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Linking rifted margin crustal shape with the timing and volume of magmatism

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Abstract

Determining the volume and timing of magmatism during rifting and breakup is challenging due to the similar density and seismic velocity of inherited continental crust, magmatic additions and serpentinized mantle; and the difficulty of dating magmatic additions. Here rules of thumb to estimate these are proposed based on the characteristics of the top basement and Moho on seismically imaged margins. A simple kinematic model is used to generate first-order crustal shapes of margins as a function of magma volume and timing of emplacement, which are successfully compared to a representative number of rifted margins. It appears that 'magma-rich margins' require melt emplacement in advance of crustal thinning but not necessarily enhanced melt volume, while margins with exhumed mantle require a delay in melt emplacement but not necessarily a low magmatic volume. An alternative classification for the magma-poor/magma-rich dichotomy is proposed to better represent the crustal shape variability of rifted margins.

KEYWORDS

depth-dependent thinning, magma, rifted margin

1 | INTRODUCTION

The binary magma-rich versus magma-poor classification of rifted margins was introduced to distinguish between margins showing markedly different crustal architectures, in particular, related to the occurrence of magmatic products (Franke, 2013; White et al., 1987; Figure 1). The 'magma-poor' qualifier is attributed to margins that display a domain of exhumed mantle and whose crustal wedge is exclusively made of continental material (Figure 1a,c), while margins whose continental crust is heavily intruded/underplated and overlain by extrusive magmatic flows are regarded as 'magma-rich' (Figure 1b,d). Yet, distinguishing between inherited continental crust, newly-created magmatic crust and serpentinized mantle is challenging because these lithologies can display

comparable geophysical properties (density and seismic velocity; Karner et al., 2021; Schön, 2015).

The only interfaces that can usually be identified with some confidence on seismic images, except in the presence of thick salt, are the top basement (i.e. pre-rift crystalline crust plus syn- and post-rift magmatic additions) and the Moho, which outline the margin crustal shape (Figure 2). First order, rifted margins can be regarded as wedging crust located between the constant-thickness continental and oceanic domains, where the top basement and Moho are largely horizontal (e.g. Chenin et al., 2017; Figure 3c). The crust of the continental domain is exclusively made of inherited continental material and is typically 37 ± 5 km thick (Mooney & Brocher, 1987). The crust of the oceanic domain consists of fully newly-created magmatic material with thickness

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between 2 and 8 km (Dick et al., 2003; Reid & Jackson, 1981). In-between, the margin crustal wedge comprises either inherited continental crust or newly-created magmatic crust, or a combination of the two.

The distribution of magmatic products along rifted margins is controlled by two main parameters, namely the volume of magma and the timing of its emplacement. In this contribution, we investigate what the shape of rifted margins can tell us about these two parameters. We first outline the shape of a representative number of rifted margins worldwide. Then, we use a simple kinematic model to explore how the volume of magma and timing of emplacement relative to crustal thinning impact margins crustal shape. Finally, we discuss how this approach may help us better understand the tectono-magmatic processes occurring during rifting and breakup.

2 | CRUSTAL SHAPE OF RIFTED MARGINS FROM SEISMIC OBSERVATIONS

From published seismic images of worldwide margins, we have selected along-dip, depth-converted lines where the top basement and Moho are well-imaged. We outline the crustal shape and use stratal relationships to distinguish between continental (brown), magmatic (violet) and exhumed mantle (green) top basement (Figure 2): we interpret the top basement displaying tilted and fault-bounded blocks overlain by wedging sediments as continental. Conversely, we consider smooth top basement underlain by SDRs and overlain by passive infill as magmatic. For each section, we identify three noteworthy inflection points in the top basement and/or Moho trend marking the onset of: crustal thinning (OT), extrusive magma emplacement (OM) and steady-state seafloor spreading (OS). On magma-poor margin sections, we also indicate the edge of the continental crust (ECC). The latter cannot be identified on magma-rich margin seismic images because it is usually covered with and intruded/underplated by magma.

