Pooled subsidence records from numerous wells reveal variations in pre-breakup rifting along the proximal domains of the Iberia-Newfoundland continental margins

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Pooled subsidence records from numerous wells reveal variations in pre-breakup rifting along the proximal domains of the Iberia-Newfoundland continental margins

Original article

Running header - Iberia-Newfoundland proximal subsidence curves

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ABSTRACT

The Iberia-Newfoundland continental margin is one of the most studied conjugate margins in the world. However, many unknowns remain regarding the nature of rifting preceding its breakup. Here a large dataset of tectonic subsidence curves, created from publicly available well data, is analysed to show spatial and temporal trends of rifting in the proximal domains of the margin. A novel methodology of bulk averaging tectonic subsidence curves is developed that can be applied on any conjugate margin with a similar spread of well data. The method does not rely on the existence of conjugate, deep seismic profiles and specifically attempts to forego the risk of quantitative bias derived from localised anomalies and uncertain stratigraphic dating and correlation. Results for the Iberia-Newfoundland margin show active rift-driven tectonic subsidence occurred in the Central segment of the conjugate margin from ~227Ma (start Norian) to ~152.1Ma (start Tithonian); in the Southern segment from ~208.5Ma (start Rhaetian) to ~152.1Ma (start Tithonian); and in the Northern segment from ~201.3Ma (start Hettangian) to ~132.9Ma (start Hauterivian). This indicates that rifting in the stretching phase of the proximal domain of the Iberia-Newfoundland margin does not mirror hyperextended domain rifting trends (South to North) that ultimately led to breakup. The insights into broad scale three dimensional spatial and temporal trends, produced using the novel methodology presented in this paper, provide added value for interpretation of the development of passive margins, and new constraints for modelling of the formation of conjugate margins.

(Keywords: North, Atlantic, Mesozoic, tectonic, backstripping, conjugate, trends)

1. INTRODUCTION

The aim of this paper is to introduce a new method for increasing the utility of spatially diverse, but incomplete well-data, in investigating subsidence and its spatial variability on rifted continental margins. We use the much-studied Newfoundland-Iberia conjugate margins of the Atlantic to illustrate our approach.

Subsidence in sedimentary basins, recorded by the stratigraphy of the basin fill, is primary evidence for deducing the tectonic processes by which continents rift. This has been quantified using well-data since pioneering studies at continental margins (e.g. Steckler and Watts, 1978) and in intracontinental settings (Barton and Wood, 1984). However, many studies that use boreholes to calculate subsidence histories focus on those few wells that have the appropriate combination of stratigraphic thicknesses, compaction criteria, depositional ages, palaeobathymetry, known eustatic sea-level signals and denudation histories across unconformities or instead rely upon the creation of synthetic wells.

Building subsidence records from only a few wells risks introducing significant sample bias to studies if the studied wells are not representative of the variability in depositional/subsidence history of the study area. This type of bias can sometimes be mitigated by backstripping 2D geological interpretations on cross-sections (e.g. Steckler et al., 1999) or even 3D volumes using well-calibrated seismic data (e.g. Hansen et al., 2007). However, 1D well data and the subsidence they record are still commonly used in frontier areas where seismic data are of insufficient quality for 2D or 3D analysis. Recent studies have focused on those wells that conform to high standards of high-quality stratigraphic data, or on a few "pseudo-wells" built from sparse seismic profiles (e.g. Alves and Cunha, 2018). Those wells that do not conform to these standards are neglected. The effect is to restrict spatial resolution for subsidence studies that risks obscuring lateral variations in subsidence rate and timing along rifted continental margins.

Restricting analysis of a problem to a specific type or quality of data while ignoring those data types that do not meet these restrictions is a documented form of interpretation bias termed Macnamara's Fallacy (e.g. O'Mahony, 2017). Interpreting the tectonic history of rifted margins using only a small part of the available well record risks introducing quantification bias. Our aim here then is to develop an approach for using non-ideal well-data, along with those of higher quality, to increase spatial resolution and to avoid falling for Macnamara's Fallacy.

An interpretation of the history of the Iberia-Newfoundland conjugate margin using a much broader array of available real well data to minimise the effects of qualitative bias has not previously been undertaken. Prior studies have examined the tectonic subsidence histories of isolated basins within the proximal domain (e.g. Maldonado et al. 1999), forward modelled the effects of tectonic subsidence on the margin from conjugate deep seismic profiles (Mohn et al., 2015), looked at tectonic subsidence across the margin as a whole using idealised, stratigraphic columns for the calculation of subsidence (Hiscott & Wilson, 1990) or through the use of synthetic "pseudo" wells (e.g. Alves and Cunha, 2018).

Key features of the Iberia-Newfoundland margin's development, such as the role of crustal thinning or 'necking' (Keen & Voogt, 1988; Lavier and Manatschal, 2006; Doré & Lundin, 2015) remains contentious (as they do with other continental margins as well). Although much work has been done on addressing issues such as this through forward modelling techniques, for example, to estimate the nature of crustal thinning during pre-breakup rifting (e.g., Brune et al., 2016), less attention has been given to the constraints of these models, especially regarding variability along and across the margin conjugates.

Furthermore, whilst passive continental margins are composed of a number of different domains, including proximal, necking, distal and others (Peron-Pinvidic et al., 2013; Sutra et al., 2013), which are known to deform in different styles at different times during the development of the margin (Mohn et al., 2015), when rifting occurred across the margin as a whole is still a contested point. In the case of the Iberia-Newfoundland conjugate margin, published work suggests that rifting across all domains of the margin occurred in four distinct episodes (Alves et al., 2002; Matias et al., 2011; Soares, 2014; Sousa Lemos Pereira, 2013). However, there is no consensus on when these four periods occur, with different authors providing different interpretations and active rifting periods that significantly overlap each other. Published modelling studies (Biari et al., 2017; Brune et al., 2017; Manatschal et al., 2007) generally adopt two active rifting phases: the first from Late Triassic to Early Jurassic, typified by slow rates of thinning and depth independent, symmetrical rifting; and a second from Late Jurassic to Early Cretaceous, where stretching speeds up dramatically with rifting becoming depth-dependent and asymmetric. In regards to continental breakup, Pinheiro (1996) and Alves et al. (2006; 2009) show breakup in the central North Atlantic margin occurs diachronously from south to north. However, the timing of continental breakup is also contested, ranging from ~132.9 Ma (start Hauterivian) to ~113Ma (start Albian) (Bronner et al., 2011; Eddy, et al., 2017; Nirrengarten et al., 2018; Vissers and Meijer, 2012).

In view of these kinds of discrepancies, we consider that additional ways of constraining the style, timing and magnitude of subsidence within individual domains may lead to a better model of overall margin development. The presence of hydrocarbon systems within the proximal domain of both sides of the Iberia-Newfoundland margin has resulted in numerous exploration wells being drilled. This provides the possibility of comparing the tectonic subsidence trends both spatially and temporally in the proximal domain. Accordingly, we pool sediment accumulation records from 56 wells across the entire proximal domain of the Iberia-Newfoundland conjugate margin to produce bulk averaged subsidence curves that describe the nature of rifting within the domain as a whole and result in inferences that can be made regarding the nature of rifting across all domains of the margin, i.e. breakup age, or rifting symmetry. This allows a generalised interpretation of continental-breakup related subsidence patterns at the Iberia-Newfoundland margin, derived from real wellbore data, for the first time.

2. METHOD

Input data for the present study were derived from publicly accessible sources (borehole data; Canada-Newfoundland Board, 2017), from published literature on the Newfoundland (Driscoll & Hogg, 1995; Fensome et al., 2008) and Iberian margins (Alves et al., 2002, 2003 & 2006; Casacão, 2015; Kullberg, 2000; Lopez & Proença Cunha, 2004; Maldonado et al., 1999; Matias et al., 2011; Soares, 2014; Sousa Lemos Pereira, 2013). All wells available in the Iberian margin literature were utilised (22); only a subset of the available wells from the Newfoundland side of the margin were utilised (33) and were selected to give as even a data spread as possible across the margin. Locations of all the wells used are shown on Fig. 1.

