift-spanning seismic transect at the time of continental break-up~~. ~~This, in turn, would make it possible to investigate further how the processes related to continental breakup are recorded in the sedimentary architecture of the conjugate Iberia-Newfoundland margins, as well as the suitability of some suggested breakup markers such as the M-Series or J anomaly as the basis for kinematic models. However, in the North Atlantic~~Currently, the difficulties of interpreting pre-Campanian seafloor and breakup markers from the margins mean that no such ~~a~~ ~~kinematic model~~rotation scheme ~~does not yet~~ exists entirely independently of ~~previous~~ existing interpretations of presumed-conjugate pairs of seismic profiles.

~~Available two-plate models built using seafloor spreading data allow us to robustly reconstruct the paleopositions of Iberia and Newfoundland only as far back to the first known isochron of undisputed oceanic origin (C34, 84 Ma) (Fig. 4). However, the incompletely-known extent of so-called ¨transitional¨ crust along the extended continental margins of the southern North Atlantic means that it is not possible to identify conjugate seismic transects on the basis of this two-plate reconstruction.~~ Work is underway on ~~Reconstructing older time slices and the break-up position on the basis of less-controversial seafloor spreading data is possible~~producing an independent model by combining the less controversial histories of pre-Campanian seafloor spreading between neighbouring Africa, North America and Eurasia in a quantitative regional plate circuit model~~,~~ ~~but requires a more complex four-plate model in which the motions of Iberia and Newfoundland are modelled in conjunction with those of the African and Eurasian plates~~ (Causer et al. in prep).

~~Here~~To add to the range of candidate conjugate profile pairs, we describe and interpret here a number of previously unpublished regional 2D seismic profiles in the SNB. The discussed seismic data were obtained from TGS-NOPEC's Southeast Grand Bank 2014 data set, which comprises ~~some~~ 34 2D seismic lines covering a combined area of 10,678 ~~55,995~~ km^2. The lines discussed were acquired using a Geostreamer 24 bit (GAS) with ~~in 2014 using a~~ 31.25 m shot point interval from a 4880 cubic inch airgun and a streamer which was 10050 m in length. Data, processing comprised Kirchhoff Curved ray pre-stack time migration and post-migration conditioning: F-X deconvolution, band-pass filter, scaling, and stretching to depth, providing high resolution images of the crustal structure offshore Newfoundland. Within the entire dataset, the three lines shown here were chosen as they were previously unpublished and span across the portion of the margin where J and M-series anomalies are found. They extend from the continental slope, through highly-extended continental crust and into exhumed mantle domains. None of these seismic lines extend far enough oceanward to image acoustic basement that can be confidently attributed to true oceanic crust. They do, however, image transitional crust previously associated with the J anomaly (M4 – M1, Whitmarsh and Miles, 1995).

Unfortunately, the conjugate TGS Iberian margin 2D seismic dataset (Fig. 4) offshore Portugal does not extend far enough through the COTZ and into the distal domain to directly image crust associated with the younger M-Series (M10 – M0) isochron interpretations, where breakup markers have been interpreted along the conjugate margin. For this reason we have also re-examined a previously published seismic profile (IAM5) (see Pinheiro et al., 1992; Afilhado et al., 2008; Neves et al., 2009).