3 | KINEMATIC MODEL

3.1 | Method

We use a simple model to generate the first-order shape of rifted margins with different volumes and timings of magma emplacement relative to crustal thinning. In our reference model (*T_n-V_n* for *Timing normal-Volume normal*), the shape of the continental crust (brown package in Figure 3c) is produced by linear thinning of an initially 37.5 km-thick crust over 150 km (Figure 3a). We calculate the corresponding thickness of magma produced by decompression melt resulting from lithosphere thinning with the same lateral distribution (green line (V_n) in Figure 3b). Decompression melting uses the model of White and McKenzie (1989) as

Statement of significance

In this contribution, based on seismic observations from worldwide margins and on the results of a simple kinematic model, it is proposed that the crustal shape of a rifted margin can be used to estimate, to first order, the volume and timing of magma emplacement during rifting and breakup. The innovative observation-driven approach presented herein requires only two first-order interfaces to be identified: the top of crustal basement and the Moho. This approach serves to overcome the problem of distinguishing between inherited continental crust, newly created magmatic crust and serpentinized mantle, which is challenging because these lithologies display comparable geophysical properties (density and seismic velocity). In addition, a new classification of rifted margins is proposed, accounting not only for the observed variability of magma volume but also for the timing of magma emplacement with respect to crustal thinning, which is ignored in the classical bimodal magma-rich/magma-poor classification.

parameterized by Chappell and Kusznir (2008). We prescribe a melt distribution of 1/3 extrusive and 2/3 intrusive/underplate onto and beneath the directly overlying continental crust (respectively, upper and lower violet package in Figure 3c; White et al., 2006).

An isostatically balanced (local isostasy is assumed) and thermally equilibrated cross-section is calculated from the thickness of continental crust and magmatic additions (Figure 3c; Figure S1.1). It shows the lateral variation of bathymetry from the unthinned continental domain (from 0 to 50 km in Figure 3c) to the oceanic domain made of a 7 km-thick magmatic crust (from 200 to 500 km in Figure 3c).

The results for model *T_n-V_n* are calculated assuming depth-uniform stretching and thinning of continental crust and lithosphere. An advance of decompression melting with respect to crustal thinning may result from lithosphere depth-dependent thinning during breakup (Lu & Huisman, 2021). Mantle depletion, or very slow rifting, may conversely delay decompression melting with respect to crustal thinning. We examine the consequences of the timing of magma emplacement by advancing decompression melting by 50 km continentward in *T_a* models and delaying it by 125 km oceanward in *T_d* models compared to *T_n* models (Figure S1.2). Magmatic volumes from decompression melting may be greater or less than the maximum 7 km of the reference model *T_n-V_n* due to higher or lower mantle potential temperatures and/or water content (Langmuir & Forsyth, 2007). For higher mantle potential temperature or increased water content, decompression melting starts deeper at a lower thinning factor and the final/maximum volume of magma is higher (10 km for *V_h* models; red line in