<Insert Fig. 1. here>

The use of wells drilled for hydrocarbon exploration presents the difficulty that they are often in sub-optimal locations for calculation of tectonic subsidence, such as on high standing blocks or next to salt diapers. Although every single chronostratigraphic unit was not present in every well, a complete picture of the sedimentary deposition across a block was calculated by utilising the averaging process as described in section 2.c to account for missing stratigraphy. Around 10 wells were used per block with at least one well per block penetrating to basement. This gave a good average of unit thicknesses across the varying structures present in the block. Figs. 2 and 3 show cross-sections of stratigraphy from each block grouped by geological period, detailed stratigraphic columns of the lithologies encountered during these periods on either side of the margin can be found in Alves and Cunha (2018). Two wells are highlighted for each block (3 for Southern Iberia) that show different thicknesses of units from each geological period. No wells were utilised in this work that were located above or adjacent to diapirs.

<Insert Fig. 2 and 3. here>

2.a. Curve Generation

The software used for modelling tectonic subsidence was Backstrip v4.3, a free to use application for Mac OSX created by Nestor Cardozo (Cardozo, 2016). The program uses Airy isostasy with exponential porosity reduction in either a water or air loaded setting to calculate tectonic subsidence by backstripping input layers sequentially. Due to the depositional environment of the continental margin the water loaded functionality was adopted. The program supports backstripping of only one sedimentary column at a time so was run individually per well with parameters specific to each.

Variable input parameters necessary to run the model include: top and base depths and ages, grain densities, porosity coefficients and surface porosities for each of the units. Lithologies used were either derived from stratigraphic columns of the individual wells or from a stratigraphic column of the basin if only unit names were available from the well data. Parameters used for each lithology can be found in Fig. 4(a)-4(c); the values used are not specific to the study area but are standard values for the lithologies present (e.g. Allen & Allen, 2013; Carmichael, 1982; Hantschel & Kauerauf, 2009; McWhorter & Sunada, 1977). The same lithology parameters were applied to units on either side of the margin. In the case of a unit that was composed of multiple lithologies, e.g. interbedded shales and sands, fractions of each lithology present were used and summed together. Densities of 1000kg/m^3 for water and 3300kg/m^3 for the mantle were used consistently for modelling subsidence at all locations.

<Insert Fig. 4. here>

Whilst data for the exact ages of each unit of an individual well were present for some Iberian wells, most unit ages were derived from chronostratigraphic data from each basin being compared to the International Commission on Stratigraphy chart (Cohen et al., 2013). If unit ages are given as a geological stage from the chronostratigraphic chart it was assumed that the unit basal age is the beginning of that stage and the unit top age is the end of the stage, unless: (1) another unit is also present during the same time period; (2) the unit was either bound or split by an unconformity; or (3) only part of a lithologically differentiated unit was present. In any of these three cases, assumptions on age were made that would best represent the well data present. Where data from an individual well contradicted that of the basin wide stratigraphic column an interpretation was used that would respect the well data.

The backstripping method possesses the capability of taking sea level fluctuations into account for calculations of tectonic subsidence although this was not used due to insufficient or inaccurate data relating to depositional depths of many of the units across the margin. Furthermore no attempt was made to correct for eroded strata, potentially indicated by unconformities. Accordingly, the computed subsidence curves do not display any periods of basement uplift. However, quantifying uplift or calculating exact numerical values of subsidence was not within the main objectives of the work, which is focused on a comparison of subsidence trends throughout the proximal domain of the conjugate margin.

2.b. Errors

There are two main sources of error present in computing the bulk averaged subsidence curves: errors in the ages used for top and bottom of units and errors in the overall magnitude of subsidence calculated using the modelling software. Using chronostratigraphic columns of each basin, maximum and minimum possible ages for deposition of the top and base of each unit were assigned and then their percentage deviations from the values used for computing the tectonic subsidence curves were calculated. For maximum ages, the base age is assumed to be the oldest possible from the chronostratigraphic column, with the top age assigned to an age halfway through the overall length of unit deposition. For minimum ages, the base age is assigned to an age halfway through the overall length of unit deposition, with the top age assumed to be the youngest possible from the chronostratigraphic column. Percentage deviations of unit ages were then collated and averaged for the Triassic, Jurassic and Cretaceous periods.

There are two sources of variability in how the backstripping software was used that affects the magnitude of subsidence that it calculates for each well. The first is the value of the input parameters used and the second is the combination of maximum or minimum values used for each input parameter. Maximum and minimum values for the input parameters, derived from the literature, are shown on Figs. 4(a)-4(c). Fig. 4(d) shows the results of all possible combinations of maximum and minimum input parameters when running the modelling software. It is worth noting that the combinations of these input parameters had a much larger effect on the calculated magnitude of subsidence than the values of input parameters used. Therefore, the combinations that were used to represent maximum and minimum subsidence conditions were selected to be representative of real world conditions, as those that produced more extreme maximum and minimum values were considered to be less likely to occur in nature.

<Insert Figs. 5-10. here>

2.c. Curve Averaging

To allow the dataset of subsidence curves to be compared they have been grouped into 6 geographic blocks. These blocks, although arbitrary, were selected to be roughly the same size whilst keeping wells from the same basin within the same block as much as possible. Wells on the Newfoundland margin were selected to keep the number of wells in each block even. The locations of the blocks and wells can be seen in Fig. 1.

Individual subsidence curves were then grouped with others from within the same block and a mean subsidence curve was calculated to represent each block as shown in Figs. 5-10. Curves of wells that did not penetrate the full depth of stratigraphy had the origin of their subsidence-axis offset to the depth of mean subsidence in the block at the age of the oldest point in the well. This was to account for the subsidence of the sediments below them that were undrilled and required that at least one well per block penetrated to basement.

Subsidence at unconformities was set to a value of 0 for the duration of the hiatus, affecting the overall averaging process. Thus, if all wells in a block present an unconformity at the same time, so also would the average curve. However, in the case of an absence of observations (i.e. redacted portion of publically available well data due to industry activity), the subsidence was set to a null value and, hence, not included in the averaging for that margin segment in the period of time it affects. For the dataset under consideration, this was encountered infrequently and its consequence was negligible.

<Insert Fig. 11. here>

The mean curves for each block were then grouped (Fig. 11a) with their respective curves from the opposite side of the margin and a mean subsidence curve was calculated to represent each of the North, Centre or South segments of the margin so that trends laterally along the proximal domain of either margin could be compared (Fig. 11b). Curves from the same side of the margin were also grouped together and a mean subsidence curve was calculated to represent either the proximal domain of Iberia or Newfoundland so that overall trends could be compared (Fig. 11c). The values of error envelopes were also grouped and averaged together in this way to give an illustrative error estimates for the three blocks.

3. RESULTS AND DISCUSSION

3.a. Tectonic subsidence trends

Individual tectonic subsidence curves, generated per well, were compared with existing databases of subsidence curves from the same area (e.g. Stapel et al., 1996) and found to be comparable to one another, indicating that the input parameters used in the work, as well as the curve generation, are sound.

The tectonic subsidence curve averaging methodology provides tectonic signatures for segments of the continental margin that are of a scale appropriate for illuminating the large-scale tectonic processes forming the continental margin as a whole, filtering out more local effects, for example, related to basement structures and sediment transport systems. Thus, the conjugate segment averaged curves seen in Fig. 11(b) each tend to define singular periods of syn-rift subsidence (lasting continuously from the Late Triassic through to the Early Cretaceous) rather than characterising a series of separate periods of active, syn-rift subsidence as suggested by the more detailed studies mentioned in the Introduction.

All three segments under consideration (North, Centre and South) display this amalgamated "syn-rift" period of continuous subsidence at a high rate, in each case accommodating the bulk of tectonic subsidence that occurs prior to breakup. However, there are differences observed in the timing at which this period occurs: in the Centre segment it occurs from ~227Ma (start Norian) to ~152.1Ma (start Tithonian); in the South segment it occurs from ~208.5Ma (start Rhaetian) to ~152.1Ma (start Tithonian); and in the North segment it occurs from ~201.3Ma (start Hettangian) to ~132.9Ma (start Hauterivian). The onset age is based on the observed break over to high tectonic subsidence rates such as typically associated with active, syn-rift extension (e.g. Allen and Allen, 2013) and the termination age is based on the transition to tectonic subsidence rates that have more the appearance of exponentially decaying (concave upwards), more typical of post-rift, passive subsidence. The choice of the termination dates is somewhat arbitrary, being only qualitatively determined, and keeping in mind that this apparent transition marks only the cessation of rifting in the proximal domain with break-up of the continental margin and, hence, the end of active rifting, occurring after.

