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3D seismic characterization of the Peridotite Ridge in the Deep Galicia Margin

by

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ABSTRACT

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In the Galicia magma-poor rifted margin, hyperextended continental crust is separated from oceanic crust by a wide transitional zone of exhumed mantle, which contains a series of margin-parallel basement ridges. The most landward of these, the Peridotite Ridge (PR), has been described for decades as largely devoid of coherent internal structure. Using new 3D seismic data, this study describes a variety of features inside and on the PR, which show it was heavily influenced by mass wasting processes. Its eastern flank contains a series of overlapping lenticular slump blocks, separated from the PR’s core by a large, landward-dipping normal fault. The western flank’s surface contains arcuate fault scarps, and its upper layer is underlined by a potential serpentinization front. Both flanks have large, chaotic landslides at their base. Normal faulting in the post-rift strata overlying the PR correlate with these mass-wasting features, suggesting a likely causal relationship.
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1 INTRODUCTION

The west coast of the Iberian Peninsula (Fig. 1) is a type example of a magma-poor rifted margin, where continental crust was hyperextended and separated slowly enough for the rising mantle to cool and harden, instead of melting (Reston and Manatschal, 2011). As a result, the continental crust of the Galicia and Iberia margins is separated from oceanic crust by a wide transitional zone of exhumed mantle (Fig. 2a), rather than by accreted mafic material (Sibuet et al, 2007). This transitional zone contains a number of margin-parallel basement ridges, the easternmost of which is a series collectively known as the Peridotite Ridge (PR) (Fig. 1). The PR is the only currently-known example of a (mostly) continuous mantle ridge extending hundreds of km across an entire region (Thommeret et al., 1988; Beslier et al., 1993).

Exhumation of mantle peridotite in an extensional setting is not unique to the Galicia margin; other examples include the Alps (Olker et al., 2003), the Pyrenees (de Saint Blanquat et al., 2016), and the island of Zabargad in the Red Sea (Bonatti et al., 1981). However, the Galicia margin is the ideal place to study this phenomenon since the rift is not only fully-developed but also well-preserved, as it is devoid of compressional overprinting from tectonic reactivation (unlike the other examples above). It is also free from magmatic overprinting, shallowly buried (~2 km of sediments in 120 myr), and bounded by oceanic magnetic anomalies that constrain the system’s age and rifting geometry (Sibuet et al., 2007; Tucholke et al., 2007).

As mantle exhumation is thought to be a key component of slow, magma-poor rifting, the study of mantle ridges offers insights into the evolution of these margins. The PR has been seismically imaged and cored in multiple locations, and the resulting studies have described its regional-scale geometry (Thommeret et al., 1998; Beslier et al., 1993; Henning et al., 2004) as well as its core-scale petrology (Boillot et al., 1987; Girardeau et al., 1987, etc.). However, due to the limitations of the previous 2D seismic datasets, little is known about the PR’s three-dimensional morphology or its internal structure. The availability of a new 3D seismic dataset over the Galicia margin, processed through pre-stack time migration by Repsol S.A., offers a valuable opportunity to explore the PR in greater detail and three dimensions. This study characterizes the morphology of the PR and the internal structure of its flanks, in order to understand its post-emplacement evolution.
FIGURE 1. Regional map of the Galicia margin (location shown in inset). Yellow lines indicate the 4 segments of the Peridotite Ridge, as identified by Beslier et al. (1993). This study addresses ridge segment R2, within the bounds of the Galicia3D dataset (red rectangle). Red brackets along ISE line 1 + Western Extension line 1 indicate the range of the cross-section in Fig. 2a.
2 BACKGROUND

2.1 GEOLOGICAL CONTEXT

Passive continental margins begin as rift zones that undergo extension until the onset of seafloor spreading. They are characterized by two general end-members: faster- and slower-spreading margins, as determined by the relative motion of tectonic plates. Faster-spreading margins are generally magmatic, and are thought to have a sharp oceanic-continental boundary. Slower-spreading margins are generally magma-poor, and accommodate extension primarily by faulting, and crustal thinning, resulting in denudation of the isostatically rising mantle (Pérez-Gussinyé et al., 2001).

The northwest coast of the Iberian Peninsula (Fig. 1) is a classic example of such magma-poor margins (Boillot et al. 1988). Offshore, the margin is geographically divided into the Galicia Bank in the north, and the Iberia Abyssal Plain in the south. Both are fruitful study areas for the investigation of passive margins, because their near-lack of magmatic overprinting and their shallow (< 5 km) sedimentary cover make it relatively easy to image deep crustal and mantle features with high-resolution seismic (Clark et al., 2007; Minshull et al., 2014).

The region as a whole is characterized by a broad oceanic-continental transition (Sibuet et al, 2007). A series of tilted, hyperextended crustal blocks gives way to a wide transitional zone of exhumed and serpentinized mantle, beyond which lies the best current candidate for the landward limit of oceanic crust (Alexanian, 2017). Within the latitudes of the Galicia margin (at least), this transitional zone is characterized by a series of margin-parallel basement ridges (Fig. 2a). Several of these were only discovered in the last few years (Dean et al., 2015), but the eastern-most ridge has been known for decades, perhaps because it is 300 km long, rises above the seafloor, and is the closest to land. The best-known feature of its kind until recently, this ridge has been referred to in the literature as “the” Peridotite Ridge (PR) and will be the focus of this study.
2.2 LOCAL SETTING

Fig. 2a shows a regional seismic cross-section of the PR’s geologic setting, as indicated in Fig. 1. The section begins at its eastern extent on the Galicia Bank, a large structural high off the coast of the Iberian Peninsula. To the west, the Galicia Bank gives way to a series of tilted, hyper-extended fault blocks of continental crust and pre-rift sediments. The western half of this set of blocks lies on a prominent feature called the S reflector, which is understood to be a regional detachment fault (Boillot et al., 1989; Zelt et al., 2003, Reston et al., 2007). S dives beneath a basin that separates the last crustal block from the PR, and does not seem to reappear on the other side.