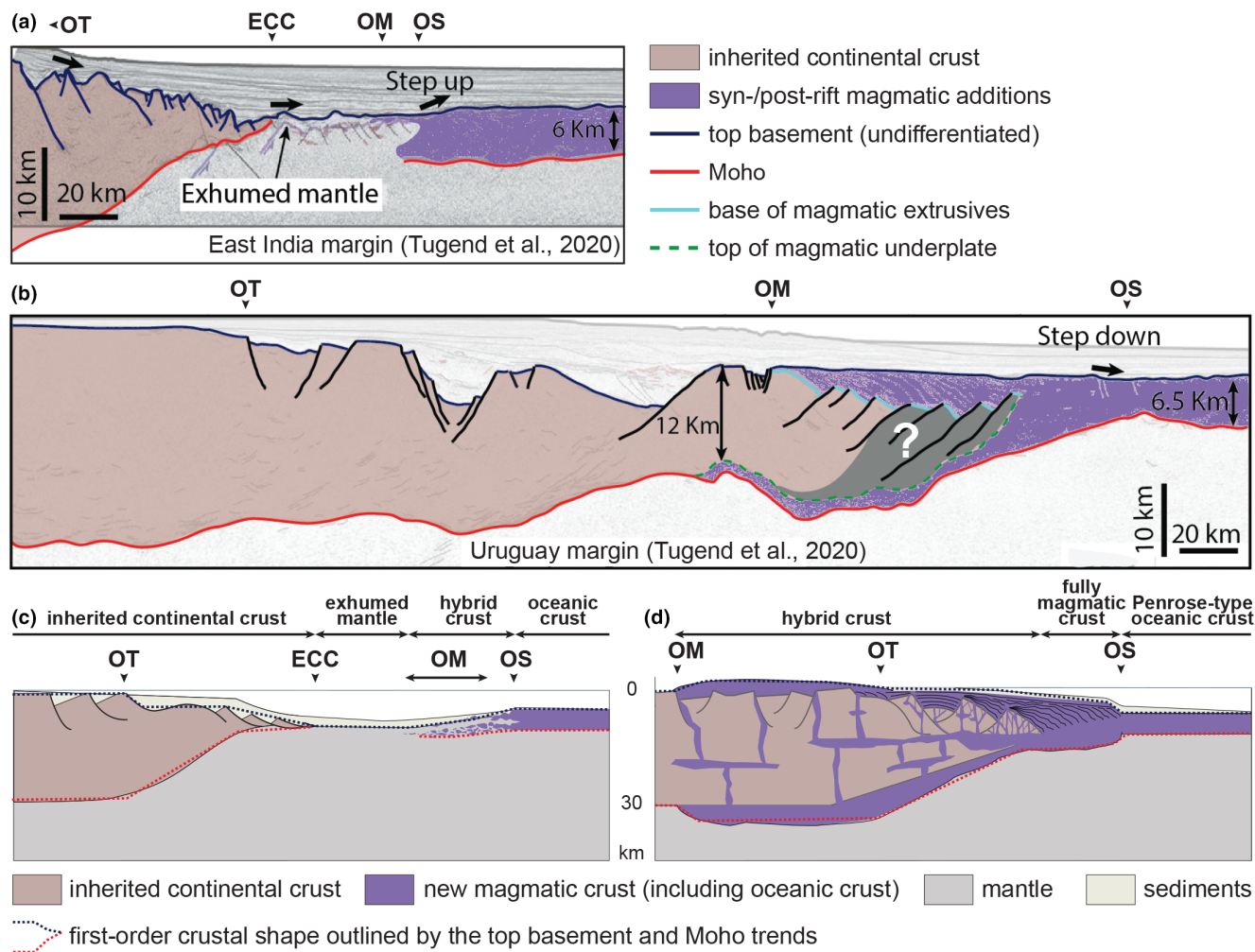


FIGURE 1 (a, b) Typical examples of a magma-poor (a) and a magma-rich (b) rifted margin where the suspected distribution of continental versus magmatic material is shown. (c, d) Schematic representations of a magma-poor (c) and a magma-rich (d) rifted margin highlighting the distribution of continental crust, hybrid crust (i.e. mix of continental, magmatic and/or serpentinized mantle material), fully magmatic crust and oceanic crust. At magma-poor margins (c), due to progressive increase in magma production during embryonic seafloor spreading, the identification of the onset of magmatism location (OM) may depend on the resolution of the seismic image. At magma-rich margins (d), distinguishing between hybrid and fully magmatic crust may not be possible due to their similar geophysical properties (density and seismic velocity); hence, the relevance of defining oceanic crust where steady-state seafloor spreading initiates. In all panels, we display the location of the following specific points, when possible: OT, onset of crustal thinning; OM, onset of extrusive magmatism (first occurrence of smooth, highly reflective top basement); OS, onset of steady-state seafloor spreading (landward limit of ca. 7 km tabular crust outboard of the crustal wedge). ECC, edge of the continental crust. Here we define ECC to mark the location of the crustal breakup.

Figure 3b). The converse is true for lower potential mantle temperature or reduced water content (3 km for VI models; blue line in Figure 3b). We provide the details of our modelling settings in Supplement S1.

We deliberately keep our model simple because we aim to investigate the variability in the final margin shape rather than its 'absolute' shape. We are aware that crustal thinning mechanisms may differ between magma-rich and magma-poor rift systems and that magma may not be distributed as 1/3 extrusive and 2/3 intrusive/underplate; however, we argue that these simplifications are appropriate for the purpose of the present study. Sophisticated deterministic

models are not more successful in tackling this issue because they suffer the same pitfalls as ours, namely the lack of knowledge of the initial mantle composition and temperature, which control the onset and volumes of melt generated (see Supplement S2 for discussion).