The quantified age error estimates for each segment subsidence curve do not overlap suggesting that the contrast in rift onset timing is robust when considering segments as a whole. Moreover, the observed Centre to South to North migration of rifting in the proximal domain can be seen in the subsidence curves from each block on either side of the margin in Fig. 11(a), also indicating that the trends are not an artifact of the averaging process.

Although the mean curve of each segment displays a pseudo “syn-rift” phase, the overall trend of these curves differs, indicating fundamental differences in the nature of rifting in the segment (Xie and Heller, 2006). From Fig. 11(b) it can be seen that the rates of subsidence, during the amalgamated “syn-rift” period vary between segments. In the Centre it occurs at a rate of ~17 m/Ma, in the South it occurs at a rate of ~14 m/Ma and in the North it occurs at a rate of ~17 m/Ma. The Centre segment curve exhibits its greatest rate of subsidence almost immediately after “syn-rift” subsidence begins, giving a trend of almost continuous rapid subsidence that lacks any significant punctuation. The North and South segments instead both display a period of low rate tectonic subsidence that precedes the initiation of the amalgamated “syn-rift” phase, and thereafter display a much more stepped trend indicating a more irregular rifting history with multiple observable episodes. This is due to only one well being present in the Northern Newfoundland block penetrating deeper than 170Ma. If the assumption is made that a higher than average amount of subsidence occurred in the well at this time, then the South and North segment mean curves would display almost an identical subsidence rate and trend.

Fig. 11(c) shows all three blocks from either side of the margin averaged together to look at cross margin trends. It can be seen that – overall, despite the diachroneity revealed by considering individual segments – one side of the margin does not rift prior to the other. There are three periods of similarity, both in rate and magnitude of subsidence, across the margin: (1) ~227Ma (start Norian) to ~199.3Ma (start Sinemurian); (2) ~182.7Ma (start Toarcian) to ~170.3Ma (start Bajocian); (3) ~152.1Ma (start Tithonian) to ~113Ma (start Albian). It is only outside of these three periods when the subsidence curves of the conjugate margins can be seen to diverge from each other, with more rapid tectonic subsidence occurring in the Newfoundland conjugate compared to the Iberian one ~199.3Ma (start Sinemurian) to ~182.7Ma (start Toarcian) and ~170.3Ma (start Bajocian) to ~152.1Ma (start Tithonian).

It is of course well-known that basins on the Newfoundland side of the margin are much thicker, with greater accommodation space provided by tectonically-driven subsidence, than on the Iberian side and that this is intrinsically linked to the asymmetric nature of this particular conjugate margin of the Atlantic Ocean (Manatschal et al., 2007). However, the bulk averaged tectonic subsidence curves computed here demonstrate that there are two possibly distinct periods during which asymmetrical stretching occurred in the proximal domain, both of them during the Jurassic, at least at a whole basin, regional, scale.

The potential impact of sediment supply on attributing to these trends was interrogated and found to be unlikely. During the period of high subsidence (Jurassic) where trends in the subsidence curves laterally and across the margin have been observed, formations are found to be very similar between blocks on the same side of the margin with the dominant depositional environment being marine, suggesting that trends laterally along the margin are tectonic in origin. During this period lithologies deposited in Iberia include marine carbonates with some shaley interbeds (Alves et al., 2002, 2003 & 2006; Casacão, 2015; Kullberg, 2000; Lopez & Proença Cunha, 2004; Maldonado et al., 1999; Matias et al., 2011; Soares, 2014; Sousa Lemos Pereira, 2013), and in Newfoundland, open marine successions of shales and sands with some carbonate interbeds (Canada-Newfoundland Board, 2017; Driscoll & Hogg, 1995; Fensome et al., 2008). Deltaic sequences, which are the most likely to indicate a sedimentary supply influence on subsidence curves, are not present on either side of the margin from Earliest Jurassic through post Aptian. Due to the slightly different depositional environments between the Iberian and Newfoundland sides of the margin during the Jurassic, a sedimentary supply effect on the disparity between overall magnitude of subsidence on either side of the margin at breakup cannot be entirely ruled out. However the depositional environments are similar enough that rates of deposition would be comparable, indicating a different cause for this disparity.

3.b. Possible implications

The objectives of the present study were to compute bulk averaged tectonic subsidence curves for appropriate conjugate blocks in the proximal domain of the Iberia-Newfoundland conjugate continental margin and to describe how these results may usefully contribute to increased understanding of the nature of stretching across margin as a whole and how the results may provide necessary constraints for future modelling studies. A thorough investigation of these results in terms of a new interpretation of the tectonic evolution of the entire Iberia-Newfoundland margin are not intended. Nevertheless, they offer additional insights into the development of the margin.

Numerous papers describe a migration of continental breakup from South to North along the Iberia-Newfoundland margin (e.g. Mohn et al., 2015; Brune et al., 2016) and although timing of breakup cannot be derived from this work, rifting leading to breakup can be seen to cease in the proximal domain, therefor inferred to migrate to distal and hyperextended domains, ~152.1Ma (start Tithonian) in the South and Centre and ~132.9Ma (start Hauterivian) in the North. These results are fitting with the observed South to North rift propagation in the hyperextended domain that lead to breakup. It notable that stretching in the proximal domain instead propagates Centre to South to North, a trend that does not mirror that of eventual breakup.

Another feature that has been noted in previous work is the depth independent symmetrical nature of initial rifting (Mohn et al., 2015; Brune et al., 2016), by which it is meant evenly distributed strain of similar timing and magnitude on both margin conjugates. Here, it was found that conjugate block average curves do appear symmetrical during the first period of rifting (Fig. 11c), suggesting that there is no large scale cross-margin propagation of rifting occurring in the early stages of margin formation, via a crustal scale, “simple” shear/fault zone (e.g. Lister et al., 1991; Wernicke, 1985). However, rifting in the stretching phase of the proximal domain was found to be generally symmetrical but with notable exceptions of contrasting subsidence rates on either side of the margin during two isolated periods of tectonic subsidence in the Jurassic. This suggests the possibility that whatever process causes asymmetry on this conjugate margin as a whole began during the rifting stage.

Manatschal et al. (2007) suggested that inherent crustal heterogeneities are an important constraint on how rifting manifests itself and propagates. One important source of heterogeneity in the study area is pre-rift magmatic underplating below Iberia. Although emplaced during the Permian, prior to the onset of rifting leading to continental breakup in this area, Mohn et al. (2015) argued that the cooling of this underplate resulted in the development of the first sedimentary depocentres during the Triassic. This could provide an explanation to the trends seen in the bulk averaged tectonic subsidence curves, with the North and South segments displaying a period of low rate subsidence during the Triassic prior to the initiation of active rifting. As this period is not evident in the curve of the Centre segment and the rate and trend overall differs from the North and South segments this may imply a lesser degree or absence of underplating beneath the Centre segment. Further, as the effects of sediment supply on observed trends has been interrogated and found unlikely to be a factor, it's possible that pre-rift underplating may also offer an explanation as to the timing of rifting initiating in each segment of the margin and may also be a factor contributing to the magnitude of subsidence in Newfoundland being ~50% higher than in Iberia at breakup.

3.c. Methodological limitations

That potentially important implications for the evolution of the Newfoundland-Iberia conjugate margin that have been identified demonstrates the strength of processing a large dataset of subsidence curves in the way described in this work, allowing a 3D view of basin subsidence trends across the margin in a very simple manner. Previous work has modelled in 2D along deep seismic lines, which limited the insight gained laterally along the margin, or has utilised idealised stratigraphic columns from basins across the margin. Whilst the use of generalised stratigraphy addresses the issue of 3D data spread it adds another stage of interpretation increasing the risk that assumptions are made that may not be applicable to all areas of the basin. By using real world stratigraphic columns encountered in wellbores and backstripping the results, therefore removing as much interpretation bias as possible, a clearer insight into the nature of rifting along the Newfoundland-Iberia margin has been gained.