To the west of the PR lies a series of five additional basement ridges, which were imaged in the two Western Extension lines collected with the Galicia3D dataset (WE1 + WE2, Fig. 1). Dean et al. (2015) classified these ridges into two categories: shorter, jagged ridges in the east, and smoother, taller ridges in the west. The composition of the ridges is unknown, but based on these morphological differences, Dean et al. (2015) interpreted the eastern group as oceanic crust and the western group as exhumed mantle (analogous to the PR). According to their study, all of the ridges, including the PR, lack any obvious layering or other internal structures. West of the tallest ridge defined among the “Western Ridges” along the line in Fig. 2a, the basement abruptly loses height and becomes very jagged, based on which Alexanian (2017) speculates this might be the onset of oceanic crust.

The shallow sedimentary section overlies all of these features. It is ~2 km at its thickest, around the PR, and is cut by a network of polygonal faults, as described by Puttock (2015). The stratigraphic framework laid out by Mauffret and Montadert (1988), and refined by Sanjurjo (2016), defines six depositional units in these sediments, beginning with a thin syn-rift package dated to the Hauterivian – Aptian (134 – 113 Ma). The post-rift units then extend from the Aptian-Albian breakup unconformity to present day.
FIGURE 2. (a) Composite cross-section through the Deep Galicia Margin, location indicated by red brackets in Fig. 1. Data compiled from Alexanian (2017), the Galicia3D PSTM volume (introduced later), and the Iberia Seismic Experiment (1997). Syn/post-rift sediments highlighted in yellow. Total section width = 270 km. (b) Close-up of PR and stratigraphic framework of the basin to its east (modified from Sanjurjo, 2016). Purple = syn-rift sediments, per Sanjurjo (2016). (c) Ridge 3a (as described by Dean et al., 2015) from Western Extension line 2. Location of same ridge shown in Fig. 2a.
2.3 PREVIOUS WORK

The presence of a peridotite basement high along the Iberian coast has been known for several decades. Boillot et al. (1980) interpreted “Hill 5100” as a serpentinite diapir, based on dredging samples, magnetic data, and a few early, closely-spaced seismic lines. They also identified the S reflector as the boundary between rigid, faulted upper crust and more ductile, plastically deformed lower crust. Boillot et al. (1980) suggested that S disappears beneath the serpentinite diapir – an interpretation that has since been both supported (Henning et al., 2004) and disputed (Borgmeyer, 2010).

Subsequent seismic acquisition, as well as core samples from Ocean Drilling Program (ODP) Legs 103 and 149, expanded the breadth of available data in support of regional-scale structural interpretations. Boillot et al. (1988) and Boillot et al. (1995) hypothesized that the Galicia margin was shaped by a series of listric faults or high-angle faults (respectively), and identified a fault-bounded basement high overlain by syn-rift sediments on its eastern flank. Thommeret et al. (1988) were the first to map this basement high as a geographically extensive ridge, running parallel to the tilted fault blocks of continental material to the east. Five years later, Beslier et al. (1993) showed that the PR consists of four distinct segments, which they labeled R1-R4 (Fig. 1).

In 1997, the Iberia Seismic Experiment (ISE) collected a regionally extensive 2D seismic dataset across the Galicia and Iberia margins (Fig. 1). Until recently, this dataset offered the best available resolution of the transitional zone in this region, and several studies included interpretations of the Peridotite Ridge. Henning et al. (2004) characterized the PR in all nine east-west ISE lines where it is visible, spanning segments R2 to R3 (Fig. 3). In the north and south, the PR’s segments appear tall and sharp, whereas in the middle they are diminished and difficult to identify. Henning et al. also interpreted a set of continuous, high-amplitude reflectors beneath the PR’s eastern flank, but saw few other internal reflections that would suggest any layering within the ridge.
As in earlier studies, Henning et al. (2004) viewed the PR as the potential lateral boundary between continental and oceanic crust. However, the WE1 and WE2 lines (Fig. 1) collected in 2013 suggest this is not the case. As noted above, these lines extend up to 100 km west of the PR and revealed five new basement ridges, some of which are similar to the PR, but none of the can be confirmed to be oceanic crust (Dean et al., 2015). Both Henning et al. (2004) and Dean et al. (2015) state that the PR is a highly symmetric feature with no clear internal reflections that suggest layering. Both studies also interpret that the S detachment fault terminates east of the PR, and does not reappear to its west.

Several models have been put forth to explain how the PR might have formed. The first is a buoyancy-driven model, as described by Henning et al. (2004), Pérez-Gussinyé (2013), and others. This model holds that localized serpentinization (and therefore density reduction) of the upper mantle by deep, hydrating normal faults can give it enough relative buoyancy to rise to the seafloor (and even pull apart any overlying crustal blocks). A competing explanation is a faulting-

FIGURE 3. Interpretations of the nine ISE lines that cross the PR, modified from Henning et al. (2004). The Galicia3D dataset used in this study roughly spans ISE lines 4 to 2.
driven model, where the PR would link in some way to the S reflector, and would essentially be a fault-modification of a core complex (Tucholke et al., 2008; John and Cheadle, 2010).

A third model was put forth by Sibuet et al. (2007), who proposed that mantle exhumation along the footwall of a downward-concave master fault could produce fractures and horst blocks due to flexural plate bending. Borgmeyer (2010) invoked this model upon interpreting a flat-topped, angular feature inside the PR as a mantle horst block, overlain by landward-dipping sedimentary strata (Fig. 4).

The studies summarized above, as well as others, have described the overall geometry and extent of the PR, its local composition, its geological context, a few internal features, and some ideas regarding its origin. However, due to the limitations of 2D seismic data, they have not addressed the PR’s surface morphology or its evolution after emplacement. The general consensus until now has been that the PR contains little coherent internal structure. Therefore, the objective of this study is to better understand the post-emplacement evolution of the PR, by characterizing its internal structure and surficial morphology using new 3D seismic data. There is also evidence to suggest that the newly discovered ridges lying west of the PR share some of its morphological features (Fig. 2c), so understanding their origin within the context of the PR can inform our understanding of their role throughout the Galicia exhumed mantle domain.