3.2 | Results

By varying only the volume and timing of magma, our simple model produces a large diversity of margin shapes (Figure 4). For all modelled margin shapes, we define the same three inflection points as

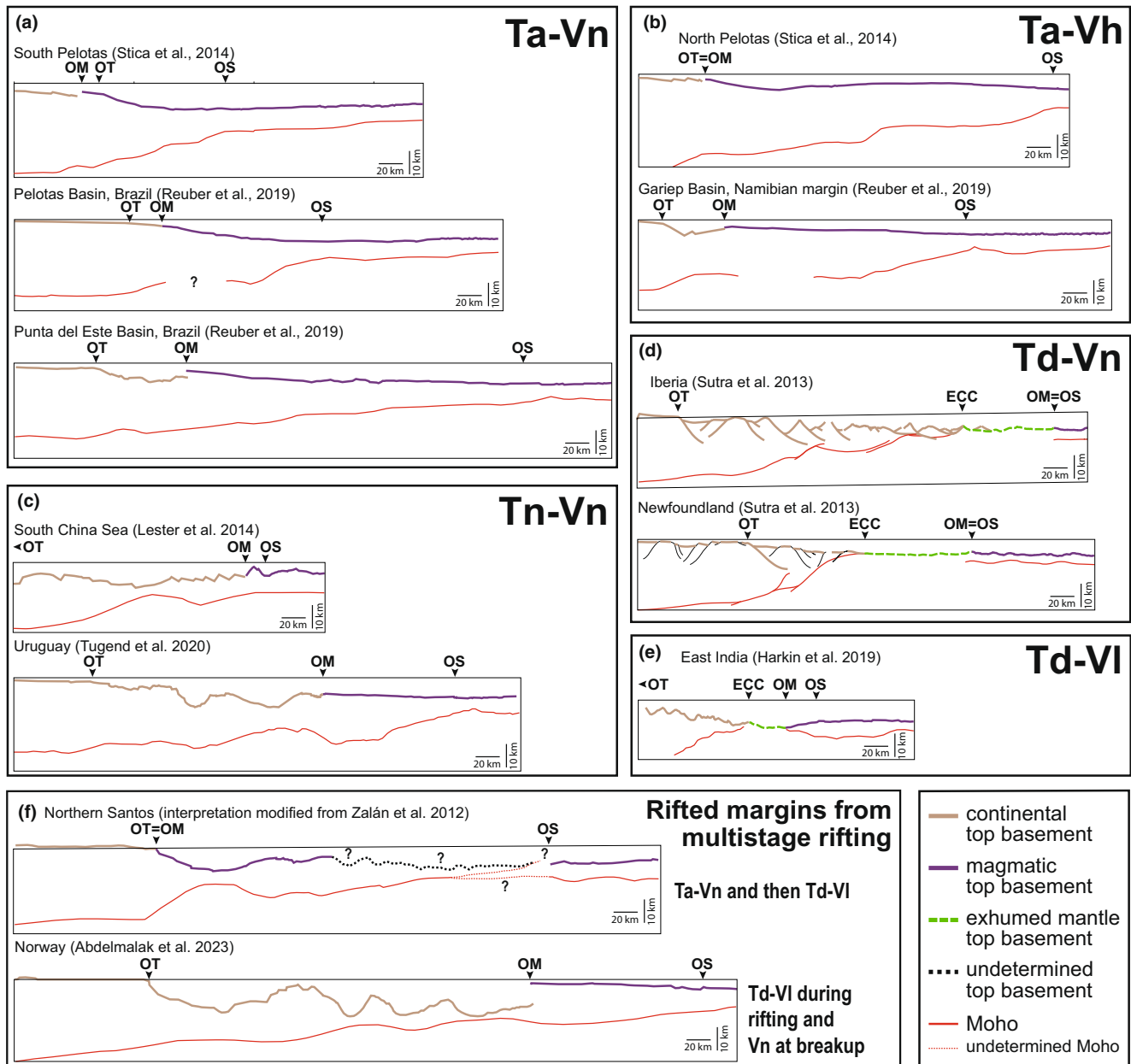


FIGURE 2 (a-f) Outline of the crustal shape (i.e. top basement and Moho) of worldwide rifted margins drawn from depth-converted seismic sections. The continental, magmatic and mantle nature of the top basement is determined based on both its seismic signature and the stratigraphic architecture of overlying sediments (see text for details). The Tx-Vy names refer to the different categories obtained from our kinematic model, where ‘T’ stands for ‘timing of melt emplacement with respect to crustal thinning’, which can be either ‘advanced’ (Ta), ‘normal/synchronous’ (Tn) or ‘delayed’ (Td); and ‘V’ stands for ‘volume of emplaced magma’, which can be either ‘low’ (VI), ‘normal’ (Vn) or ‘high’ (Vh) compared to what we consider a ‘standard’ magmatic system producing a 7 km-thick oceanic crust. Specific inflection points of the crustal wedge are highlighted, namely the onset of crustal thinning (OT), the first occurrence of magma (OM), the onset of steady-state seafloor spreading (OS), and where possible, the edge of the continental crust wedge/location of the crustal breakup (ECC).

these observed on our seismic sections (OT, OM and OS), plus ECC (Figure 4).