The stratigraphic framework of the SNB has not been investigated in detail as part of this study. Due to the lack of drilling data, sediments have been grouped into Synrift 1, Synrift 2, Breakup-sequence, and Post-Rift packages based on seismic-stratigraphic observations. Synrift 1 corresponds to a sedimentary sequence that formed during fault-controlled extension, and is characterised by reflectors which mimic changes in basement structure, often short in length and at times chaotic, and onlapping structural highs. Synrift 2 is instead characterised by more continuous reflections, arising from what we interpret as infill strata deposited between the end of fault-controlled rifting and onset of seafloor spreading, also known as “sag sequence” (Masini et al., 2014). Based on its high amplitude and continuous nature, we consider our Breakup sequence to mark the rupture of the lithosphere and onset of seafloor spreading, which we later tentatively date as taking place near the Aptian – Albian boundary (e.g. Mauffret and Montadert, 1987; Boillot et al., 1988; Pinheiro et al., 1992; Tucholke et al., 2007; Péron-Pinvidic et al., 2007)., Although new research (Alves and Cunha, 2018) in the conjugate Tagus Abyssal Plain (TAP) proposes the presence of two break-up sequences, the first of which initiated in Berriasian times, (145 Ma) our new seismic dataset does not allow us to repeat such an interpretation. Finally, post-rift strata are found overlying a prominent unconformity. They have been dated at DSDP Site, 398, on the Iberian margin (Fig. 1), as Cenomanian in age (Wilson et al., 1989; Alves et al., 2003; Soares et al., 2012).

4 Results

4.1 Line A – Southern South Newfoundland Basin

Line A, located in the southern South Newfoundland basin, is a 444 km long margin-scale 2D seismic section, which images the entire crust beneath the Grand Banks area and offshore Newfoundland. Part of this line is shown in figure 5aa. This 2D seismic section extends from the continental slope, through the COTZ into the distal domain.

The crust of the continental shelf beneath the Southern Grand banks is tectonically thinned by a crustal scale rift margin fault seen in the landward part of the profile between 2 and 6-7 s TWT (Fig. 5). Its hanging wall is deformed by numerous landward-dipping intra-rift faults with variable offsets. At depth this large fault is traceable to around 10 s TWT, coinciding with our interpretation of the seismic Moho (Fig. 5b).

More distally, the margin is characterised by a series of domino-style rotated fault blocks, bounded by landward dipping faults of varying displacements (Fig. 5b). At depth, these faults seem to terminate against a high amplitude reflector traceable to depth (Fig. 5c). This high amplitude reflector can be traced to the top basement and interpreted as an exhumation fault marking the distal extent of thinned continental lithosphere. Oceanward of this point, the basement is deformed by a series of alternating landward and oceanward dipping normal faults (Fig. 5d). This change in seismic character of the basement and its coincidence with the high amplitude reflector can be interpreted as the transition from highly extended continental crust to exhumed mantle. Landward of this location, the continental crust in the rift basin has been thinned progressively via landward dipping intra-rift faults and larger oceanward dipping faults, possibly detached at depth (Fig. 5a-b). However, eastward of the high-amplitude reflector the imaging of acoustic basement is poor due to the presence of high-impedance post-rift strata.

In the most seaward part of the profile, high amplitude reflectors are traceable within what we interpret as a volcanic edifice (Fig 5c). Within it, reflectors dip in opposing directions, which may be a result of velocity pull-up (e.g. Magee et al., 2013). Short discontinuous reflectors within the volcanic edifice are observed to on-lap on to syn-rift 1 strata and the interpreted top of the exhumed mantle (Fig. 5e). Although sediments associated with break-up and post-rift sequences also on-lap this syn-rift 1 / basement high, their seismic character is noticeably different. On-lapping reflectors within the volcanic edifice are shorter, brighter than and not as planar as those observed in the breakup and post-rift sequences (Fig. 5e). Beneath these brighter non-planar reflections the basement is poorly imaged, AaAccordingly, we interpret the internal high-amplitude reflectors as sills, as observed interpreted elsewhere in the basin (e.g. Hansen et al., 2004) as well as on Lines B and C–. We have also tentatively identified a potential hydrothermal vent dyke, marked by distorted seismic imaginga vertical zone of chaotic and low-amplitude reflectivity underneath topped by a moundedconical body situated on the flank of a

~~seismic~~basement high~~s~~ (e.g. Planke et al., 2005). Imaging beneath the edifice is poor, rendering interpretations of the underlying basement difficult.

4.2 Line B – Central South Newfoundland Basin

Line B, located in the central South Newfoundland Basin images a 264 km long crustal transect from unequivocal continental crust beneath the landward continental shelf, through highly extended continental crust in the COTZ, and into a zone of exhumed mantle with magmatic additions (Fig. 6 a-b).