**FIGURE 4.** Uninterpreted (a) and interpreted (b) portion of ISE line 4 where it crosses the PR, after Borgmeyer (2010). Light blue: seafloor. Orange: base of post-rift. Dashed black: interpreted horst block inside PR. Dashed pink: S reflector (per Borgmeyer, 2010).
3 DATA AND METHODS

The Galicia3D multichannel reflection and long-offset seismic survey was conducted in 2013 using the NSF RV Marcus Langseth and RV Poseidon. The 3D seismic dataset spans 20 km (~N-S) by 68 km (~W-E), with an azimuth offset of 2.75° W of N. The data were processed through pre-stack time migration (PSTM) by Repsol S.A. For this study, the data were interpreted in Schlumberger Petrel using a combination of 2D manual picking and 3D auto-picking. The former is necessary when picking steep faults, rough/uneven surfaces, or other irregular boundaries; the latter is faster, but best suited to picking smooth, consistent features like sedimentary horizons or detachment faults. Auto-picked interpretations were verified manually.

The processed Galicia3D dataset contains 800 inlines spaced at 25 m, and 5500 crosslines spaced at 12.5 m. This study analyzed the western half of the full dataset, as noted in Fig. 2a. For vital and/or complex features like the surface of the PR, interpretation was performed on every inline, and every 2-4 crosslines. For smoother features, like sedimentary strata, every 2-4 inlines and every 10-15 crosslines were used. As one of the main advantages of 3D data, a variety of oblique intersections were also used, to offer a strike or dip view of features that may not be oriented exactly parallel / perpendicular to the dataset. Interpretations were verified using the 3D viewing capabilities of Petrel, by looking for spikes (anomalies) in the resulting surfaces.
4 RESULTS

4.1 MORPHOLOGY OF THE PERIDOTITE RIDGE

The 3D surface shown in Fig. 5a represents the base of the post-rift sediments (synonymously, the top of syn-rift basement) in the western part of the Galicia3D volume. The locations of cross-sections shown in other figures are also indicated. In this region, this surface includes the top of the Peridotite Ridge (segment R2, per Beslier et al., 1993; see Fig. 1), at least above 8500 ms TWT.

The PR is tallest (~2 km) and widest (~15 km) in the south, growing shorter and narrower toward the north. Its axis is oriented roughly parallel to the short axis of the seismic survey (azimuth ~3° W of N). The western flank of the PR exhibits several arcuate, scoop-like features (Fig. 5a): two obvious examples lie in the south, along line 14, and another lies in the north along line 8d (between lines 6a and 6b). The eastern flank features two semi-circular, low-relief bulges near its base, with the large lobe in the south and the slightly smaller lobe to its north. The northeast corner of this map view captures the edge of the first large crustal block lying to the east of the PR (see Fig. 2a).

Fig. 5b shows an oblique view of this top-basement surface, looking toward the east. The two scoop-like features on the western flank are even more apparent from this perspective, and a small bump is evident near the base of the northern one. This angle (and the inset, side-on view) also highlights the changes in height of the PR’s peak. Where the PR is tallest, in the south, the peak is well-defined and protrudes above the seafloor (which lies at approx. 7 s TWT). The peak then gradually decreases in height until it flattens out and reaches a “step” (at approx. inline 510) that corresponds to the seafloor (Fig. 8a). After this step, the peak abruptly loses height, and then flattens out again until another, smaller step at approx. inline 725. After this step, the sharp peak gradually breaks down into a flat, jagged plateau in the north.
FIGURE 5. (a) Morphology of the Peridotite Ridge (PR), shown as two-way traveltime to the base of the post-rift sediments. See text for more information about how this is defined. Locations of seismic sections shown in Figs. 6-8 and Figs. 11-14 are indicated. Map area 20 km x 25 km. (b) View of the PR from the west (45° declination). (c) Profile view, looking due east.
4.2 INTERNAL STRUCTURE OF THE PERIDOTITE RIDGE

The internal structure of the PR and its surroundings is well-displayed on cross-sections that span the western third of the Galicia3D volume. Fig. 6 shows four west-to-east inlines, with locations shown in Fig. 5a. These inlines span 25 km, from the distal western flank of the PR to the beginning of the S reflector in the east. Throughout these sections, the post-rift sedimentary column is highlighted in yellow, and the basement is uncolored except to highlight specific features. On average, the sedimentary section is ~1.5-2.0 km thick near the base of the PR’s flanks.

The PR changes size and shape from north to south. In the north (Fig. 6a), the ridge is relatively short, narrow, and trapezoidal. To the south (Fig. 6d) it appears triangular, wider, and taller, protruding up to 500 m above the seafloor. Most of the PR’s reflectivity and discernible structure is concentrated along its flanks. The core (i.e., center) of the ridge, particularly toward the south, is transparent by comparison.

Two prominent reflectors are visible throughout the N-S extent of the volume: one in the east flank (E), and one in the west flank (W). Both are positive-impedance reflectors that dip away from the ridge’s axis, and seem to define the lower boundaries of the more reflective portions of their respective flanks. The two reflectors do not intersect in the south, but they converge northwards as the ridge grows narrower and shorter, ultimately meeting near the top of the ridge at the northern end of the volume (Fig. 6a, Fig. 7a). Borgmeyer (2010) also noted this trend, and interpreted the two reflectors as a single structure on ISE line 4 (Fig. 3).

There are clear differences between Reflectors E and W. Reflector E is very prominent and easy to follow across the entire N-S range of the volume. It begins just below the surface of the eastern flank, and extends to depth eastward toward the S reflector, but without an obvious intersection; S terminates ~5 km east of Reflector E (Fig. 6a). Reflector E gradually loses amplitude with depth, fading out without a clear termination. By contrast, Reflector W consistently begins near the center of the PR, roughly mimics the western slope in shape, and soles into a bowl-shaped basin of high-amplitude discontinuous reflectivity at the base of the western flank. It does not approach the PR’s surface at any point. In these TWTT sections, Reflector W generally has a shallower slope than Reflector E, with the exception of a steep “kink” near the intersection of crossline 8e (Fig. 6a).