In our ‘standard’ model (Tn-Vn; central panel in Figure 4), OM occurs when the continental crust is thinned to ca. 13 km and OS corresponds to a step down of top basement onto oceanic crust. In contrast, in all models with a delay in the start of decompression melting (Td models; right-hand side column in Figure 4) the crust

wedges to zero prior to magma emplacement. A zone of exhumed mantle occurs between ECC and the oceanic domain, and hence OS corresponds to a step up of top basement onto oceanic crust. In all other models, no zone of exhumed mantle occurs and hence OS corresponds to a step down of top basement onto oceanic crust.

The distance between OT and OM varies both as a function of the magma volume (shorter distance when higher volume) and the

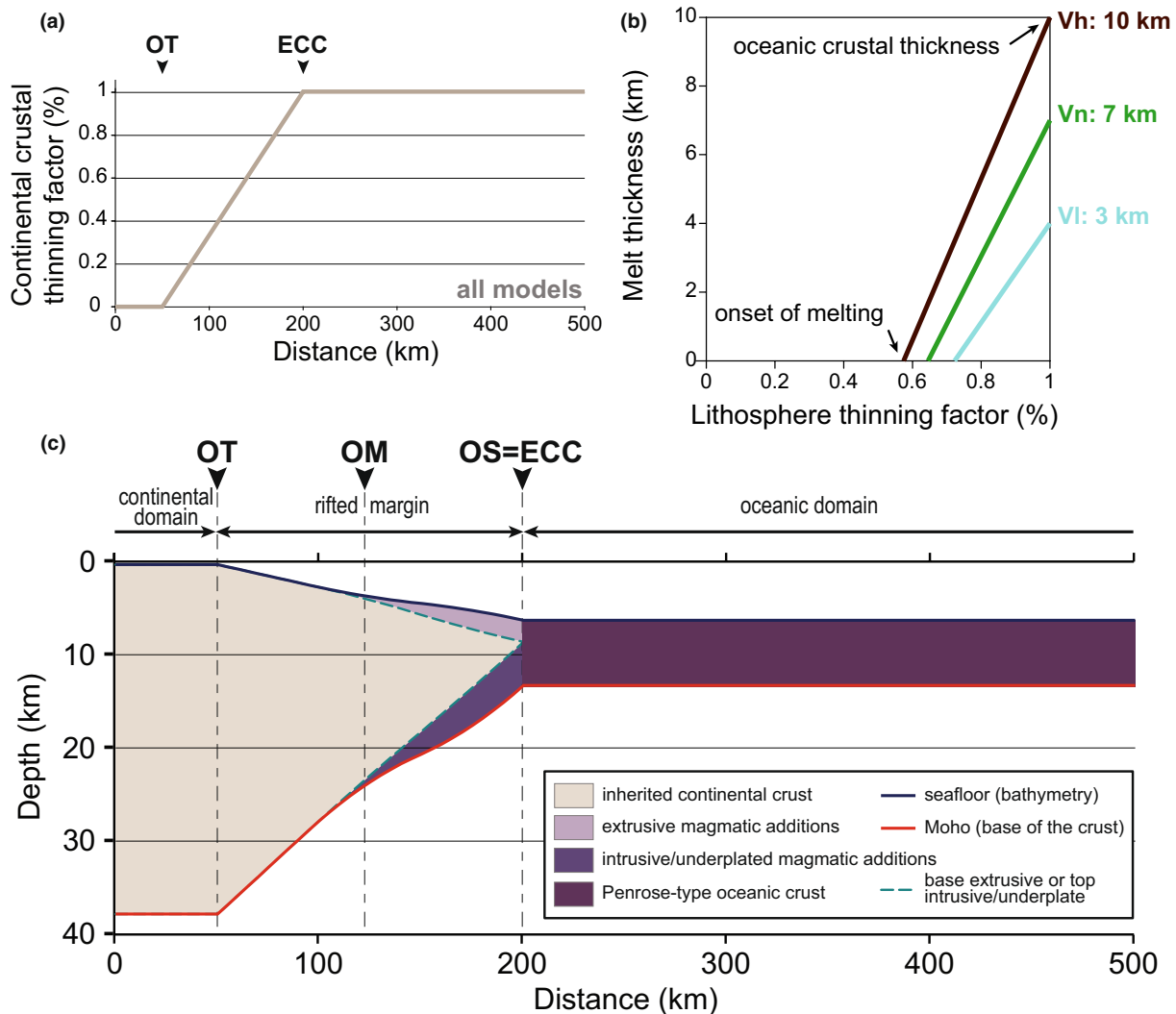


FIGURE 3 (a) Shape of the thinning factor taper imposed on the continental crust of all our modelled margins. OT points to the onset of crustal thinning and ECC to the edge of the continental crust wedge. (b) Volume of melt emplaced as a function of lithosphere thinning for our models with different magma volumes (VI: 'low volume' producing a 3 km-thick oceanic crust; Vn: 'normal volume' producing a 7 km-thick oceanic crust; and Vh: 'high volume' producing a 10 km-thick oceanic crust); Figure recolored from Chappell and Kusznir (2008). (c) Crustal cross-section of model Tn-Vn (Timing normal-Volume normal) assuming local water-loaded Airy isostasy and thermally equilibrated lithosphere. For details on our model setting see Supplement S1.

timing of magmatism onset (shorter distance when advanced magmatism). As a result, rifting with delayed magmatism and/or lower magmatic budget produces a crustal wedge shorter and sharper compared to their homologues with advanced magma timing and/or higher magma volumes.

4 | COMPARISON BETWEEN MODEL RESULTS AND SEISMIC OBSERVATIONS

Using our model results to categorize the selected rifted margins (Figures 2 and 5a), we see that magma timing is 'advanced' when OM occurs where crustal thickness is >20 km, 'normal' when OM sits on a 13 ± 7 km-thick crust, and 'delayed' when exhumed mantle

occurs (i.e. when OS is a step up onto oceanic crust). Because assessing the proportion of continental versus magmatic material is difficult due to their similar geophysical characteristics, we consider magma volume is 'high' when there is only limited accommodation oceanward of OM and 'normal' or 'low' when accommodation still significantly increases oceanward of OM. For margins that display a zone of exhumed mantle, we consider that magma volume is 'low' when the first oceanic crust is less than 5 km.

