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The continent-to-ocean transition in the Iberia Abyssal Plain

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ABSTRACT

Conceptual models of magma-poor rifting are strongly based on studies of the nature of the basement in the continent-to-ocean transition of the Iberia Abyssal Plain, and suggest that exhumed mantle abuts extended continental crust. Yet, basement has only been sampled at a few sites, and its regional nature and the transition to seafloor spreading inferred from relatively low-resolution geophysical data are inadequately constrained. This uncertainty has led to a debate about the subcontinental or seafloor-spreading origin of exhumed mantle and the rift-related or oceanic nature of magmatic crust causing the magnetic J anomaly. Different interpretations change the locus of break-up by >100 km and lead to debate of the causative processes. We present the tomographic velocity structure along a 360-km-long seismic profile centered at the J anomaly in the Iberia Abyssal Plain. Rather than delineating an excessive outpouring of magma, the J anomaly occurs over subdued basement. Furthermore, its thin crust shows the characteristic layering of oceanic crust and is juxtaposed to exhumed mantle, marking the onset of magma-starved seafloor spreading, which yields the westward limit of an ~160-km-wide continent–ocean transition zone where continental mantle has been unroofed. This zone is profoundly asymmetric with respect to its conjugate margin, suggesting that the majority of mantle exhumation occurs off Iberia. Because the J anomaly is related to the final break-up and emplacement of oceanic crust, it neither represents synrift magmatism nor defines an isochron, and hence it poorly constrains plate tectonic reconstructions.

THE WEST IBERIA RIFTED MARGIN

The structure of the West Iberia Margin has influenced the creation and development of conceptual models of continental rifting. Dredging and drilling led to the discovery of exhumed mantle next to heavily faulted continental crust, several kilometers thick, in the Deep Galicia Margin offshore of Iberia (Boillot et al., 1980) and triggered further work to characterize the West Iberia Margin basement. Ocean Drilling Program (ODP) leg 173 in the Iberia Abyssal Plain of the West Iberia Margin also sampled exhumed mantle at basement highs (Whitmarsh et al., 1998). Geophysical data allowed extension of the exhumed mantle domain regionally (e.g., Minshull et al., 1998). These findings promoted the non-volcanic or magma-poor rifting model, where continental thinning and break-up is followed by mantle exhumation with little evidence of melting.

The conceptual magma-poor model has been broadly adopted as a template for interpreting the structure and formation processes of other rifted margins, where basement sampling has not been carried out. However, at the West Iberia Margin, there is debate about the presence and significance of magmatism within the exhumed mantle domain of the continent-to-ocean transition (e.g., Whitmarsh et al., 2001; Eddy et al., 2017) and its potential role in the termination of mantle exhumation (Bronner et al., 2011). Furthermore, the debate about the West Iberia Margin involves the location and nature of the onset of seafloor spreading. In the Iberia Abyssal Plain, seismic data were used to propose mantle exhumation across an ~80-km-wide region (Dean et al., 2000) followed by several magnetic lineations that were inferred to originate from seafloor spreading prior to the Cretaceous Magnetic Quiet Zone (Russell and Whitmarsh, 2003). Reevaluation of the same seismic data extended the mantle exhumation across an ~100-km-wide region (Minshull et al., 2014), but the critical segment from mantle exhumation to potential seafloor spreading, across the magnetic J anomaly, has been inadequately investigated with ocean-bottom seismometers (OBSs), up to ~60 km apart (Fig. 1; Fig. S1 in the Supplemental Material[1]). The limited resolution of the seismic data in the Iberia Abyssal Plain has fostered speculation about the structure and nature of the rocks that form the crystalline basement and the processes that governed the continent-to-ocean transition, as well as the first seafloor spreading. For example, the prominent magnetic J anomaly off Iberia may not be oceanic, but rather synrift magmatism (Bronner et al., 2011), and thus it would not mark a seafloor spreading isochron (Nirrengarten et al., 2017).