**FIGURE 6 (next 2 pages).** Interpreted portions of inlines (a) 850, (b) 590, (c) 375, and (d) 145, ordered from north to south, as indicated in Fig. 5a and on map inset on each section. Shading: blue = water, yellow = post-rift sediments, pink = landslides, other colors = slump blocks inside PR. Reflectors: red = W, yellow = E, green = S, pink/blue = other reflectors inside PR; violet = normal faults in post-rift sediments. Positions of intersecting lines presented in this study shown on horizontal and vertical axes.
The relationship of Reflectors E and W to the three-dimensional morphology is shown in Fig. 7a. As noted above, the two reflectors are separate in the south and converge toward the north, where Reflector W actually “wraps over” the core of the PR, into the eastern flank (Fig. 6a). The differences between Reflectors E and W are even more obvious in 3D view: Reflector W is rough and irregular, similar to the surface of the PR, whereas Reflector E is smooth, steep, and features two prominent undulations oriented parallel to its dip (~10 km wide in the north, ~7 km wide in the south). Eastward, the S reflector is separated from reflector E by a ~5 km gap.

**FIGURE 7.** (a) Oblique view of reflectors W, E, and S, intersected by the northernmost inline (870), looking north. Note the smoothness of Reflector E compared to Reflector W. (b) 3D view of the shallow reflector lying just beneath the surface of the western flank (blue dotted line).
4.3 SHALLOWER FEATURES

Both flanks of the PR display some unique features above reflectors E and W. Another continuous reflector lies just beneath the surface of the western flank above reflector W, as shown in Figs. 6b-6d (blue dotted line). Although not as extensive as reflector W (Fig. 7b), it does exhibit similar scoop-like features described earlier on the surface of the PR (Fig. 5), although they are less pronounced on this surface.

The eastern flank contains an assortment of lens-shaped bodies (Fig. 6a-6c): some rest directly on reflector E (Fig. 6c), some lie on a concave reflector that splays off of reflector E (Fig. 6b, pink dotted line), and some are stacked on other lenses beneath them. All of these features dip downslope, together with the rest of the flank material. Most of them, particularly closer to the center of the ridge, have smooth, well-defined boundaries, and exhibit either fine layering or very low-amplitude (‘transparent’) seismic character. These various lens-shaped bodies will be described further in Section 4.5.

Both the east and west flank feature distinctive, wedge-shaped bodies lying near their bases, directly beneath the overlying sedimentary strata (pink shaded areas, Fig. 6c). In Fig. 6c these two features appear roughly the same size, but the eastern one is really much greater in extent and volume, as shown in Fig. 6d. Both bodies thin upslope, thicken downdip to the basement floor, then gradually thin away from the PR. Unlike the lenticular bodies described in the paragraph above, these surficial features have irregular bases and tops, and their internal seismic texture is chaotic and discontinuous. The eastern wedge is particularly chaotic, lacking any internal layering; although its downdip extent contains some short, discontinuous reflectors inclined toward the PR. The western wedge is characterized by somewhat smoother, more continuous reflectors, at least along line 6c. This line also cuts through one of the scoop-like features located higher upslope (Fig. 5), suggesting a possible relationship between the scoop and the downslope wedge.

The nearly flat-lying, parallel sedimentary strata above the PR exhibit several offset horizons, indicative of normal faulting. Some of these faults intersect the PR above irregularities in its surface, suggesting a possible connection between the flanks of the PR and the overlying sediments. All of these faults dip away from the PR (i.e., westward above the west flank, eastward above the east flank). One of the most obvious features is a fault that appears to extend directly from the intersection of reflector E with the eastern flank (Fig. 6b).
4.4 ALONG-STRIKE FLANK STRUCTURE

Along-strike variations in the internal structure of the PR and its flanks are visible on cross-sections parallel to the ridge. Fig. 8 shows six north-south crosslines, with locations indicated in Fig. 5a: Figs. 8a-8c step down the eastern flank, Figs. 8d-8f step down the west. Fig. 8a lies near the center of the ridge, and thus captures the northeast edge of reflector W, but otherwise shows little structure or internal reflectivity. It does show the pronounced “step” in the PR’s peak coinciding with the seafloor (as mentioned in section 4.1), as well as the smaller step at approx. inline 725.

A cross-line that cuts through the upper eastern flank (Fig. 8b) illustrates the complex spatial relationships of the subsurface bodies introduced earlier. The concave reflector (pink) observed to splay off of Reflector E in Fig. 6b defines the base of a series of overlapping, lens-shaped bodies (Fig. 8b). The undulations on Reflector E are also very evident, due to the steep dip of Reflector E within this portion of the flank, here cut by a vertical plane. For comparison, closer to the base of the eastern flank (Fig. 8c), where the slope of Reflector E is lower, the amplitudes of the undulations are more subdued. Reflector E is also more difficult to interpret consistently across the section here, as it begins to fade with depth. Compared to Fig. 8b, some of the lens-shaped bodies grow larger downslope (blue, red), while others thin out (green, violet).

The crosslines shown in Figs. 8d-8f step down the western flank. Across all three lines, reflector W tracks closely with (and on average ~750 ms below) the surface of the PR. It consistently demarcates a boundary between a highly reflective upper layer and the PR’s non-reflective, transparent core. In Fig. 8d this boundary is slightly less obvious than in Figs. 8e and 8f, since the PR is more homogeneous closer to its center (Fig. 6, Fig. 8a). The shallow (blue) reflector seen in Fig. 6 again tracks closely with the surface (due to its proximity), but its extent shrinks downslope (Fig. 8f).

FIGURE 8 (next 2 pages). Interpreted crosslines (a) 7735, (b) 7935, (c) 8010; (d) 7580, (e) 7480, (f) 7380. Crosslines (a) – (c) step down the eastern flank; (d) – (f) step down the western flank, as indicated in Fig. 5a and the map inset on each panel. Reflectors and shaded regions colored as in Fig. 6. Positions of intersecting lines presented in this study shown on horizontal and vertical axes.
The crossline in Fig. 8d shows the most distinct reflectivity beneath Reflector W; several northward-dipping reflectors appear to terminate against it. This line also captures two of the “scoop” features observed in Figs. 5b and 7b, which appear in cross-section (along strike) as sharp recesses in the PR’s surface (this is more obvious with the southern one). In both cases, a small normal fault extends from the northern side of the recess into the overlying sedimentary column. Reflector W does not seem to mirror the recesses, but the shallow reflector does, perhaps because of its proximity to the surface.