We have identified five of the nine margin types of our model, namely Ta-Vh, Ta-Vn, Tn-Vn, Td-Vl and Td-Vn (Figures 2 and 5a). We have not found margins combining advanced magmatism with low magma volumes or delayed magmatism with high magma volumes. Among our selected examples, 'normal' timing of magma emplacement seems to occur only for 'normal' magma volumes.



FIGURE 4 Crustal cross-section of our nine models with different volumes (vertical direction) and timings of magma emplacement relative to crustal thinning (horizontal direction), assuming local water-loaded Airy isostasy and thermally equilibrated lithosphere. Tx-Vy names refer to the different categories obtained from our kinematic model, where 'T' stands for 'timing of melt emplacement with respect to crustal thinning', which can be either 'advanced' (Ta), 'normal/synchronous' (Tn) or 'delayed' (Td); and 'V' stands for 'volume of emplaced magma', which can be either 'low' (Vl), 'normal' (Vn) or 'high' (Vh) compared to what we consider a 'standard' magmatic system producing a 7 km-thick oceanic crust. Specific inflection points of the crustal wedge are highlighted, namely the onset of crustal thinning (OT), the first occurrence of magma (OM), the onset of steady-state seafloor spreading (OS) and the edge of the continental crust wedge/location of the crustal breakup (ECC).

5 | DISCUSSION

5.1 | What can we learn from rifted margins crustal shape and inflection points?

At magma-poor rifted margins, the crustal wedge is exclusively made of inherited continental material. Inflection points in the top basement and/or Moho trend have successfully been used to define rift domains related to different deformation styles (Sutra et al., 2013), and hence to provide information about the dominant tectonic process that formed the different rift domains (e.g. pure-shear extension, viscoplastic necking, Coulomb wedge; Chenin et al., 2022) and crustal rheology, which depends on the nature of the crust, geotherm, extension rate and amount and timing of magma emplacement, among others (Sapin et al., 2021). Noteworthy, the occurrence of a step up of top basement onto oceanic crust is diagnostic of exhumed mantle since the latter is denser than oceanic basalts (Hopper et al., 2004).