The proximal part of the margin is characterised by numerous parallel oceanward-dipping normal faults following a staircase-like pattern. Their vertical extents are difficult to map with certainty. Some of these faults are seen to terminate downwards against a high amplitude reflector, which we interpret as a deep-seated landward dipping detachment fault originating at the basinward limit of continental lithosphere (Fig. 6c~~a~~). Oceanward of this high amplitude reflector, the transition from highly extended continental crust to zones of exhumed mantle is marked by a smoother seismic characteristic of top basement.

In the exhumed mantle zone, a prominent basement high bisects the breakup sequence. The internal structure of the high is poorly imaged, making interpretations within it challenging (Fig. 6~~b~~d). Landward of this high, a series of large basement faults bound a relatively-symmetrical 80 km wide sub-basin infilled with a thick syn-rift sedimentary sequence. Towards the seaward part of the profile we interpret a package of seaward dipping reflectors (Fig. 6e~~c~~), the top of which is marked by a high amplitude reflector. This package coincides with the interpreted location of the J Anomaly. Here, by analogy to drilled margins with similar characteristics (e.g. the south Australian margin, Ball et al., 2013), we suggest the acoustic basement to comprise a mixture of sediments and lava flows. Laterally, SDRs are seen to onlap onto a fault, perhaps indicating a degree of control by extension processes on magmatism (Fig. 6e~~c~~).

4.3 Line C – Northern South Newfoundland Basin

Line C, located in the northernmost part of the South Newfoundland Basin is a 444 km long section which images the continental margin across the Grand Banks and offshore Newfoundland. Figure 7a-b shows a 180 km long oceanward segment of this seismic line, focusing on the continental shelf, highly extended continental crust and the COTZ.

At the base of the continental slope, which is characterised by a series of oceanward dipping faults, a landward dipping high-amplitude reflector can be traced to a depth equivalent of 10 s TWT. Oceanward, the basement is characterised by regularly spaced landward-dipping domino-style rotated fault blocks (Fig. 7c~~a~~), above which we identify the presence of sedimentary packages corresponding to syn-rift 1, syn-rift 2 and the breakup sequence.

As before, we tentatively interpret the transition between extended continental crust and transitional crust from the smoothing of top basement. The COTZ is presumed to be floored by exhumed mantle, as recovered at sites 1276-1277 (Tucholke and Sibuet, 2007) further north in the Northern Newfoundland Basin (NNB). Within our interpreted region of exhumed mantle, individual fault blocks are no longer interpretable. The prominent basement high shown in figure 7d~~b~~ may be interpreted as a serpentinite diapir, as seen elsewhere within the Iberian Abyssal Plain and offshore the Galicia Bank region (e.g.(Boillot et al., 1980, 1995)

4.4 IAM5 – Tagus Abyssal Plain

The wide-angle 350 km long seismic profile IAM5 images crust from the continental slope into the distal domain of the Tagus Abyssal Plain (TAP) (Fig.9). Although previously described in detail in the literature, (e.g. Pinheiro et al., 1992; Afilhado et al., 2008; Neves et al., 2009), we take this section into consideration in order to provide an Iberian conjugate to the new seismic profiles described previously.

IAM5 is characterised by large oceanward-dipping and smaller landward-dipping basement faults in the COTZ, some of which propagate upwards into 'undifferentiated' syn and post-rift sequences. A rise in basement toward the ocean is observed some 160 km from the base of the continental slope. Here, fault blocks still consistently dip toward the continent. Additionally in this distal domain, a high amplitude reflector is traceable above top basement, to 6s TWT. Although the syn and post-rift breakup sequences are undifferentiated, the presence of sediments older than Base Cenozoic has not been interpreted within this high (see Neves et al., 2009).