The crossline in Fig. 8e intersects the western flank beneath where reflector W locally becomes much steeper, at least in the north (Figs. 6a-6b). There is significantly less coherent reflectivity beneath Reflector W here (than in Fig. 8d), with the exception of one steep reflector terminating against Reflector W, just south of the intersection with the inline in Fig. 6c. There is a dramatic “step” in the profile of the ridge, but this is a consequence of intersecting the flank at different heights (Fig. 5a). The most unique feature on the crossline in Fig. 8e is the zone of finely-layered, highly continuous reflectors spanning approx. inlines 300 – 650 (middle of the section). North and south of this region, the seismic character again becomes chaotic and discontinuous, but there is no discrete boundary between the two facies. Further down the flank (Fig. 8f), this zone of continuous reflectivity disappears, and the high-amplitude material above Reflector W lacks any discernible structure.

FIGURE 9 (next 2 pages). Interpretations of intersecting sections: (a) Inline 850, crossline 8020, and 45° NW-SE plane between them; (b) Inline 765 and crossline 7940; (c) Inline 850, crossline 8180, and 45° NW-SE plane between them; (d) Inline 850, crossline 8180, and 45° NW-SE plane between them.
4.5 DETAILED STRUCTURE OF THE EASTERN FLANK

As noted above, the eastern flank of the PR contains several overlapping features with well-defined boundaries, but complex shapes and spatial relationships. Figs. 9a-9d provide a more detailed look at these features. These bodies can be categorized into two groups, one to the north, and the other to the south. The two groups also correspond to the two major undulations in reflector E (Fig. 8c, Fig. 9b). Both groups are characterized by a large, wide unit near the surface (shown in orange and pink), underlain by smaller, generally lens-shaped bodies below. The orange body to the north is characterized by closely-spaced sub-parallel reflectors, whereas the shallow pink body to the south is more chaotic. The deeper lenses tend to be more transparent, with little to no discernible internal reflectivity (Figs. 9a-9d).

The more chaotic facies in pink to the south has a jagged, irregular surface. It is thickest near its center, and thins outward toward the northeast (Figs. 9b, 9d), corresponding to a bulge in the basement morphology at the flank’s base (see Fig. 5a or Fig. 6c). By comparison, the surficial unit spanning the northern half of the flank (orange) has a smooth surface, and is very distinctly and finely layered – not unlike the overlying sedimentary strata (Fig. 8b-8c, Fig 9). This layering generally parallels the surface of the PR, although it is deflected above the underlying bodies (Fig. 9b). The unit as a whole is thickest toward the center of the PR, and thins outward toward the northeast (Fig. 9b, 9d).

The boundary between these two shallow units (orange and pink) is difficult to define, in part because the reflective character of the pink unit is quite similar to the underlying material (Fig. 9a-9b). They converge approximately above the along-strike high in reflector E (Fig. 9b). Where they do meet, the pink unit appears to overlie the orange one (Fig. 9b, 9d).

Additional differences are evident between the northern and southern groups of features. In the south, there are few discernible internal structures below the shallow chaotic body. The exception is one lens-shaped feature (shaded red, Fig. 9a-9b) that gradually separates into two lobes downdip (Fig. 8c, Fig. 9a). This feature has smooth, well-defined boundaries, and fine layering similar to the orange unit, especially at the base, particularly when viewed along strike (Fig. 6c, 8c). Southward, this red unit becomes less reflective and difficult to trace. No other reflective bodies stand out in this region.
In contrast, the northern group includes several lenticular bodies, bounded at the base by a large, upward-concave reflector (pink) that appears to splay from Reflector E near the top of the PR (Fig. 6b, pink dashed line). These structures are stacked upon each other in complex arrangements, but their relative positions can be deciphered in 3D (Figs. 8-9). The deepest body (violet) lies up against the southern side of the concave reflector, and is partially overlain by another lens-shaped body to the north (green). Both are overlain by a more extensive but irregularly-shaped feature (blue), and the entire package is capped by the shallow orange unit. All three lenses have a discontinuous but fairly low-amplitude seismic texture – more reflective than the core of the PR, but less than the orange or pink units at the surface.

4.6 TIME-SECTIONS

Horizontal time-sections across the PR intersect both flanks and the adjacent basins, further clarifying the character and context of key features in map view. Fig. 10 shows a series of progressively deeper horizontal time-sections that provide a summary of the characteristics described so far: the PR’s narrowing toward the north, its key reflectors, low-reflectivity center, finely-layered shallower units, and highly reflective outer flanks. The reflective wedges at the base of both flanks are seen to be lobate in map view, consistent with the fan shaped aprons observed in Fig. 5a. Fig. 10 also resolves the spatial relationships between the lens-shaped bodies, showing the stacking arrangements evident in the cross-sections.

Figs. 10c-10d also show the PR’s decreasing reflectivity with depth, and highlight the differences in seismic character between the two sides of the basin separating reflectors E and S. The west side closest to the PR is highly reflective, but mostly chaotic, making it difficult to interpret – while the east exhibits more easily-discernible structures described elsewhere (Jordan, 2016), but with very low amplitudes. The boundary between the two domains is diffuse.

FIGURE 10 (next 2 pages). Horizontal time-sections through the PR and the adjacent basin. (a) 8300 ms, (b) 8700 ms, (c) 9200 ms, (d) 9400 ms. Color shading as in Fig. 6.
4.7 FAULTING IN OVERLYING SEDIMENTARY SECTION

A variety of normal faults occur in the post-rift sediments overlying the PR, some of which were introduced earlier. Of these faults, two groups stand out: those extending above the intersection of reflector E with the PR (Figs. 11-13), and those extending above the sides of the scoop-like features on the western flank (Fig. 14).

The section shown in Fig. 11a cuts obliquely (SW-NE) through the eastern flank of the PR, and highlights a phenomenon also seen in Fig. 6b: the apparent continuation of reflector E, where it offsets the PR’s surface, into the overlying sediments. This can also be seen in the crossline in Fig. 12, where the southernmost fault in the post-rift sediments extends upward from reflector E where it approaches the surface of the PR.