It is important to note, however, that the mean curves produced in this work do not represent subsidence at any real-world location. They have been created in a way to show average subsidence of designated blocks so that relative trends along and across the margin as a whole can be identified, and as such do not represent any tangible real world location.

4. CONCLUSION

By creating average subsidence curves for the Iberia-Newfoundland margins of the northern Central Atlantic Ocean from a large dataset of wells from the conjugate proximal margins themselves, the results of this work provide additional insights into the conjugate margin's development. The findings suggest that the main rifting phase and associated tectonic subsidence began earlier in the central part of the proximal margin (~227Ma, start Norian) than in its southern segment, (~208.5Ma, start Rhaetian) and in its northern segment (~201.3Ma, start Hettangian).

The rifting trend identified in this work, contrast with the overall south to north trend of breakup along the Atlantic that has been recorded in previous studies, showing that rifting in the proximal domain prior to continental breakup does not necessarily mirror the trend of rifting in the hyperextended domain. The timing of initial subsidence as it is expressed in each block of the studied margin segment could be linked to the differential distribution of pre-rift, magmatic underplating below Iberia. Other observations, such as the Newfoundland side of the margin subsiding 50% more than the Iberian side prior to continental breakup, which occurs during two isolated periods in the Jurassic, could also be explained by the presence of magmatic underplating below Iberia.

The results of this analysis of the Iberia-Newfoundland margin demonstrates the usefulness of using our proposed workflow for identifying subsidence trends in large datasets of wellbore data along conjugate margins and supplements rather than only complements results based on deep seismic lines that other studies have relied upon. The potential for introducing bias to studies by focusing just on a limited number of wells was recognised from the earliest attempts to backstrip stratigraphic records in basins. The approach applied here to the Iberia-Newfoundland margin offers opportunities for limiting these biases. Simply ignoring wells that do not have the full data record necessary for accurate backstopping is an example of Macnamara's Fallacy - risking the introduction of significant quantification bias in a study. However, wells still need screening to avoid incorporating those sites where the stratigraphic record has responded to non-tectonic motions such as caused by salt mobility. Together the results obtained in this work may be used to provide insights into the geodynamic scale processes driving lithosphere rifting prior to continental breakup and more relevant constraints for future forward modelling studies on the Iberia-Newfoundland margin and on conjugate margins in general.

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FIGURE CAPTIONS

Figure 1. (Colour online) Plate reconstruction of Iberia-Newfoundland at chron M0 (125Ma, start Aptian) from Sibuet and Tucholke (2012) and Srivasta et al. (2000). Locations of all wells used in the study are shown as black dots. The green lines display the arbitrary blocks used in this work for curve averaging. The grey box indicates the Newfoundland-Gibraltar Fracture Zone.

Figure 2. (Colour online) Map of present day Newfoundland with present day depocentres displayed and labelled and with all wells used in the study shown, wells penetrating to basement in red. The green lines display the blocks used in this work for curve averaging. Section a-a' is adapted from DeSilva (1999). Section b-b' is adapted from Fagan (2010). Key of units in cross sections can be found in Fig. 3. Well Carey J-34 is offset from the cross section but sits in an equivalent structural location.

Figure 3. (Colour online) Map of present day Iberia with present day depocentres displayed and labelled and with all wells used in the study shown, wells penetrating to basement in red. The green lines display the arbitrary blocks used in this work for curve averaging. Section c-c' is adapted from Alves et al (2006). Section d-d' is adapted from Pimentel and Pena dos Reis (2016). Section e-e' is adapted Rasmussen et al (1998).

Figure 4. (Colour online) Input parameters of each lithology used (the lithology labelled salt, represents all evaporites) in the model along with maximum and minimum values that have been used to calculate the error of the model: (a) Porosity Coefficient (C); (b) Surface Porosity (Φ); (c) Grain density (ρ). (d) Output variations of running the model under all possible input parameter configurations and the configurations used. 1=Min

ρ, Min C and Max Φ; 2 = Min ρ, Max C and Max Φ; 3= Min ρ, Min C and Min Φ; 4= Min ρ, Max C and Min Φ; 5= Max ρ, Min C and Max Φ; 6= Max ρ, Max C and Max Φ, 7= Max ρ, Min C and Min Φ; 8= Max ρ, Max C and Min Φ.

Figure 5. (Colour online) (a) Tectonic subsidence (water loaded) of individual wells of the North Newfoundland block and their numerical mean. (b) Maximum and minimum errors for both subsidence and age on the North Newfoundland block mean curve.

Figure 6. (Colour online) (a) Tectonic subsidence (water loaded) of individual wells of the North Iberia block and their numerical mean. (b) Maximum and minimum errors for both subsidence and age on the North Iberian block mean curve.

Figure 7. (Colour online) (a) Tectonic subsidence (water loaded) of individual wells of the Centre Newfoundland block and their numerical mean. (b) Maximum and minimum errors for both subsidence and age on the Centre Newfoundland block mean curve.

Figure 8. (Colour online) (a) Tectonic subsidence (water loaded) of individual wells of the Centre Iberia block and their numerical mean. (b) Maximum and minimum errors for both subsidence and age on the Centre Iberian block mean curve.

Figure 9. (Colour online) (a) Tectonic subsidence (water loaded) of individual wells of the South Newfoundland block and their numerical mean. (b) Maximum and minimum errors for both subsidence and age on the South Newfoundland block mean curve.

Figure 10. (Colour online) (a) Tectonic subsidence (water loaded) of individual wells of the South Iberia block and their numerical mean. (b) Maximum and minimum errors for both subsidence and age on the South Iberian block mean curve.

Figure 11. (Colour online) (a) Mean tectonic subsidence curves (water loaded) for each block on either side of the margin. (b) Mean tectonic subsidence curve (water loaded) for each

segment of the margin and their associated error as an envelope. (c) Mean tectonic subsidence curve (water loaded) for each side of the margin as a whole and their associated error as an envelope.

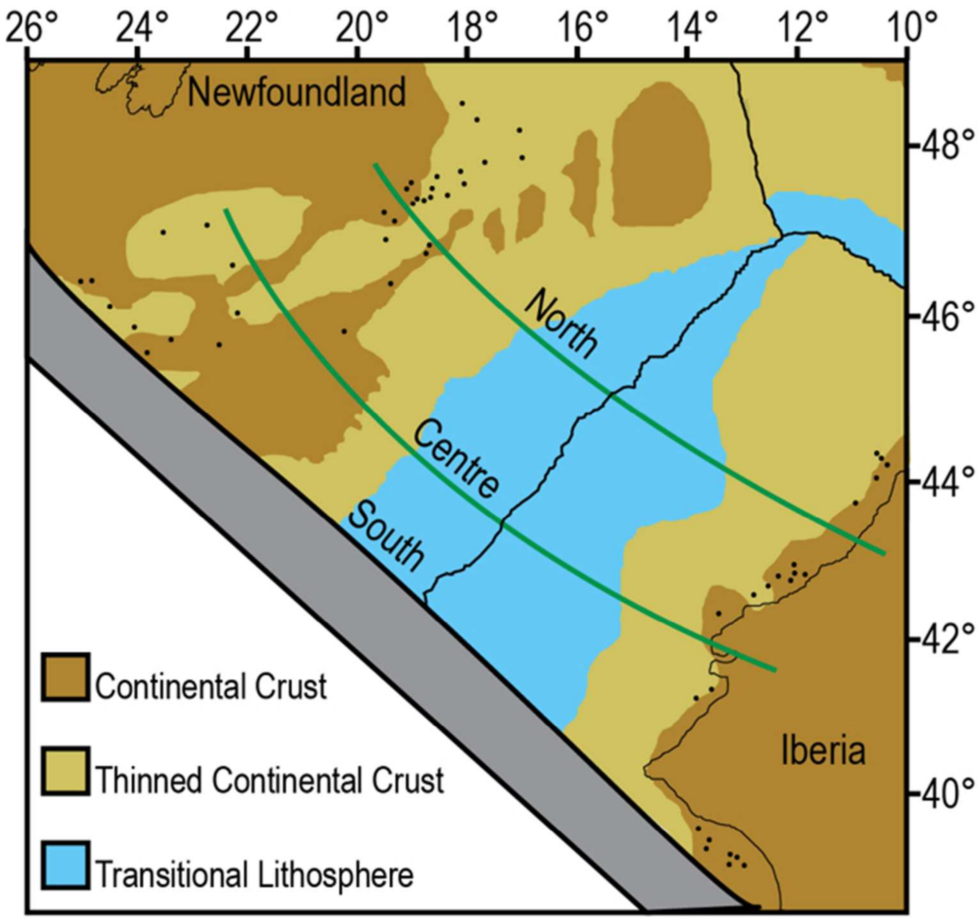

Plate reconstruction of Iberia-Newfoundland at chron M0 (125Ma, start Aptian) from Sibuet and Tucholke (2012) and Srivasta et al. (2000). Locations of all wells used in the study are shown as black dots. The green lines display the arbitrary blocks used in this work for curve averaging. The grey box indicates the Newfoundland-Gibraltar Fracture Zone.