5 Discussion

The Iberia-Newfoundland margins have been extensively surveyed and studied over the past decade. The three seismic lines presented here, across the previously poorly-documented Southern Newfoundland Basin (SNB), further illustrate the complexity of this conjugate margin and are interpretable within the context of the existing and growing literature on extended continental margin processes. We interpret these lines as extending from the continental shelf, through highly extended continental crust and into distal deepwater basin characterised by the presence of exhumed mantle.

Our interpretations of the geological and structural history of the SNB also allow us to speculate about the origin of magnetic anomalies previously interpreted as diagnostic of oceanic lithosphere and extensively used as grounds upon which to base plate tectonic reconstructions of the North Atlantic.

5.1 Magnetic isochron interpretation: M-series and J-Anomaly

Some authors (e.g. Srivastava and Tapscott, 1986; Srivastava et al., 1990, 2000) identify the presence of M-Series magnetic reversal isochrons from magnetic anomalies recorded along the Newfoundland margin, attributing them to the presence of oceanic lithosphere. Our results do not support such an interpretation. Instead, along both lines A (Fig. 5) and B (Fig. 6) these anomalies (M1-M4) are sourced within zones of exhumed mantle which, in places, may be intruded by magmatic additions of uncertain age. In Line B (Fig. 6), the interpreted M-Series isochrons coincide with the high-amplitude oceanward dipping reflectors that we interpret as SDR packages of interbedded volcanics and sediments. The formation of these features is usually associated with mantle dynamics during plate rupture rather than the formation of steady-state igneous crust (e.g. Keir et al., 2009). Here, they may indicate the "onset" of magmatic-driven extension (Tugend et al., 2018) preceding the establishment of seafloor spreading and production of true oceanic lithosphere. The volcanic edifice, sills and feeder dykes in Line A (Fig. 5) may also be coeval with the final stages of plate rupture, or, a relic of post-rift magmatism as suggested by (Stanton et al., 2016). Post-rift volcanism associated with volcanism is generally associated with volcanic chains such as the Madeira Tore Rise, or isolated seamounts identified in the Northern Newfoundland Basin (Nirrengarten et al., 2017). However, to date no seamounts as shown in Line A have been identified in the SNB.

Our interpretations align with those of Russell and Whitmarsh, (2003) and Sibuet et al., (2004) who attribute the subdued amplitudes of the Newfoundland margins' magnetic anomalies as indicative of source bodies in highly-extended continental crust and exhumed mantle, rather than the upper layers of a 'standard' 7 km-thick oceanic crust.

Our seismic Line B (Fig. 6) images crust associated with the J Anomaly in the SNB. The anomaly coincides with an area of interpreted interbedded sedimentary and igneous packages, which are on-lapping a basement fault. This might indicate that, at the time of magmatism, plate divergence was still controlled by tectonic faulting and the transition to seafloor spreading had not yet occurred. Although we acknowledge that the limited quantity of new data available to us is not, on its own, sufficient to draw a complete picture, it suggests that the J anomaly does not represent a boundary between purely oceanic lithosphere and exhumed mantle transitional domains (e.g. Reston and Morgan, 2004), but instead that its source lies within or on the latter.

Although our results suggest that M-series magnetic anomaly isochrons within the Newfoundland margin do not originate from purely oceanic lithosphere, they can be used to estimate the minimum possible age of the basement underlying them.

Based on this, we suggest that the Newfoundland margin may have been magmatically-influenced since the Early Aptian (coinciding with M4, ~128 Ma) (Fig. 5), earlier than previously thought (e.g. Tucholke and Ludwig, 1982; (Tucholke et al., 2007; Stanton et al., 2016).

According to Bronner et al., (2011) the J Anomaly results from Late Aptian (120 – 103 Ma) magmatism, preceding seafloor spreading. They suggested that northward propagating magmatism from which the J Anomaly originates began in the Northern Central Atlantic and was restrained at the Newfoundland Fracture Zone for 10 Myrs before reaching the NNB in the Iberian-Newfoundland rift at the Aptian-Albian transition (112 Ma). Our results suggest a slightly different timing, with magmatic activity present in the SNB at a time coinciding with M4 (128 Ma), some 6-8 Ma younger than that proposed by Bronner et al., (2011). Although are data suggest an earlier age of magmatism than Bronner et al., (2011) we cannot comment on first ages of magmatism further north along margin.