**FIGURE 11.** (a) Interpretation of oblique section shown in inset. Shows an offset in the surface of the PR, and in the overlying sediments, due to a fault above reflector E. Positions of intersecting lines shown on top axis. (b) Horizontal time-section at 7300 ms TWTT (location noted by yellow arrow in (a)). Concentric amplitude variations within the pink domain correspond to local subsidence immediately adjacent to the fault. Yellow line indicates position of (a).
FIGURE 12. Interpretation of part of crossline 7855, cutting through the eastern flank of the PR, showing several normal faults in the post-rift sediments coinciding with concave reflectors inside the PR. The blue, green, and orange lenticular units all lap down onto the pink reflector below. Similar lenticular bodies may lie between the pink and yellow reflectors, but are not clearly traceable on other cross-sections (Fig. 6a-6b). Positions of intersecting lines presented in this study shown on horizontal and vertical axes.

More detailed investigation of this faulted zone reveals that at least five distinct faults occur above Reflector E (Fig. 13). As shown in the inset in Fig. 13, these faults are arranged en echelon, and generally (but not exactly) follow the trend of reflector E. Thus, although there appears to be a correlation between these faults have an en echelon arrangement above reflector E, and generally follow the trend of reflector E. It is clear, however, that reflector E itself does not extend into the post-rift sediments. The faults above Reflector E show greater and more varied offset than others observed within the post-rift sediments, and the strata hosting them contain growth wedges (Fig. 11a). In horizontal time-section (Fig. 11b), the sedimentary reflectors show that subsidence was centered along these faults and decreases radially.
FIGURE 13. Oblique view of the surface of the PR (translucent light gray), viewed from the northeast. The surfaces defining reflector E and the S reflector are shown below. A series of small normal faults (solid colors) intersect or approach the eastern flank of the PR, offsetting the overlying sedimentary strata above reflector E. **Inset:** Blow-up of these faults viewed from the top, showing their en-echelon arrangement. White line indicates the location of section shown in Fig. 11a.
Compared to the faults observed above E, the normal faults above the edges of the scoop-like features on the western flank show far smaller and more consistent offsets (Fig. 14). There are no discernible growth strata adjacent to these, and the maximum offset is miniscule compared to that of the faults above E.

FIGURE 14. Oblique cross-section through the two “scoop” features on the western flank, shown in Fig. 5a. Reflectors and shaded regions colored as in Fig. 6. Positions of intersecting lines shown on top axis.
5 DISCUSSION

5.1 OVERVIEW OF RESULTS

As detailed above, the 3D seismic volume over the Deep Galicia Margin reveals a diversity of structures within the Peridotite Ridge, most never before seen. The relatively transparent core of the ridge is separated from the more reflective flanks by two distinct reflectors, E and W, which underlie the east and west flanks respectively. The flank reflections occur in a variety of geometries (lenses, wedges, diffuse regions) and seismic facies (high amplitude, low amplitude / transparent, parallel/continuous, chaotic/disrupted), but all generally dip downslope away from the ridge, at least in time sections. Several other reflectors are recognized across the ridge, including a concave reflector that appears to “splay off” of E, and a shallow reflector lying just beneath, and approximately parallel to, the west flank’s surface.

Mapping the surface of the PR reveals that it is tall and angular in the southern part of the survey area, but short and more trapezoidal toward the north. This may indicate that the southern end is more intact and preserved, relative to the north, which may have experienced greater deformation. The surface of the PR also reveals several scoop-like features on the western flank. Small normal faults extend from above these scoops, and above the shallow reach of reflector E, into the post-rift sediments overlying the PR.
5.2 ORIGIN OF REFLECTORS E AND W

Reflectors E and W are prominent features within the PR. The two reflectors share some common characteristics: they define the lowest and most notable structures on their respective flanks, are oriented sub-parallel to the flank slopes in our time sections, and they sole out within or beneath the basins on either side of the PR. However, the two reflectors also differ in many respects.

Reflector E is smooth, diverges downward from the east flank of the PR, and appears to offset of the surface where it intersects the eastern flank. Based on these characteristics, we interpret Reflector E to be a large normal fault that cuts the eastern flank of the PR. Its prominent dip-parallel undulations (Fig. 7a) are consistent with this interpretation, as such undulations, also referred to as corrugations or grooves, have been documented on normal faults and core complexes elsewhere (e.g., Ferrill et al., 1999; Granger et al., 2008, Schuba et al., 2018). Reflector E lacks a clear downdip termination, but instead gradually loses amplitude with depth until it becomes indistinguishable from its surroundings. The cause of its disappearance is not clear, but could result from signal attenuation with depth, or from a change in the properties of the fault resulting in a decrease in the acoustic impedance contrast, where it extends into the mantle.

In contrast to reflector E, reflector W has a rougher surface, and its shape more closely mimics the surface of the PR. It does not exhibit any significant grooves, scarps, or other clear morphological features. Unlike reflector E, reflector W does not intersect the surface of the PR. Reflector W terminates beneath a basin to the west of the PR characterized by high-amplitude reflectors, rather than extending deep into the mantle like reflector E. Given these differences, Reflector W does not appear to be a normal fault, as we interpret for reflector E. However, Reflector W clearly demarcates the interface between the western flank’s high-amplitude upper zone and the PR’s relatively transparent core. This raises the possibility that W represents a compositional boundary – potentially, a well-defined serpentinization front.
Serpentinization occurs when peridotite is exposed to water and temperatures of \( \sim 200-600^\circ C \). It is a strongly exothermic \((+250^\circ C)\) process that increases a rock’s volume by up to 40\%, reduces its density from 3.3 to as low as 2.7 g/cc, and largely destroys its preexisting structure (MacDonald and Fyfe, 1985). Generally, serpentinization creates a gradient, since hydration and temperature (its regulating factors) are usually gradients themselves (temperature in particular). However, several studies have interpreted distinct serpentinization fronts, corresponding to the seismic Moho in oceanic lithosphere (Debret et al., 2013; Skelton et al., 2005; Minshull et al., 1998). Debret et al. (2013) described one such front, in the Lanzo massif of the Western Alps, as a sharp transition from slightly (< 20\%) serpentinized peridotites to foliated serpentinites (~100\%) over several decameters. Citing Escartin et al.’s (2001) finding that 15\% serpentinization reduces the strength of altered peridotite to that of pure serpentine, Debret et al. (2013) argue that the 15\% serpentinization horizon should therefore create a mechanical decoupling layer. Lithosphere below this layer would be shielded from further alteration, while the less rheologically competent zone above it would preferentially accommodate further deformation, water circulation, and serpentinization – overwriting the serpentinization gradient, and creating a sharper boundary. Skelton et al. (2005) made a similar argument: the hydrothermal expansion and anisotropic permeability of deforming serpentinite should inhibit further fluid access, making serpentinization spatially self-limiting.