At magma-rich margins, the crustal wedge is made of either a combination of continental and magmatic crust or of fully magmatic crust. The first magma emplacement is likely to correspond to an inflection point (decrease in the aperture angle between the top basement and Moho), since magmatic addition starts to counterbalance

crustal thinning. In Tn-Vn, this inflection point occurs where the crust is thinned to ca. 13 km, that is in a comparable location to that marking the transition between the necking and hyperextended domain in a magma-poor margin (e.g. Sutra et al., 2013). Therefore, one cannot use inflection points by themselves to hypothesize about the tectono-magmatic processes involved at magma-rich margins; these should be interpreted in the light of the continental versus magmatic nature of top basement. One exception may be OS, since when top basement steps down onto oceanic crust, one can confidently suggest the occurrence of significant magmatic products adjacent to the oceanic crust.

5.2 | What controls the volume and advance/delay in magma emplacement during rifting?

Melt volume produced by decompression melting during rifting depends both on mantle potential temperature and water content (Figure 5b); their relative importance is much debated. Higher values of these increase the volume of melt produced while lower values produce a decrease. The effect on the margin shape of this variation is illustrated by models with Vh, Vn and Vl.

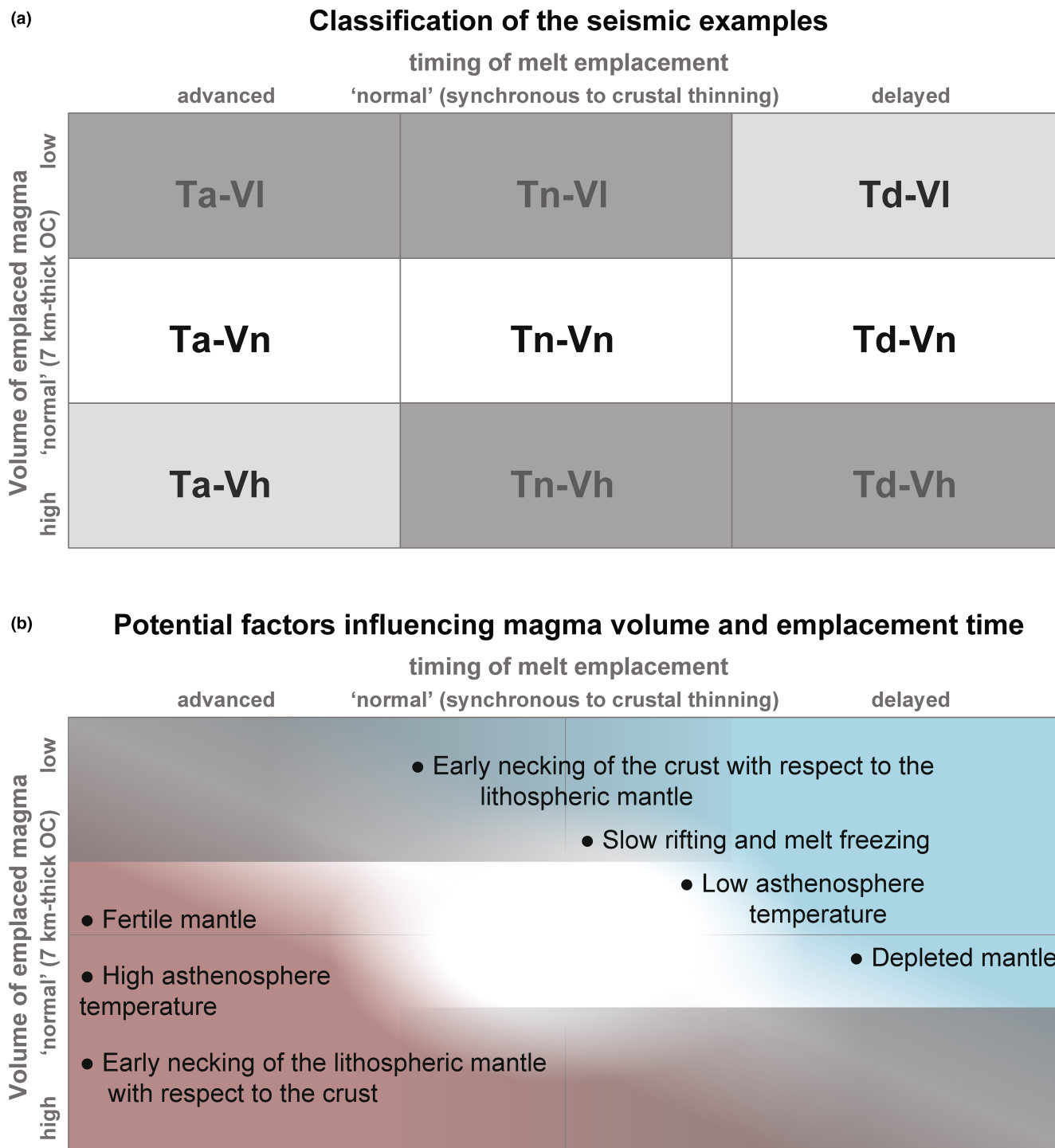


FIGURE 5 (a) Table summarizing the model categories of Figure 4 commonly observed (white background), rarely observed (light grey shading) and not observed (dark grey shading) in nature. (b) Graph summarizing the potential factors influencing the volume and timing of magma emplacement.

The advance or delay in rift-related decompression melting with respect to crustal thinning and represented by models with Ta, Tn and Td may arise from several mechanisms (Figure 5b). Depth-dependent lithosphere stretching, of which simple shear is the most extreme expression, may advance the thinning of the lower continental lithosphere and the onset of decompression melting with respect to crustal thinning. This advance of melting would be amplified by

thermal and melt buoyancy in the lower lithosphere (Forsyth, 1992; Sotin & Parmentier, 1989), including through small-scale convection (Mutter et al., 1988), producing model Ta-Vn. If there is also higher asthenosphere temperature or water content, this would increase the depth of decompression melt initiation and melt volume further, consequently amplifying buoyancy and the advance of melting with respect to crustal thinning giving model Ta-Vh.