At the Deep Galicia Bank Margin to the north of the Iberia Abyssal Plain, where the magnetic J anomaly is not present (Fig. S1), modern seismic data are interpreted to indicate that the oldest igneous oceanic crust is a 0.5–1.0-km-thick carapace, only locally present, overlying serpentinized mantle (Davy et al., 2016), but normal oceanic seafloor spreading crust composed of basalts, sheeted dikes, and gabbroic rocks has not been detected. The seismic velocity structure of the Iberia Abyssal Plain–exhumed mantle domain (Minshull et al., 2014) and the anomalous Deep Galicia Margin (Davy et al., 2016) are similar and mimic the seismic structure of oceanic lithosphere emplaced at ultra-slow spreading rates (Grevemeyer et al., 2018a). Therefore, the abyssal plains of the West Iberia Margin may represent ultra-slow spreading lithosphere (Srivastava et al., 2000), and the J anomaly would be a magnetic isochron (Sibuet et al., 2007). Thus, improving our knowledge of the basement structure in the Iberia Abyssal Plain, which crosses all of the rifting process stages from east (old) to

[1]Supplemental Material. Description of methods and supplemental Figures S1–S11. Please visit https://doi.org/10.1130/GEOL.S.18863987 to access the supplemental material, and contact editing@geosociety.org with any questions.

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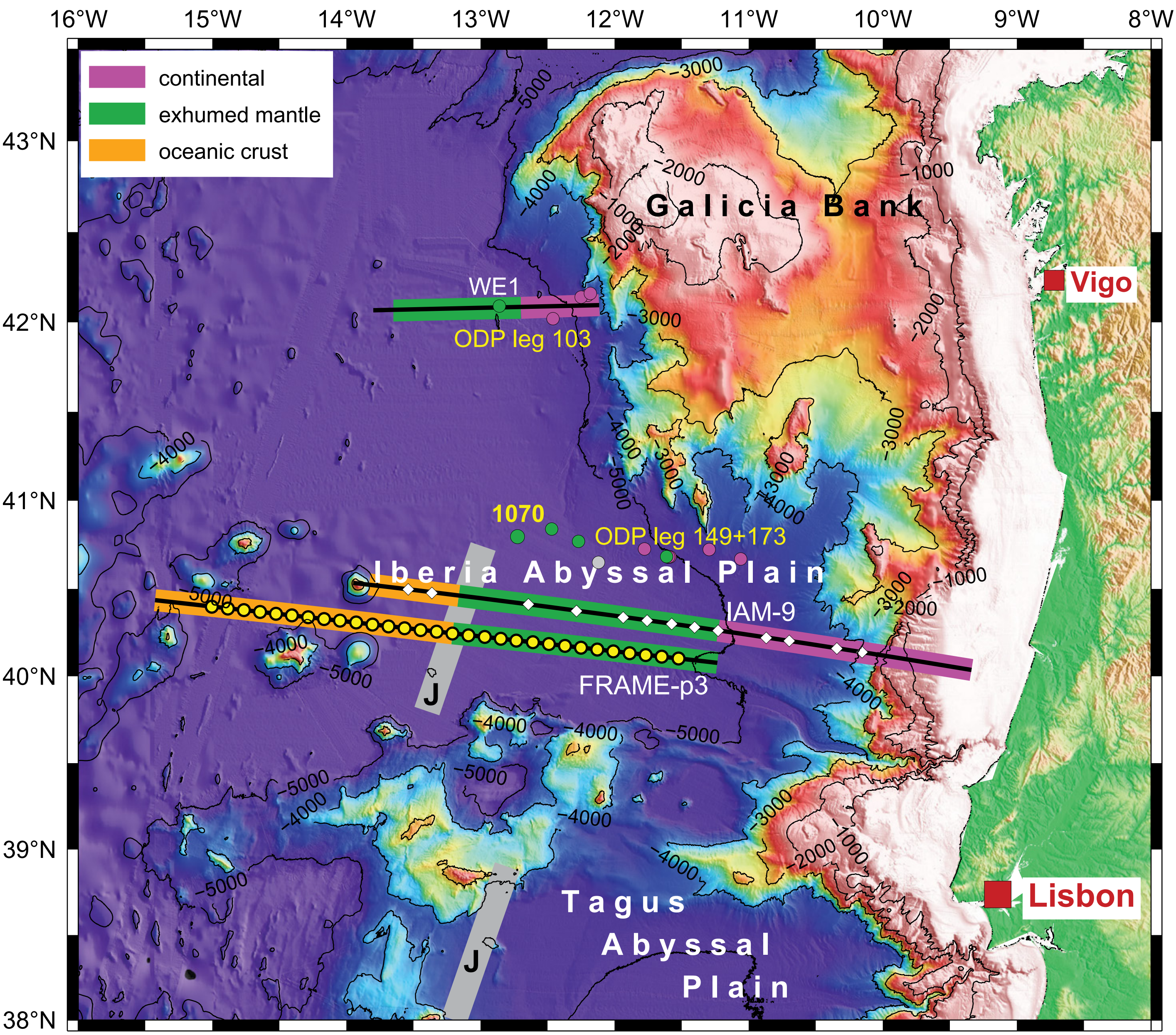