To date, velocity modeling studies of the Galicia3D volume have not detected a sharp boundary within the PR (Bayrakci et al., 2016; Davy et al., 2016), and the general expectation has been that serpentinization in the unroofed mantle decreases gradually with depth (Leythaeuser, 2004). However, the studies described above support the possibility that reflector W represents a distinct serpentinization front. Of course, it seems unlikely that only one side of the PR would have such an alteration boundary, so it is possible that both Reflectors E and W initiated as serpentinization fronts, and that Reflector E then was activated as a major fault. We suggest that both surfaces likely define weak interfaces within the ridge, but normal slip may have initiated along one and not the other, for reasons unknown at this time.
5.3 SERPENTINITE FOLIATION

Another interesting characteristic of the PR is the distinct layering that occurs near the surface of the PR, best developed at the northern end of the eastern flank (Figs. 6a-b, 8b-c, 9b-d, and 10b). In this location, it is observed to wrap over the top of the PR, dipping dominantly in the downslope direction on either flank. On the western flank, this layered package overlies reflector W, and also appears near the middle of the flank (Fig. 8e). On the eastern flank it appears to be cut by fault E, occurring both above and below it depending on location (Figs. 6a-b). Similarly layered material makes up a large, slightly folded unit (orange) which overlies reflector E, running subparallel to the PR along its lower east flank.

The development of foliation during serpentinization, as described above, offers one possible explanation for the origin of such layering. An alternative possibility is that the observed layering is a relict fabric preserved in the uplifted peridotite, e.g., due to mylonitization during shearing within the mantle or during exhumation. Supporting evidence for this origin comes from a core sample taken at IODP Leg 103 Site 637, which penetrated 74 m into the PR’s upper eastern flank, yielding clinopyroxene-bearing spinel harzburgite, > 90% serpentinized, cut by veins of calcite and serpentine (Boillot et al., 1987). Girardeau et al. (1988) noted a strong and consistent downdip (E-NE) foliation with porphyroclastic and mylonitic textures, concluding that after low partial melting, the upper part of the PR experienced plastic deformation in simple shear, at high stress (~180 MPa) but decreasing temperatures (1000°-850°C), probably at depths < 7 km. They suggested that after ductile shearing, the peridotite experienced brittle deformation, which facilitated complete serpentinization and fracturing (Girardeau et al., 1988). These observations may define the closest analog to explain the layering we observe at the seismic scale, supporting the interpretation that the layering (i.e., foliation) formed prior to, or early in, the PR’s uplift.
5.4 MASS WASTING ON THE PERIDOTITE RIDGE

Several features observed within the seismic volume provide evidence for slope failure along the PR. These include the irregular morphology of the PR beneath the post-rift sediments, including scoop-shaped features along the upper western flank, and broad bulges adjacent to the base of the eastern flank (Figs. 5a, 6c). The reflective character of the east flank, in particular, is very variable. As shown in Fig. 9, sharp boundaries separate smooth, lenticular domains stacked on top of each other, distinguished by low-amplitude internal reflectivity defining planar- to broadly-folded layering (green, blue, orange) or more chaotic reflectivity (pink). The abundance of such features suggests a prolonged and diverse history of mass wasting from the PR’s flanks.

The stacking arrangement of the lens-shaped bodies in the eastern flank suggest repeated slope failure events, most resulting in relatively coherent deposits with limited internal deformation. The three deeper bodies (purple, green, and blue) with comparatively transparent internal character are capped by the orange unit, which seems to retain the surface-parallel layering noted on the flanks of the PR (Figs. 9b-d), and thus may have been displaced as a coherent block.

The exception to this pattern is the wedge-shaped body that caps the basement surface of the southern eastern flank (pink), which has a rough, jagged boundary and a high-amplitude, chaotic seismic character (Fig. 6c-6d, Fig. 9, Fig. 10a-10b). This body also has a long ‘tail’ that extends up the slope of the PR (dip view, Fig. 6d; strike view, Fig. 9b). The chaotic unit also features a broad downslope bulge (Fig. 5a), intersected by short inclined reflectors that dip toward the PR. These appear as curvilinear reflections in a time-slice (O’Connor, 2016 – Fig. 15a) and as undulations on the surface of the wedge (Fig. 15b). These pervasive reflectors are interpreted to be thrust faults formed by contraction of the toe of the landslide during downslope transport (see also O’Connor, 2016). The characteristics and dimensions of the pink body contrast with the underlying bodies, suggesting a larger failure, with greater displacement and internal deformation than experienced by the smooth, lens-shaped bodies below it.
FIGURE 15. (a) Horizontal time slice and (b) vertical cross-section of the chaotic MTD at the base of the PR’s eastern flank (modified after O’Connor, 2016). Interpreted thrust faults are shown in red dashed lines. Thin line in (a) shows location of vertical section in (b). (c) 3D surface of the top of this interpreted MTD, with RMS amplitude overlay, highlighting arcuate high-amplitude zones that correspond to the interpreted thrusts shown in (a).

As suggested by O’Connor (2016), all of these characteristics identify the feature as a classic mass-transport deposit (MTD): with upslope extensional, midslope translational, and downslope contractional domains. The analogous wedge-shaped body on the western flank (Fig. 6c) shares these characteristics as well, but is a much smaller feature (Fig. 10b).

The differences between this elongated, chaotic wedge and the smooth, lenticular bodies within the eastern flank suggest a difference in their mode of deformation and displacement. O’Connor (2016), focusing on the former feature, identified it as a slump. However, the seminal mass-wasting classification framework laid out by Varnes (1978) (and subsequently by Cruden and Varnes, 1996) defines slumps as small-offset, rotational displacements along a concave slip
surface, lacking significant internal deformation of the material displaced. Based on our observations, that best describes the deeper, lens-shaped bodies (Fig. 6a-6c, 8b-8c, 10b-10c), not the chaotic wedges lying at the base of each flank. These would be better described as translational landslides, causing far greater displacement and internal deformation.