Further north (e.g. Tucholke et al., 2007; Bronner et al., 2011; Nirrengarten et al., 2017), ODP drilling of rocks associated with the J Anomaly in the NNB revealed a similar assemblage of exhumed mantle and intrusive and extrusive mafic rocks. The drilling results suggested that magmatic activity had been persistent from ~128 Ma (M4) to ~70 Ma (Jagoutz et al., 2007).

Although the J anomaly may be associated with events immediately preceding first seafloor spreading, these events are neither instantaneous in time nor isochronous along the margin, which renders the J Anomaly unsuitable as a kinematic marker. e.g. Nirrengarten et al., 2017).

5.2 Conjugate pair matching

The wide range of processes interpretable from our new data and previous studies of the Iberia-Newfoundland margins illustrates a degree of asymmetry that makes it impossible to unequivocally identify conjugate pairs of seismic transects from their geometric and stratigraphic characteristics alone. An alternative approach could be to select conjugates by rotating margin-wide seismic lines into coincidence at pre-drift times. However, the results of doing this are strongly dependent on the choice of rotation scheme and their inherent uncertainties. Figure 8 illustrates the wide range of pre-rift positions resulting from seven published plate kinematic models for Barremian times (Rowley and Lottes, 1988; Srivastava et al., 1990; Sibuet and Collette, 1991; Labalis et al., 2010; Seton et al., 2012; Greiner and Neugebauer, 2013). Plate reconstructions to younger time slices are unsuitable for identifying conjugates because of the significant underlap they result in between the seismic surveys either side of the ocean. Similarly, full-fit reconstructions back to early Jurassic times result in large overlaps of the extended continental margins (Fig. 8).

Seton et al's. (2012) reconstruction (Fig. 8, b2) is based on an ‘extreme-oceanic’ interpretation, with magnetic isochron picks in the sequence back to M20 (Srivastava and Tapscott, 1986; Srivastava et al., 2000). This model keeps Iberia fixed to Africa throughout Barremian times. Alternatively, the model of Greiner and Neugebauer, (2013) (Fig. 8, b1), relies on the magnetic dataset of Srivastava et al., (2000) alone to produce best-fitting reconstructions of M-Series isochrons interpreted from dense magnetic data off Newfoundland and sparser data off Iberia. In contrast, prior to chron M0, Srivastava et al's., (1990) (Fig. 8, b3) relies more strongly on seismic interpretations of conjugate changes in basement characteristics, conjugate fracture zones, and conjugate COB segments.

The reconstruction of Seton et al., (2013) results in significantly more overlap of the COTZ envelopes than that of Greiner and Neugebauer, (2013). Overlaps in the COTZ suggest that the extended continental margins had not yet reached their present-day widths at this time. The early stages of continental separation, as described by these models, are subject to significant uncertainty, resulting from (a) the assumption that M-series anomalies are of oceanic origin and (b) the difficulty in interpreting subdued magnetic signals. This is illustrated by the differences in the reconstructions produced by the models, shown in figure 8, b1 and b2. Despite the differences between the models of Greiner and Neugebauer, (2013) and Seton et al., (2013), both suggest Line ~~C~~B as a conjugate to IAM5 prior to seafloor spreading (Fig. 9).

Alternatively, the model by Srivastava et al., (1990) suggests a conjugate pair consisting of ~~lines B~~Line C and IAM5 (Fig 9). Their rotation scheme is derived from a model in which structural markers are used to constrain the position of Iberia during the Barremian, most notably Keen and Voogd's (1988) COB, which they interpreted to coincide with a prominent landward dipping reflector (the L reflector, see Reid, 1994). The use of this feature shifts Iberia’s palaeo-position 50 – 100 km further south than that modelled using identified magnetic isochrons alone.