Figure 1. Bathymetric map showing the West Iberia Margin, layout of the wide-angle seismic line FRAME-p3, and geological domains derived from seismic data (IAM9 is our revised interpretation). Yellow circles are seismic stations and black line is shot point track. Wide-angle seismic lines IAM-9 (diamonds indicate seismic stations) in the Iberia Abyssal Plain (Dean et al., 2000) and WE1 in the Deep Galicia Margin (Davy et al., 2016) are discussed in the text. Colored dots are Ocean Drilling Program drill sites (Whitmarsh et al., 1998); Site 1070 is labeled. Gray bars outline the high-amplitude magnetic J anomaly (see Figs. 2B and S1 [see footnote 1] for magnetic field). The domain color coding used here is used in all figures.

west (young), will help to test the accuracy of existing rifting models, the nature of the continent-to-ocean transition, the role of magmatism in the termination of mantle exhumation, the initiation of seafloor spreading, and the validity of the currently inferred structure for plate kinematic reconstructions (Nirrengarten et al., 2018).

We present results from a new wide-angle seismic profile collected in 2018 during the FRAME (Formation of Geological Domains in the Western Iberian Margin and Tectonic Reactivation of their Limit) cruise aboard the Spanish vessel RV *Sarmiento de Gamboa* in the Iberia Abyssal Plain ~20 km south of seismic line IAM-9 (Fig. 1). Thirty (30) ocean-bottom seismometers and hydrophones spaced ~10–12 km apart recorded air gun shots fired along a 360-km-long profile. The profile is centered at the J anomaly and provides improved imaging of the basement seismic structure across the continent-to-ocean transition in the Iberia Abyssal Plain.

SEISMIC VELOCITY STRUCTURE

High-quality records of ocean-bottom seismic data (Figs. S2–S3) were used for seismic mirror imaging (Grion et al., 2007) and a joint wide-angle reflection and refraction travel time tomography along FRAME profile P3 (FRAME-p3) using tomo2D software (Korenaga et al., 2000). Mirror imaging provides the structure of the sediment cover to the top of the basement (Fig. S4), and the tomography provides a P-wave velocity (Vp) model (Fig. 2) and associated uncertainty for the entire crust and uppermost mantle (Figs. S5–S6).

The maximum Vp in the upper 4 km of the basement, and the occurrence of wide-angle, crust/mantle boundary (Moho) reflections, define long-wavelength lateral changes in velocity structure: the western domain has ~6.9 km/s maximum Vp and Moho reflections, and the