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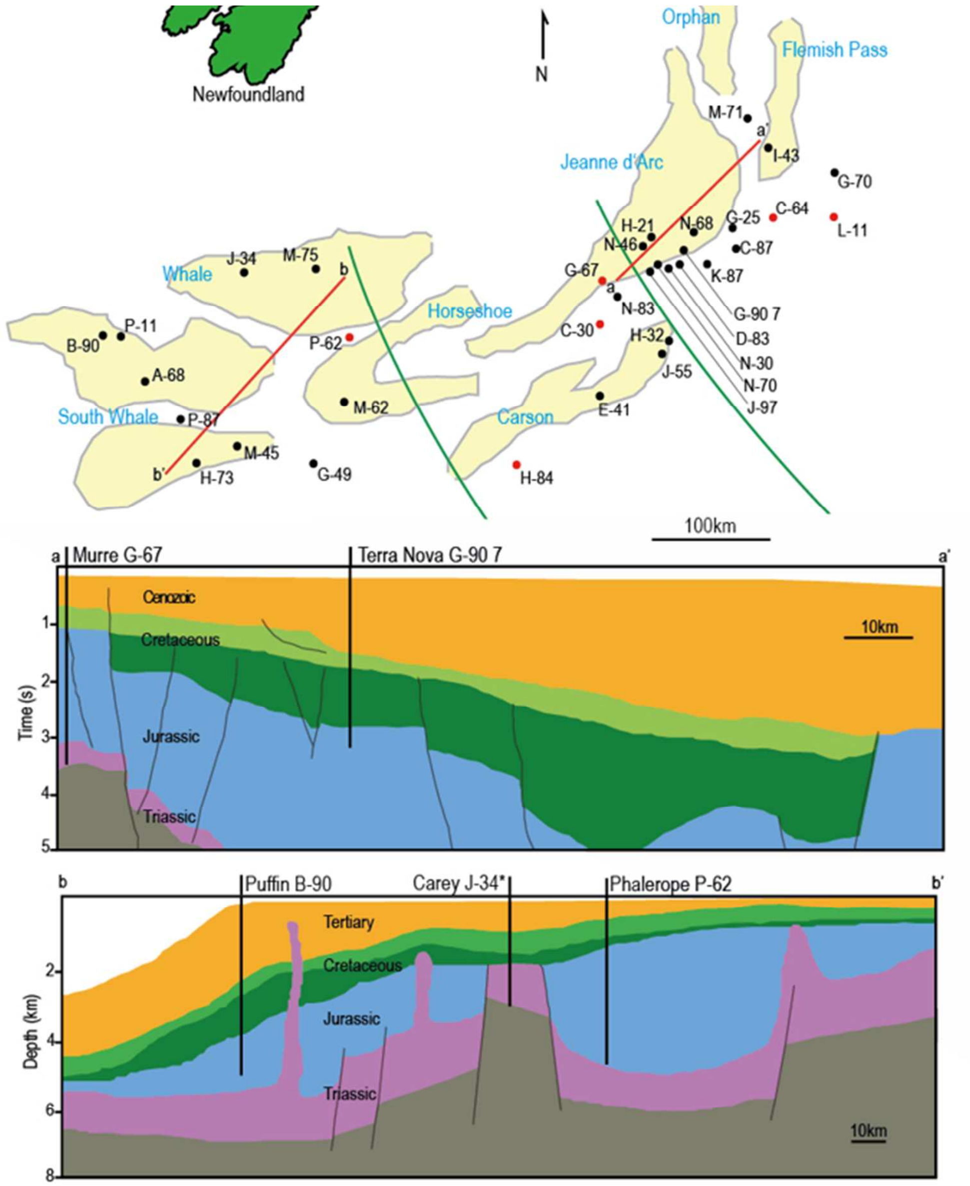

Map of present day Newfoundland with present day depocentres displayed and labelled and with all wells used in the study shown, wells penetrating to basement in red. The green lines display the blocks used in this work for curve averaging. Section a-a' is adapted from DeSilva (1999). Section b-b' is adapted from Fagan (2010). Key of units in cross sections can be found in Fig. 3. Well Carey J-34 is offset from the cross section but sits in an equivalent structural location.

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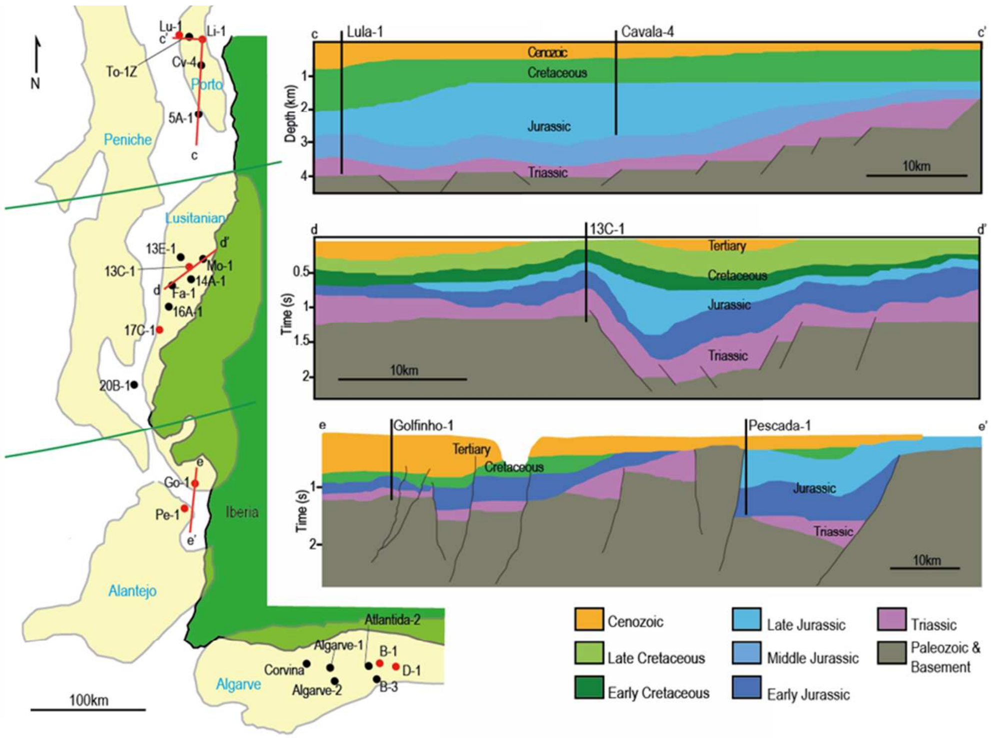

Map of present day Iberia with present day depocentres displayed and labelled and with all wells used in the study shown, wells penetrating to basement in red. The green lines display the arbitrary blocks used in this work for curve averaging. Section c-c' is adapted from Alves et al (2006). Section d-d' is adapted from Pimentel and Pena dos Reis (2016). Section e-e' is adapted Rasmussen et al (1998).