The validity of the ‘L’ reflector as a breakup marker can, however, be questioned on the basis of the huge variety of alternative COB interpretations published before and since Keen and Voogd's, (1988) study, which in this region differ by up to 200 km (Eagles et al., 2015). More specifically, Funck et al., (2003) identified the L Reflector offshore Flemish Cap to lie well inboard of the COTZ within the continental slope. We tentatively interpret a high landward dipping reflector traceable into the continental shelf in our Line C (Fig. 7), similar to the described ‘L’ Reflector thought to mark the COB.

Discriminating between “good” and ‘bad” reconstructions on the basis of the transects they reunite is clearly challenging. In the case discussed here, no strong arguments can be made regarding which of our new seismic lines (Line B or Line C) is the more likely conjugate to IAM5 based on their structural and stratigraphic characteristics. Neither line displays features which can be solely attributed to an upper/lower plate setting in asymmetric margins (e.g. Lister et al., 1986). . The proximal domains of both Line B and C in the SNB are characterised by progressive continental lithosphere thinning by tectonic faulting, in places observed to terminate against large continent-dipping detachment faults. Faulting of continental lithosphere can also be observed on the Iberian side in line IAM5, although in this case detachment surfaces are not imaged. Across the interpreted transitional domains, exhumed mantle, diapirs and extrusive flows are present in Lines B and C but absent in line IAM5, where underplating has been suggested instead, although its age is uncertain (Mauffret et al., 1989; Peirce and Barton, 1991; Pinheiro et al., 2004; Bronner et al., 2011). The Madeira Tore Rise, located at the distal end of IAM5, results from alkaline magmatism post-dating breakup, which may have also resulted in the formation of volcanic edifices such as that seen in Line A in the SNB.

These observations illustrate the challenge of discriminating between "good" and "bad" rotation schemes on the basis of the conjugate transects they produce. This challenge could be greatly eased if informed by robust plate models built from high-confidence data with quantified uncertainties.

5 Conclusions

In this paper we have presented and described three new seismic transects from the Southern Newfoundland Basin, and used them to discuss the validity of widely used so-called breakup markers along the Iberian – Newfoundland margins and the use of these features for plate kinematic modelling. In addition, we have illustrated the uncertainties in current plate models by restoring seismic transects to their pre-breakup locations utilising existing rotation schemes of Barremian age. Interpretation of our new seismic dataset has revealed that:

- M-series magnetic anomalies are not diagnostic of true oceanic crust beneath the SNB. Instead they are attributed to susceptibility contrasts between zones of highly-extended continental crust and exhumed mantle in the basin floor. Similarly, the high-amplitude J Anomaly coincides with a zone of exhumed mantle punctuated by significant volcanic additions, and at times characterised by interbedded volcanics and sediments.
- In the southern part of the Newfoundland margin, we suggest J-anomaly source bodies to be the result of mantle dynamics preceding plate rupture. Previously-published studies show that, further north, the J-anomaly is either too weak to recognise, or missing altogether. Although associated with events immediately preceding first seafloor spreading, these events are neither instantaneous in time nor isochronous along the margin, which renders the J Anomaly unsuitable as a kinematic marker.
- Our results show that magmatic activity was underway in the SNB at a time coinciding with M4 (128 Ma), earlier than previously thought. SDR packages onlapping onto a basement fault suggest that, at this time, plate divergence was still being accommodated, at least partially, by tectonic faulting.
- Differences in the relative positions of Iberia and Newfoundland according to published Barremian age plate reconstructions built on the basis of structural data vs. magnetic data illustrate the uncertainties introduced into the modelling procedure by the use of extended continental margin data (dubious magnetic anomaly identifications, breakup unconformity interpretations). In the SNB, we interpret the extent of the COTZ to reach oceanward to at

least M0 (118 Ma). As a result, a complementary approach is needed for constraining plate kinematics of the Iberian plate pre M0 times. In this respect we anticipate the palaeoposition of Iberia could come to be more confidently reconstructed using a larger more comprehensive plate model that encompasses the central and southern North Atlantic Oceans.