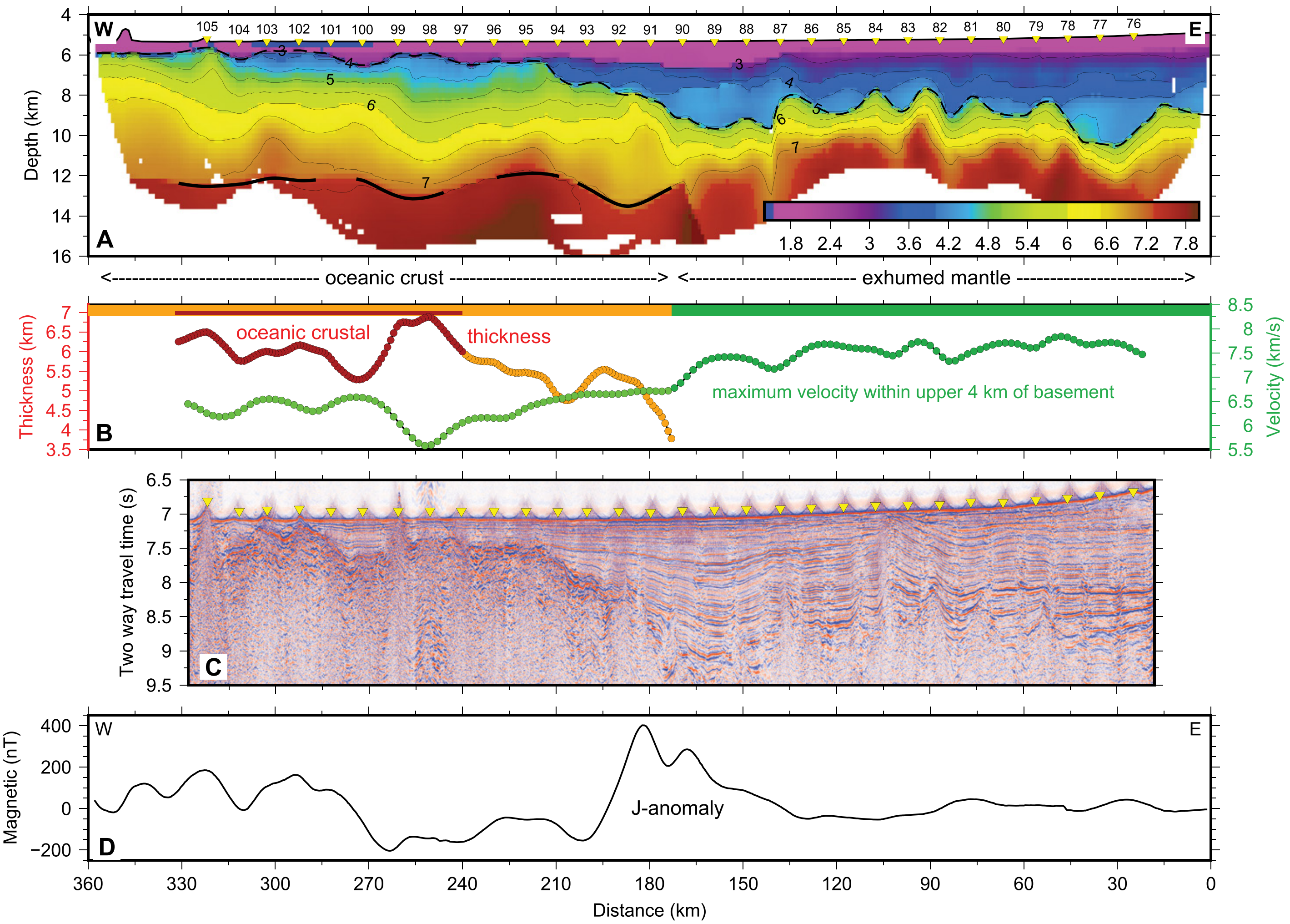

Figure 2. Seismic results. (A) Mean P-wave velocity model; thick black lines at ~12 km depth are seismic Moho segments derived from wide-angle PmP reflections. P-wave velocity model uncertainty analysis is presented in the Supplemental Material (see footnote 1). (B) Maximum seismic velocity (green) in uppermost 4 km of the basement (broken line in A) and crustal thickness (red). (C) Seismic reflection image obtained from mirror imaging. (D) Shipboard magnetic data.

eastern domain has ~7.5 km/s maximum Vp and no Moho boundary (Figs. 2A and 2B). The top of the basement abruptly shoals from the deeper eastern domain to the shallower western domain (Fig. 2C). Shipborne magnetic data shows that the ~30-km-wide peak of the magnetic J anomaly is centered across the eastern edge of the western domain (Fig. 2D), with the anomaly flanking slopes extending west and into the eastern domain. Thus, the J anomaly occurs over a major change of crustal Vp structure and concurrent with the change in top basement relief.