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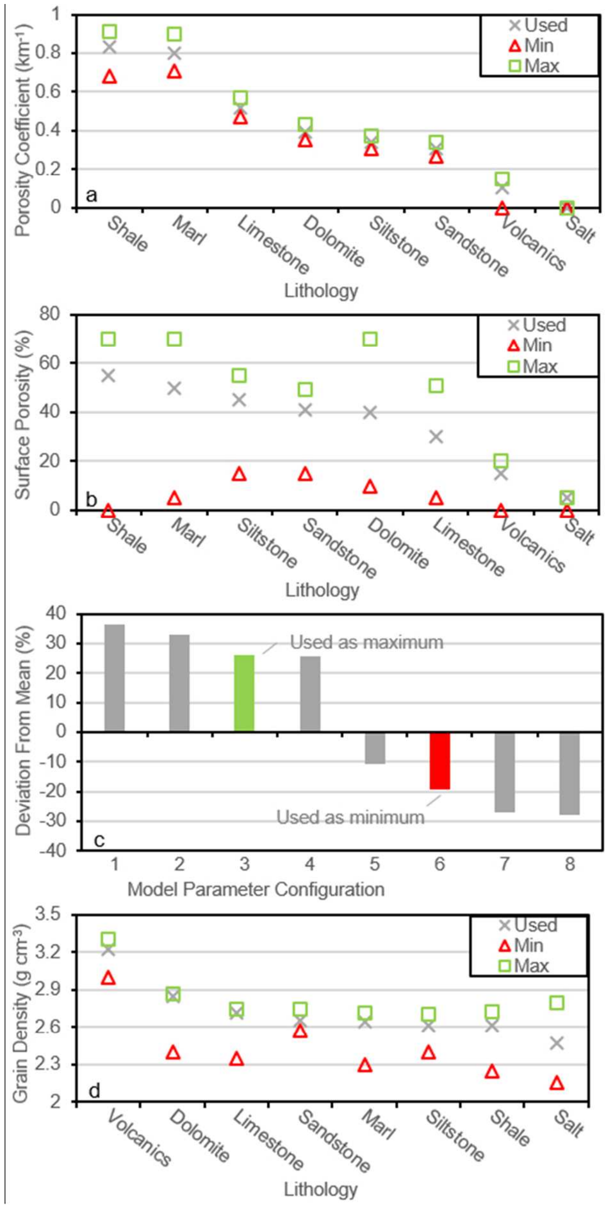

Input parameters of each lithology used (the lithology labelled salt, represents all evaporites) in the model along with maximum and minimum values that have been used to calculate the error of the model: (a) Porosity Coefficient (C); (b) Surface Porosity (Φ); (c) Grain density (ρ). (d) Output variations of running the model under all possible input parameter configurations and the configurations used. 1=Min ρ, Min C and Max Φ; 2 = Min ρ, Max C and Max Φ; 3= Min ρ, Min C and Min Φ; 4= Min ρ, Max C and Min Φ; 5= Max ρ, Min C and Max Φ; 6= Max ρ, Max C and Max Φ, 7= Max ρ, Min C and Min Φ; 8= Max ρ, Max C and Min Φ.

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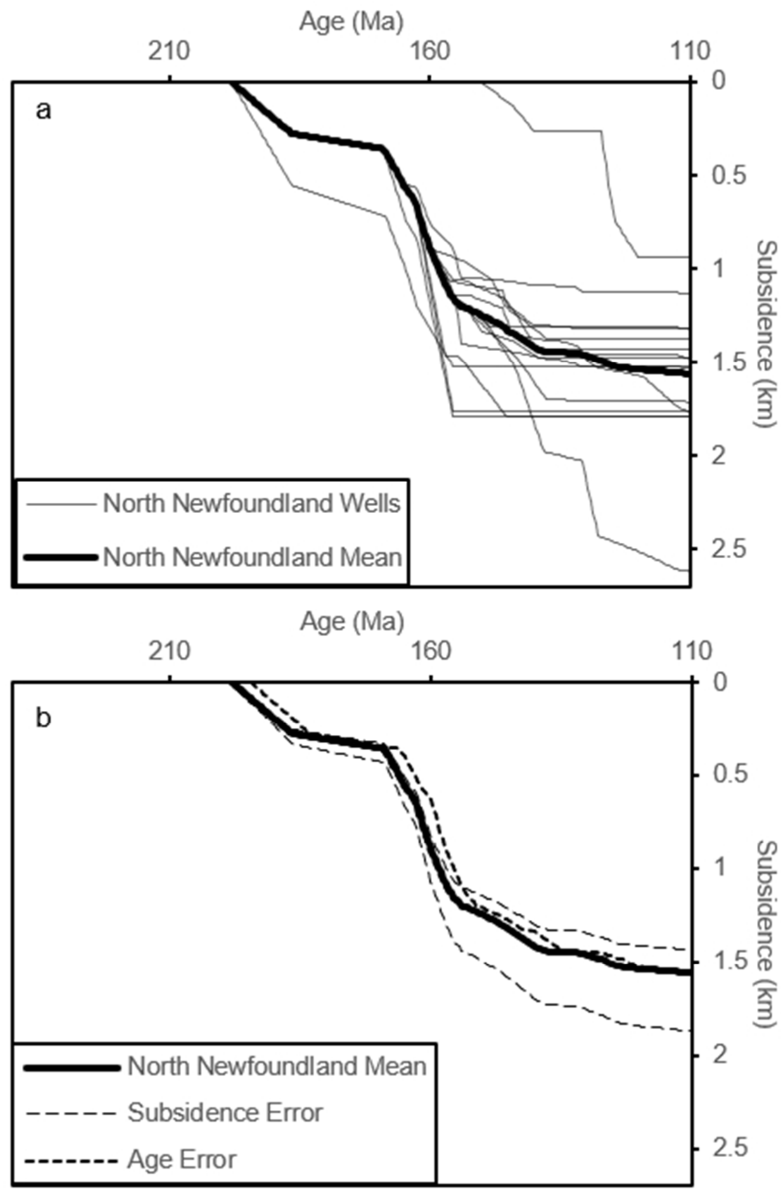
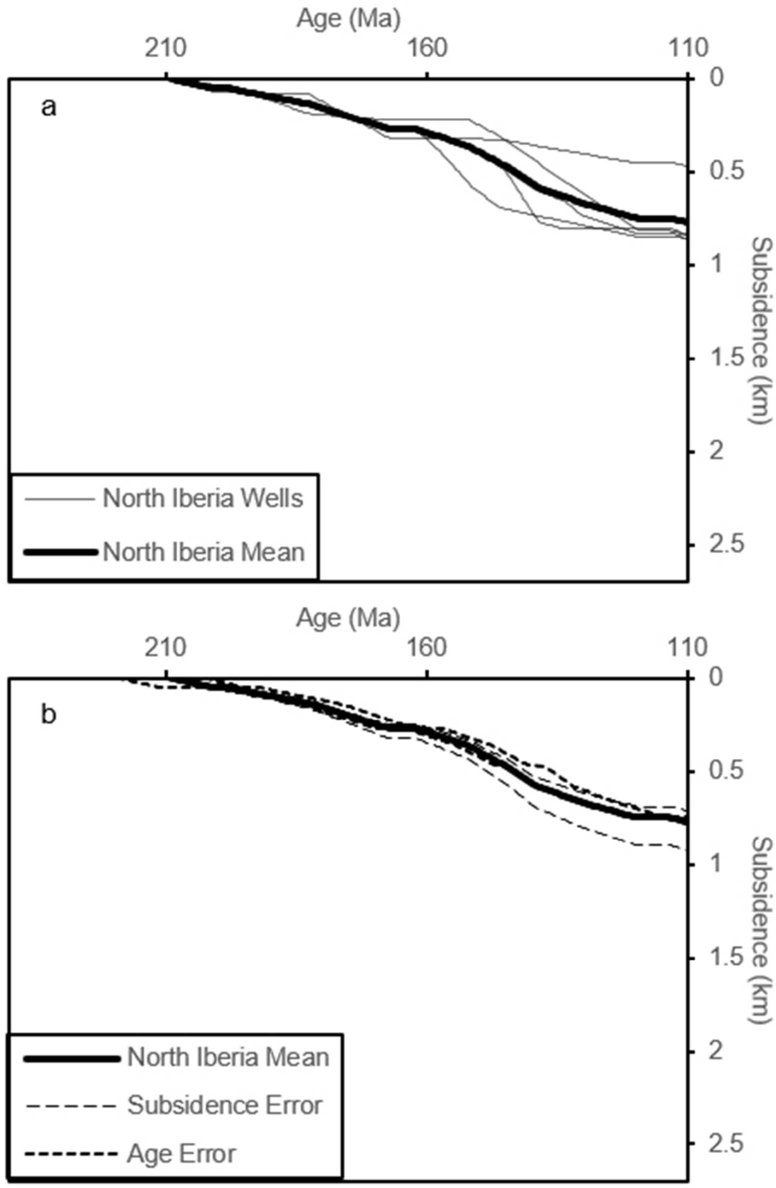


(a) Tectonic subsidence (water loaded) of individual wells of the North Newfoundland block and their numerical mean. (b) Maximum and minimum errors for both subsidence and age on the North Newfoundland block mean curve.