Magma-rich margins are sometimes associated with mantle plumes, which can produce advanced decompression melting with respect to crustal thinning due to higher asthenosphere temperature or increased water content. However, the observation of magma-rich margins with thick SDRs and magmatic intrusion/underplate immediately followed by the first oceanic crust thinner than normal (e.g., Uruguay, N-Argentina, Guyana; Sauter et al., 2023; Trude et al., 2022) implies that mantle plumes are not the only and/or most common cause of magma-rich margins.

To explain mantle exhumation at rifted margins requires the delay of decompression melting with respect to crustal thinning. While this might be explained by lithosphere depth-dependent thinning where the crust thins faster than the lithospheric mantle, other factors may be important. It is noted that a larger delay (125 km) is required to create exhumed mantle in our modelling than the advance (50 km) required to generate a magma-rich model. Very slow rifting would allow partial re-equilibration of the rift geotherm and delay the onset of decompression melting. Lower asthenosphere potential temperature and water content would also delay the onset of melting. These are represented in model Td-VI. A depleted lithospheric mantle may also delay magma extraction relative to the timing of magma generation by mantle refertilization transiently 'absorbing' upwelling melts, as exemplified in the former Alpine Tethys margins (Müntener et al., 2010).

6 | SUMMARY AND OUTLOOK

Magma-poor and magma-rich margins can be easily distinguished based on the morphology of the top basement and the basement-sediment stratal relationships. At magma-poor margins, the shape and inflection points of the continental wedge provide insights into the tectonic processes at play during rifting. Although the shape of magma-rich margins is more challenging to interpret because of the comparable geophysical characteristics of continental and magmatic material, the location of the first magmatic extrusives and the dip-angle of the magmatic top basement provide insights into the timing and volume of magma emplacement with respect to crustal thinning. However, we stress that mindful consideration of the local geological history is crucial to apply these rules of thumb. For instance, when rifting was achieved through several extension and/or magmatic phases, each one may display variable timing and/or magma volume (e.g. Norway–Greenland or the Santos Basin offshore Brazil; Figure 2f). Or when a plume overprints the rifting system, one should keep in mind that neither the timing nor the volume of the produced magma can be predicted.

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DATA AVAILABILITY STATEMENT

The details of our code are explicated within the manuscript and supplementary material.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Supplement S1 and S2:

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