P-wave velocity alone cannot discriminate the nature of crystalline rocks. However, basement lithologies common in deep-water oceanic basins have distinct velocity-depth distributions from the top of the basement to the Moho that provide reference models for comparison with FRAME-p3 (Fig. 3). Gravity modeling, using empirical relationships for Vp-to-density conversion, supports the finding that major heterogeneities occur at <~14 km, and the interpretation of the nature of the crystalline rocks of the basement presented here (Fig. S7).

The Vp-depth relationship in the eastern domain (30–140 km) varies laterally, so that at ~1.6 km beneath the top basement, Vp ranges from 6.0 to 7.3 km/s and at 3.5 km depth Vp ranges from 7.2 to 7.7 km/s (Figs. 2 and 3B). However, Vp increases with depth with similar, comparatively steep gradients from 4.5 to 5 km/s at the top basement, to 6 km/s at ~0.6–1.6 km deeper, and to ~7.3–7.6 km/s at ~1.6–3.1 km from the top basement (Fig. 3B). The lack of wide-angle Moho reflections indicates a gradual increase toward mantle Vp of >7.4 km/s and no seismic boundary marking the base of the crust. The Vp-depth relationship and lack of wide-angle Moho reflections in the eastern domain mimic Vp models of serpentinized peridotite of exhumed mantle measured by modern experiments elsewhere, like in the Tyrrhenian Sea (Prada et al., 2014) or the Cayman Trough (Grevemeyer et al., 2018a) (Fig. 3).

The western domain (180–340 km) Vp-depth structure has a high-gradient upper crust and a low-gradient lower crust, is comparatively slower, and the base of the crust supports wide-angle Moho reflections. We plotted the Vp-depth profiles in two colors to denote two regions: orange lines in Figure 3A display 180–240 km along the line, corresponding to crust formed during the magnetic J anomaly, and red lines show 260–340 km formed during the Cretaceous Magnetic Quiet Zone. The crust accreted during the J anomaly resembles oceanic crust, but it is only 4 to <5.5 km thick (Fig. 3A) and hence thinner than normal oceanic crust (Chen, 1992). The crust thickens westward to 6–7 km in the Cretaceous Magnetic Quiet Zone. There, the line runs between large seamounts (Fig. 1), and the structure may be affected by the younger buildup of seamounts (Merle et al., 2009). The western segment crust from 260–320 km is 6 ± 0.3 km thick and has a classical oceanic crustal structure.