- Our new data and previous studies of the Iberia-Newfoundland margins illustrate a diversity of features that define conjugate asymmetry and along-strike variability to the extent that it becomes impossible to unequivocally identify conjugate pairs of seismic transects from their geometric and stratigraphic characteristics alone. Although our new data do not provide sufficient clarity about conjugate pairs of, they are helpful to clarify the temporal context for future plate kinematic reconstructions.
- A robust plate kinematic model built from well-constrained spreading data and involving a larger plate circuit would provide the basis to generate virtual rift-spanning seismic transects at the time of continental break-up. This, in turn, would make it possible to investigate further how the processes related to continental breakup are recorded in the sedimentary architecture of rifted margins. Such a plate model does not yet exist.

Acknowledgements: We thank TGS NOPEC for the provision of the seismic data for this paper, and the COMPASS Consortium, Royal Holloway University of London for funding support. We would also like to thank Alexander Peace for his fair and constructive review of our manuscript. Figures were produced using the Generic Mapping Tools (GMT, (Wessel and Smith, 1991).

Figure captions:

Fig. 1: Study area showing the location of structural and tectonic features significant to our study. White envelopes mark the extent of the COTZ as compiled by Eagles et al., (2015). ~~Magnetic picks as interpreted by Srivastava et al., (2000).~~ Double black line: mid-ocean ridge; Red dashed lines: fracture zone traces. Background image is derived from Sandwell and Smith (2014) gridded satellite-derived bathymetry using the Generic Mapping Tool, Wessel & Luis, (2017). ~~AB, Alentejo Basin; AM, American Margin; BP, Bonavista Platform; CB; Carson Basin, CBFZ; Cumberland Belt Transfer Zone, EOB; East Orphan Basin, ES; Estremadura Spur, FC; Flemish Cap, FP; Flemish Pass, GB; Galicia Bank, GBA; Grand Banks, GIB; Galicia Interior Basin, HB; Horseshoe Basin, IAP; Iberian Abyssal Plain, IB; Iberia, J'DA; Jeanne d'Arc Basin, LB; Lustanian Basin, MTR; Madeira Tore Rise, NFL; Newfoundland, NS; Newfoundland Seamounts, NNB; North Newfoundland Basin, NB; Southern Newfoundland Basin, OK; Orphan Knoll, PB; Parentis Basin, POB; Porto Basin PIB; Peniche Basin, SIAP; Southern Iberian Abyssal Plain, TAP; Tagus Abyssal Plain, TS; Tore Seamounts, WB; Whale Basin, WOB; West Orphan Basin.~~ (b) and (c) Location of M-series magnetic isochrons (Srivastava et al., 2000) ODP Legs 210 (Tucholke et al., 2004), (c) 103 (Boillot et al., 1987) and 173 (Whitmarsh et al., 1998). FC; Flemish Cap, FP; Flemish Pass, GB; Galicia Bank, GBA; Grand Banks, GIB; Galicia Interior Basin, IAP; Iberian Abyssal Plain, IB; Iberia, MTR; Madeira-Tore Rise, NFL; Newfoundland, NNB; North Newfoundland Basin, SNB; Southern Newfoundland Basin, TAP; Tagus Abyssal Plain.

Fig. 2: Six stages of development of the North Atlantic, from Late Jurassic to Late Cretaceous. Bright green envelopes show the maximum extent of the Continent-Ocean Transition Zone ~~(Pérez-Diaz and Eagles, 2014)~~(Eagles et al., 2015). Light green shading shows oceanic lithosphere extent according to Sibuet et al., (2007) for the Atlantic and Sibuet, et al., (2004) for the Bay of Biscay. Pink star: location of the triple junction between EUR-IB-NA. Adapted from Vissers and Meijer, (2012).