124x183mm (96 x 96 DPI)



(a) Tectonic subsidence (water loaded) of individual wells of the North Iberia block and their numerical mean. (b) Maximum and minimum errors for both subsidence and age on the North Iberian block mean curve.

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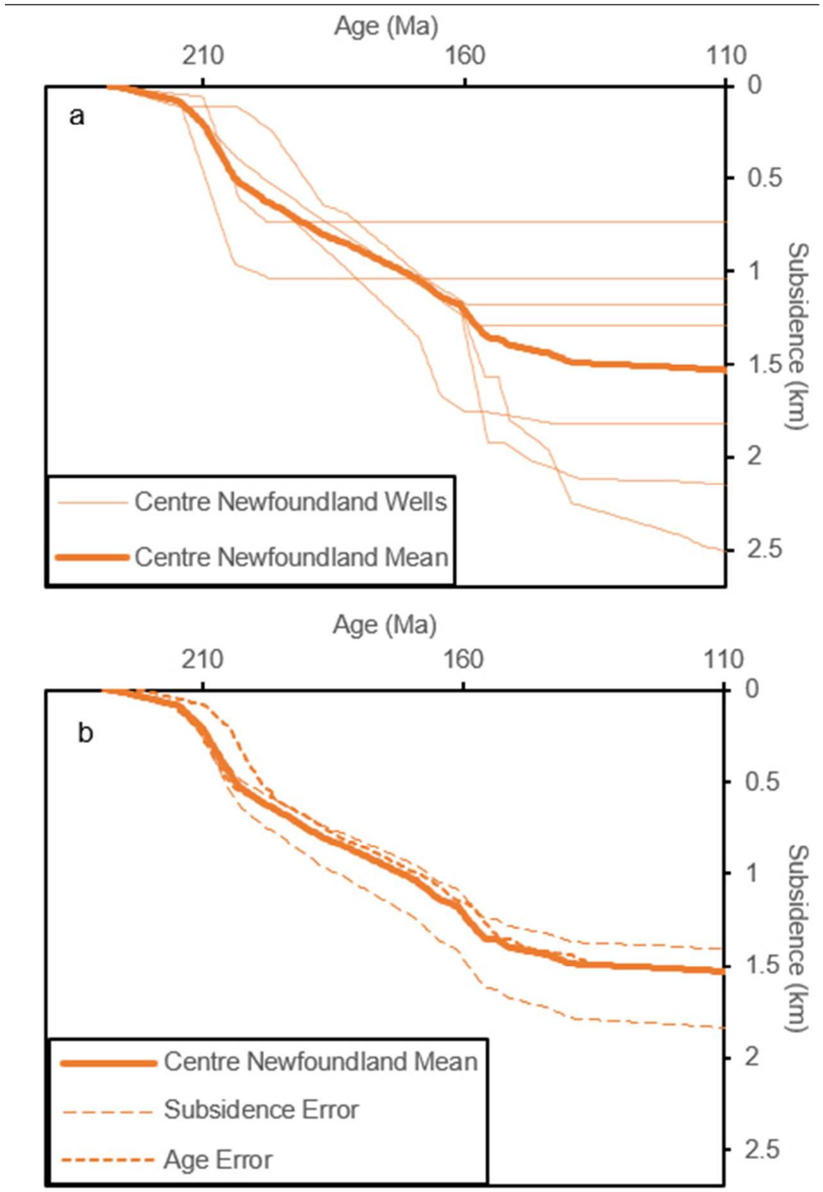

(a) Tectonic subsidence (water loaded) of individual wells of the Centre Newfoundland block and their numerical mean. (b) Maximum and minimum errors for both subsidence and age on the Centre Newfoundland block mean curve.

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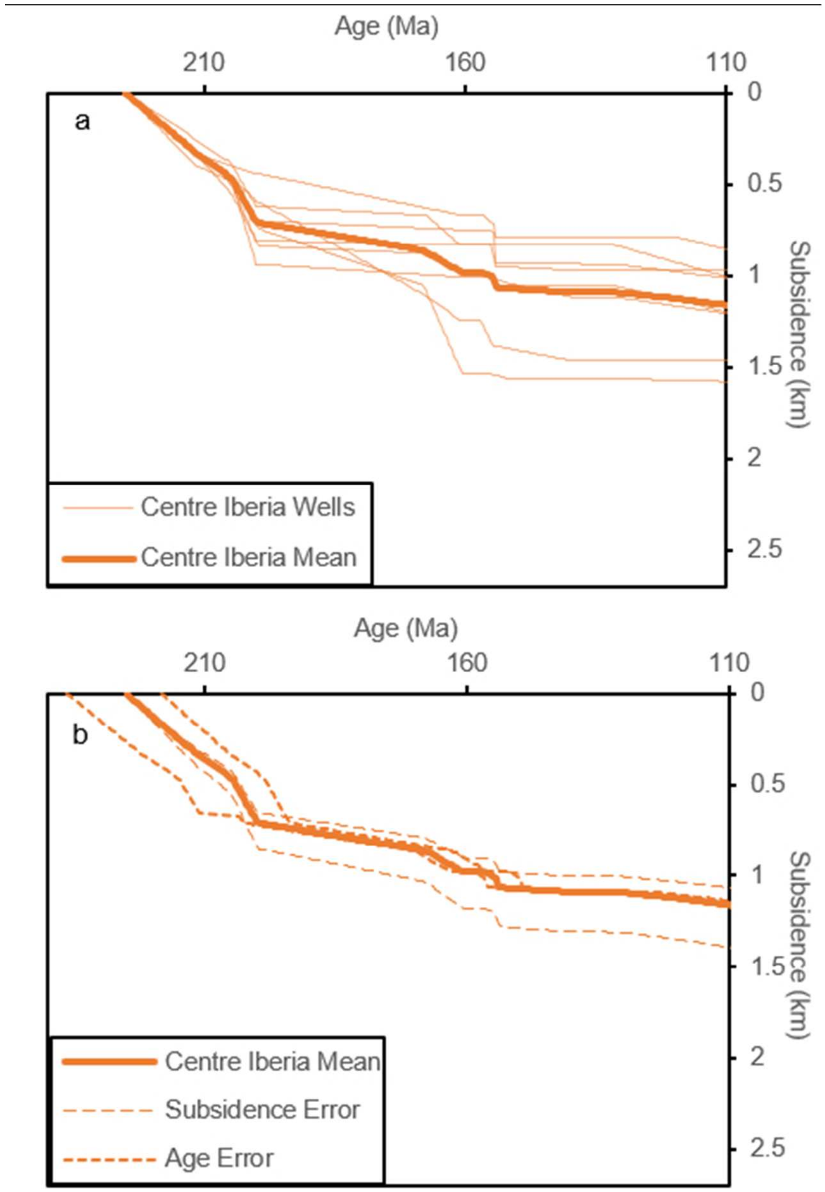

(a) Tectonic subsidence (water loaded) of individual wells of the Centre Iberia block and their numerical mean. (b) Maximum and minimum errors for both subsidence and age on the Centre Iberian block mean curve.