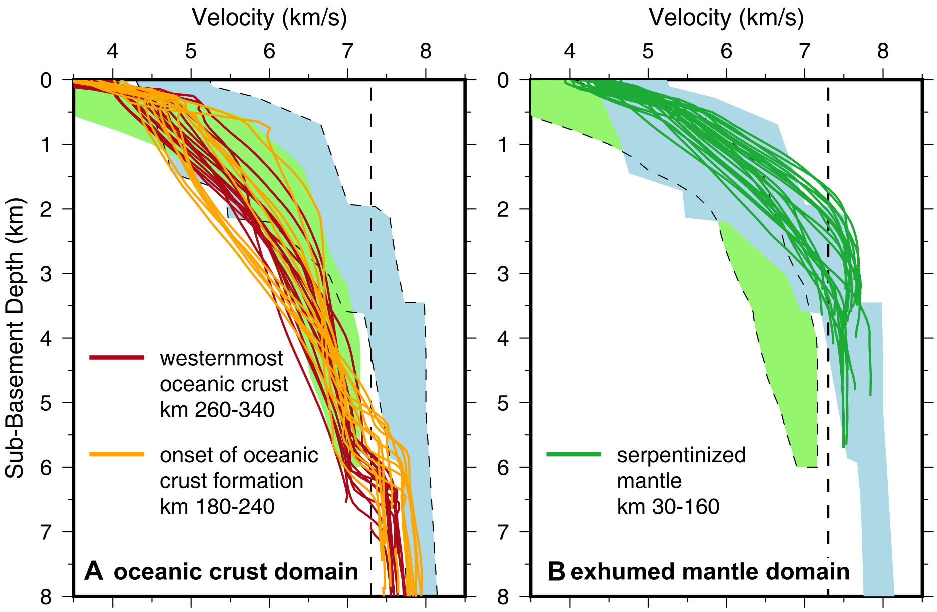

Figure 3. Comparison showing velocity-depth relations within the basement along FRAME (Formation of Geological Domains in the Western Iberian Margin and Tectonic Reactivation of their Limit) profile P3 (FRAME-p3) and velocity-depth reference models for igneous crust formed at the Mid-Atlantic Ridge (green field; after Grevemeyer et al., 2018b) and partially serpentinized, exhumed mantle (blue field; after Prada et al., 2014). (A) Western oceanic crustal domain: orange lines correspond to 180–240 km, which represents oceanic crust that formed during the magnetic J anomaly; red lines correspond to 260–340 km and oceanic crust that formed during the Cretaceous Magnetic Quiet Zone. (B) Exhumed mantle domain: blue lines from 30 km to 160 km overlay the partially serpentinized mantle reference field. Color coding is as in Figures 1 and 2.

DISCUSSION

The FRAME-p3 model indicates that exhumed mantle extends for ~160 km to approximately the J anomaly basement, which disagrees with published studies (Dean et al., 2000; Minshull et al., 2014) of the Iberia Abyssal Plain structure ~20 km to the north based on seismic line IAM-9, but the difference may be related to data resolution. Sparse ray coverage due to OBS spacing along line IAM-9 yields insufficient resolution to determine the oceanic crust-exhumed mantle boundary, and locates it ~50 km (Dean et al., 2000) to ~30 km (Minshull et al., 2014) east of the J anomaly. The basement between the J anomaly and exhumed mantle was inferred to be oceanic and to contain seafloor-spreading magnetic anomalies (Russell and Whitmarsh, 2003, Nirrengarten et al., 2017). To evaluate the velocity model uncertainty of IAM-9, we inverted the traveltime picks of Minshull et al. (2014) using the tomographic procedure of FRAME-p3. The results show that traveltime data are consistent with exhumed mantle also abutting the J anomaly crust along IAM-9 (Fig. S8), although model uncertainty is high (Fig. S9).

Magnetic lineations in the Iberia Abyssal Plain are indistinct in surface magnetic data (Fig. S1) but occur locally in deep-tow magnetic data (Russell and Whitmarsh, 2003). Yet, studies infer that spreading anomalies M1–M5 either related to restricted magmatism (Srivastava et al., 2000; Russell and Whitmarsh, 2003) or serpentinized peridotite ridges (Sibuet et al., 2007) that formed through ultra-slow spreading. However, seafloor-spreading magnetic anomalies on the flanks of the ultra-slow spreading Southwest Indian Ridge (Hosford et al., 2003) and Gakkel Ridge (Gaina et al., 2011) are readily identified. The crustal structure is also different: the Iberia Abyssal Plain basement reveals exhumed mantle with minor evidence of magmatism, whereas ultra-slow crust and lithosphere indicates a different scenario, with spreading flipping between episodic magmatic accretion and mantle exhumation (Grevemeyer et al., 2018a). These differences, including a lack of clear magnetic lineations (Fig. S1), support the interpretation that exhumation at the Iberia Abyssal Plain mostly unroofs cold, continental lithospheric mantle rather than hotter asthenospheric mantle.

The only continuous and regional magnetic lineation of the West Iberia Margin is the high-amplitude J anomaly, yet its origin is controversial. The J anomaly runs along the western regions of the Tagus Abyssal Plain and along the Iberia Abyssal Plain (Fig. 1; Fig. S1). However, the J anomaly was originally defined on oceanic lithosphere of the South American and African plates to the south of the Newfoundland–Azores–Gibraltar paleo-plate boundary (Pitman and Talwani, 1972). There, the J anomaly contains the M0–M4 lineations of the Mesozoic series and occurs on ~12-km-thick voluminous crust of a basement ridge in the South American plate (Tucholke and Ludwig, 1982). On the African plate, the conjugate J anomaly occurs on the basement ridge along the Madeira–Tore Rise (Verhoef et al., 1991), although the rise contains volcanoes that formed at a younger age (Merle et al., 2009).