Fig. 3: (a) Location of ~~M~~magnetic profiles taken across the Southern Newfoundland Basin and conjugate Tagus Abyssal Plain shown in (b) and (c) respectively. ~~-~~(b) Four along-track magnetic anomaly profiles (solid black lines) from the SNB, shown alongside the synthetic anomaly isochron model for comparison (dashed line). Pink shading marks the high amplitude J Anomaly, ~~The J Anomaly corresponds to the high amplitude portion of the profiles,~~ identified as M0 - M1 by Rabinowitz et al., (1978). ~~shown in pink,~~ (c) Two along-track magnetic anomaly profiles (solid black lines) from the TAP, shown alongside a synthetic anomaly isochron model for comparison (dashed line). Pink and blue shading indicate the high amplitude J Anomaly, identified as ~~and~~ M0 – M4 by ~~in the Tagus Abyssal Plain~~ (Whitmarsh and Miles, 1995). (b) and (c) adapted from ~~shown in blue. Profiles have been adapted from~~ Srivastava et al., (2000). Abbreviations as in fig 1.

Fig. 4: Map showing the positions of Iberia, relative to North America from first unequivocal oceanic crust (83Ma) ~~modelled using the Generic Mapping Tool (GMT).~~modelled on the basis of seafloor spreading data~~ and following the inversion method of Nankivell (1997)~~ ~~Blue and red~~Red lines ~~are the TGS Iberian and Newfoundland datasets, respectively.~~ Show the position of seismic section A – C, ~~Positions of seismic lines were~~ provided by TGS. Abbreviations as figure 1.

Fig. 5: (a - b) Un-interpreted and i~~I~~nterpreted seismic reflection profile (“Line A”) from the southern South Newfoundland Basin~~, offshore Newfoundland~~. Interpretation shows the basement structure and sedimentary units. (c~~a~~) Basement structure at the base of the continental slope, (~~b~~d) Ocean-ward dipping reflectors in the syn-rift 1 sediments, shows fault migration ocean-ward, (~~c~~e) Volcanic edifice present in the proto-oceanic zone with associated sills and magmatic vents. All data courtesy of TGS.

Fig. 6: (a - b) Un-interpreted and i~~I~~nterpreted seismic reflection profile (“Line B”) from the central South Newfoundland Basin~~, offshore Newfoundland~~. Interpretation shows the basement structure and sedimentary units. (~~a~~c) Crustal collapse of the hanging-wall in a large scale landward dipping fault within extremely thinned continental crust, (d~~b~~) Section of syn-rift sediments within the exhumed mantle zone, shown to be rotated toward the continent, (e~~c~~) Bright amplitude reflectors which dip oceanward, a mixture of sediment and magmatic flows beneath an igneous top basement. All data courtesy of TGS.

Fig. 7: (a - b) Un-interpreted and ~~I~~interpreted seismic reflection profile (“Line C”) from the northern South Newfoundland Basin~~, offshore Newfoundland~~. Interpretation shows the basement structure and sedimentary units. (~~a~~c) Continental crust thinned by small normal faults, (d~~b~~) Possible serpentinite diaper within the basement high of the zone of exhumed mantle. All data courtesy of TGS.

Fig. 8: Reconstructions of the COTZ envelope from Eagles et al. (2015) at (a) Aptian, (b) Barremian and (c) Tithonian (‘full fit) times, showing the range of virtual conjugates generated by alternative rotation schemes. Blue and red lines are the TGS Iberian and Newfoundland datasets, respectively. The positions of lines were provided by TGS. See figure 4 for abbreviations.

Fig. 9: Comparison of ‘conjugate’ seismic lines chosen on the basis of alternative rotation schemes for Barremian times. (a) Conjugates according to Greiner and Neugebauer, (2013) and Seton et al., (2013) and (b) Srivastava et al., (1990). Conjugate comparisons are hung on 10s TWT. Full interpretations of Lines B and C refer to figures 6 and 7, ~~Newfoundland data are courtesy of TGS. K~~ey as in figures ~~6~~5-~~8~~7.

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