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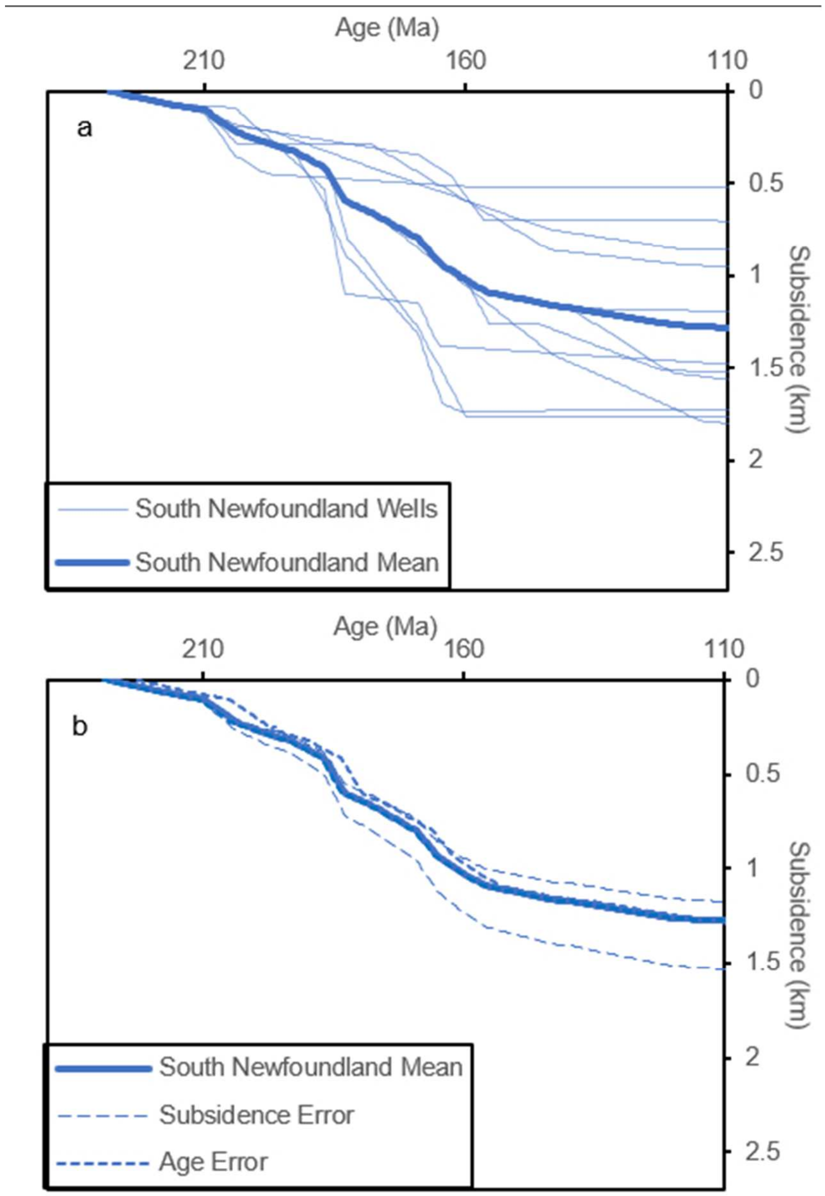

(a) Tectonic subsidence (water loaded) of individual wells of the South Newfoundland block and their numerical mean. (b) Maximum and minimum errors for both subsidence and age on the South Newfoundland block mean curve.

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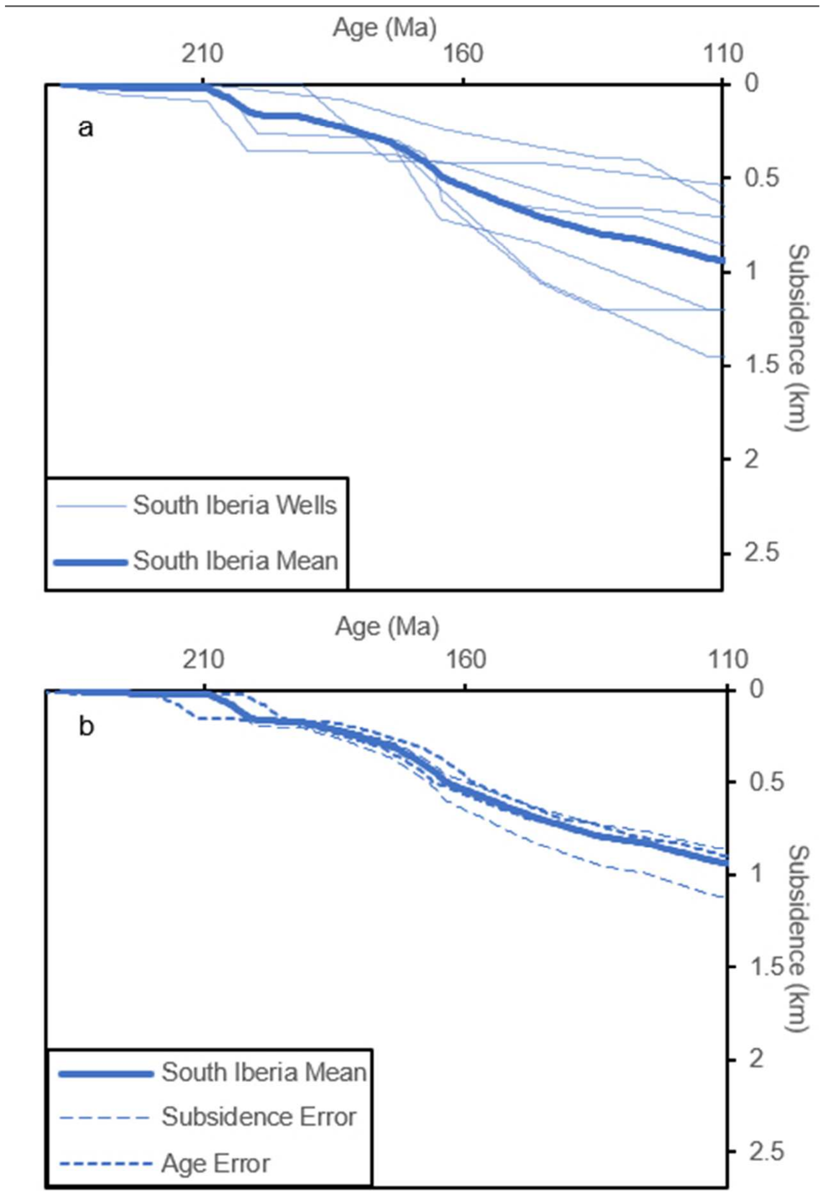

(a) Tectonic subsidence (water loaded) of individual wells of the South Iberia block and their numerical mean. (b) Maximum and minimum errors for both subsidence and age on the South Iberian block mean curve.

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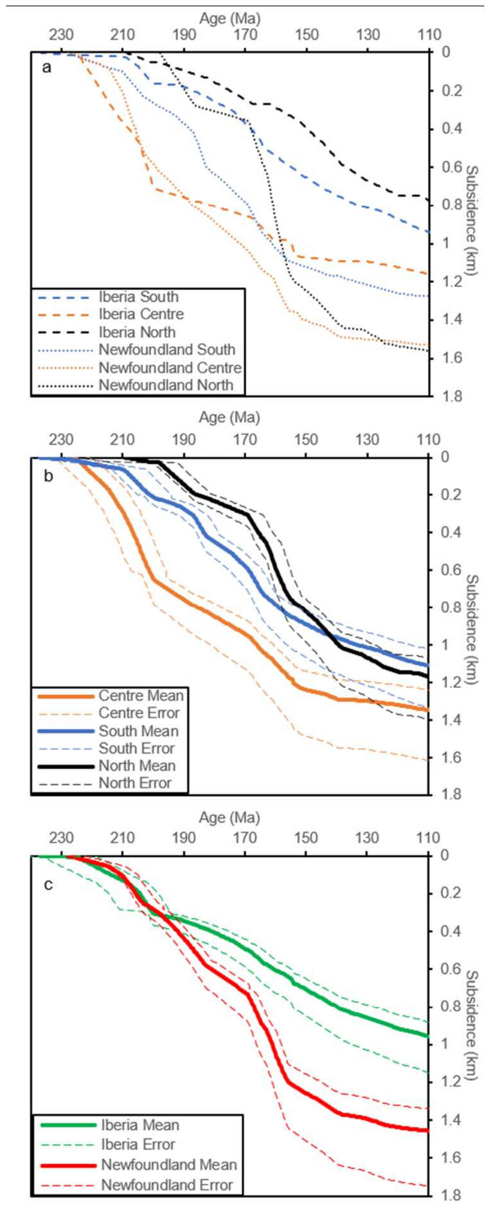

(a) Mean tectonic subsidence curves (water loaded) for each block on either side of the margin. (b) Mean tectonic subsidence curve (water loaded) for each segment of the margin and their associated error as an envelope. (c) Mean tectonic subsidence curve (water loaded) for each side of the margin as a whole and their associated error as an envelope.

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