The J anomaly may extend into the West Iberia Margin (Tucholke and Ludwig, 1982; Russell and Whitmarsh, 2003), but it has been argued that it was not formed by seafloor spreading and is not an isochron, and thus should not be used for kinematic reconstructions (Nirrengarten et al., 2017, 2018). Based on magnetic field modeling, the J anomaly has been associated with a basement ridge of thick crust formed by synrift magmatic underplating and extrusive volcanism on preexisting exhumed mantle (Bronner et al., 2011; Szameitat et al., 2020). In contrast, the FRAME-p3 model shows that the J anomaly actually occurs over subdued basement relief (Figs. 2A and 2C) on 4–5-km-thick crust and that it marks the onset of seafloor spreading. The well-resolved velocity structure shows the characteristic layered structure of oceanic crust with a steep upper gradient and gentle lower crustal gradient, which is similar to the structure of oceanic crust formed at the Mid Atlantic Ridge (Grevemeyer et al., 2018b; Christeson et al., 2019). Thin oceanic crust abruptly abuts exhumed mantle and therefore indicates that break-up in the Iberia Abyssal Plain was associated with modest magmatism at seafloor spreading onset rather than the voluminous synrift magmatism proposed by Bronner et al. (2011), and the seismic structure does not support their model with gabbro underplated under previously exhumed mantle or preexisting oceanic crust. Our new IAM-9 model crust at the J anomaly is 1–1.5 km thicker, but it is close to a tall seamount (Fig. 1) that was emplaced at a younger age (Merle et al., 2009) and might have thickened the basement through magmatic activity after crustal accretion (Fig. S8).

In spite of the up to hundreds of kilometers of uncertainty in plate reconstruction (Neres et al., 2013; Barnett-Moore et al., 2017), seismic line Screech-2 off Newfoundland (Van Avendonk et al., 2006) is usually assumed to provide the structure conjugate to the Iberia Abyssal Plain. Screech-2 structure is strongly asymmetric, with an ~90-km-wide expanse of ultra-thin (thickness <10 km) continental crust (Van Avendonk et al., 2006) compared to the ~30-km-thick continental crust landward of the domain of exhumed mantle in the Iberia Abyssal Plain (Dean et al., 2000). Furthermore, Screech-2 seismic velocity supports <50 km of exhumed mantle pre-J anomaly compared to the ~160 km in the Iberia Abyssal Plain.

The J anomaly is a seafloor-spreading lineation in the Iberia Abyssal Plain that is similar to the conjugate pair of magnetic anomalies in the African and South American plates south of the paleo-plate boundary. To the north of the high-amplitude

J anomaly (Fig. 1; Fig. S1), ODP Site 1070 sampled serpentinized peridotite (Shipboard Scientific Party, 1998) that was intruded by ~124 m.y. old (M0–M1) gabbro veins (Eddy et al., 2017), and the seismic structure of line WE1 (Davy et al., 2016) west of the Galicia Bank (Fig. 1) is similar to that of mantle exhumed in the Iberia Abyssal Plain (Fig. S11). We propose that the onset of seafloor spreading in the Iberia Abyssal Plain was roughly coeval with mantle exhumation to the north from approximately ODP Site 1070 and extended along the Deep Galicia Margin.

In conclusion, the J anomaly marks the abrupt onset of seafloor spreading, bounding the seaward extension of ~160 km of exhumed mantle that is not present in the conjugated Newfoundland margin. Break-up at the Iberia Abyssal Plain occurred by seafloor spreading at about the M0 chron, while mantle exhumation continued to the north. The continent-to-ocean transition structure supports mantle exhumation of cold continental mantle, while the seismic structure and strong magnetic signature of the J anomaly supports melt extraction from asthenospheric mantle and the formation of oceanic crust.

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