On the western flank, an apparent correlation exists between one of the upslope scarps and the landslide at its base (Figs. 5b, 6c); we suggest a causal relationship between them, i.e., that slope failure and landsliding created the scoop-like scarps. Why the other scarps lack such well-defined deposits at their base is unclear; perhaps that material was distributed more broadly within the adjacent basin, rather than piling up directly below the source.

The diversity of slumps and landslides observed on both flanks of the PR indicates that mass wasting was a prolonged and morphologically influential phenomenon. At first glance, this may seem surprising, given the rigidity of peridotite and the relatively low slopes of the PR (20-28°, per Henning et al., 2004). However, two factors may account for the long history of slope failure in this setting: tectonic uplift with related faulting, and serpentinization.

The PR is an exposure of mantle rock that has been uplifted relative to the surrounding basins, either by faulting (Tucholke et al., 2008; John and Cheadle, 2010) or buoyancy (Henning et al., 2004; Pérez-Gussinyé, 2013). Such tectonic uplift and associated faulting introduces zones of weakness that may serve as glide planes for subsequent mass wasting events. In particular, the large-scale and repeated landsliding documented along the eastern flank may have accompanied slip on fault E. Earthquakes associated with tectonic uplift could also have triggered slope failure, even in the absence of large faults, possibly accounting for the smaller landslides observed on the western flank.

The other, and perhaps more important factor in the prevalence of mass wasting on the PR is its extensive serpentinization, discussed above. Serpentinization decreases the strength of the original rock, and in conjunction with shear can introduce significant foliation, defining low-
friction surfaces. Mass wasting may have been facilitated by slip along these surfaces. Differences in the degree of serpentinization and foliation development may account for the difference in the amount of mass wasting between the east and west flanks, including the preponderance of smoothly-bounded lenticular geometries in the northeast. As observed in Fig. 6b and Fig. 12, the concave slip surface (pink) on which these lenses lie splays off from fault E near the top of the PR (even the gap between these two surfaces is smooth and lenticular in strike-section – Fig. 12). This suggests that the presence of fault E may have enabled greater hydration of the eastern flank, locally increasing serpentinization and foliation, and promoting the formation of low-friction slip surfaces such as the concave fault. Without a similar hydrating fault like E, the western flank may have experienced less hydration, resulting in less mass wasting.

Similar correlations between serpentinization and mass wasting have been documented elsewhere. Serpentinite seamounts exhibit very similar slope failures and landsliding (Fryer, 1992; Oakley et al., 2007), even though they form through serpentinite diapirism, not tectonic denudation. Bonatti et al. (1973) described sedimentary serpentinites at the Mid-Atlantic Ridge, suggesting that they may have been emplaced by gravity-driven slumping or turbidite transport of serpentinite debris. Cannat et al. (2013) compared mafic and ultramafic slopes within the Mid-Atlantic Ridge’s axial valley, and found that whereas mafic regions had non-cohesive landslides with an average slope of 32°, ultramafic regions had sliding deformable rock masses with an average slope of just 18° (nearly half). They therefore argued that wherever mantle is unroofed by a detachment fault with an emergence angle of > 20°, tectonic and erosional forces will reduce it to < 20° (citing erosional scars cutting through slope-failure blocks, as well as evidence of tectonic slope reactivation). The slopes of the PR in this area are on the order of 20-28° (Henning et al., 2004; Dean et al., 2015), somewhere in the middle of Cannat et al.’s (2013) categorization.
5.5 FAULTING IN THE POST-RIFT SEDIMENTS

As described in section 4.7, several normal faults cut the post-rift sediments above the landslide scarps on the western flank, and above the top of fault E in the eastern flank. Their correlations with faults that cut the PR invites the interpretation that slip may have occurred on the PR faults as recently as the Miocene, based on the stratigraphic framework of Mauffret and Montadert (1988). The landslide deposits, however, are much older, as they are completely buried beneath the oldest post-rift sedimentary strata. Thus, any late-stage slip on the PR faults could only have involved very minor offset.

An alternative explanation for these small-offset faults in the post-rift sediments is differential compaction, which occurs as sediments compact during burial along the slopes of topographic highs such as the PR (Mehl, 1920; Merriam, 1999; Williams, 1987). The faults showing small, uniform offsets above the arcuate scarps on the western flank are consistent with differential compaction, localizing above sharp slope breaks left by previous landslides.

The faults in the sediments above fault E (Fig. 13) could also be a result of differential compaction. However, the small offset in the PR surface at the intersection with fault E suggests another explanation. They may have been caused by later slip on E, or perhaps more likely, on one of the secondary faults that splays off of fault E (such as the pink concave fault in Fig. 12). The faults above fault E are distinguished from the western post-rift faults not only by their larger offsets, but also by the presence of growth strata in their hanging-wall (Fig. 11a), evidence for syn-kinematic deposition. Their en-echelon arrangement suggests that they might have formed sequentially northward or southward, but such a sequence is not clearly decipherable from the offsets in the sedimentary strata.
5.6 SPATIAL AND TEMPORAL RELATIONSHIPS OF MASS WASTING FEATURES

The distribution of mass-wasting deposits along the PR provides some new insights into the processes active on the ridge and their relative timing. First of all, the landslides are deeply buried beneath well-bedded post-rift sediments, indicating that they all occurred prior to the earliest deposition of these sediments. According to the stratigraphic frameworks (Fig. 2b) of Mauffret and Montadert (1988) and Sanjurjo (2016), this constrains major landsliding to have preceded the Hauterivian, approx. 134 Ma. However, as discussed above, some of the post-rift faults above fault E and the western landslide scarp offset sedimentary strata as recent as the Miocene, and some of that movement may have been related to slump reactivation. These two observations suggest that mass wasting on the flanks of the PR has continued over an extended period of time (>100 myr), although the greatest activity was clearly prior to the deposition of the relatively undeformed post-rift strata.

The relative timing of the slumps and landslides can be constrained by their spatial distributions, at least along the eastern flank. The largest and most chaotic of the deposits (pink) is clearly the youngest, defining the broad landslide apron that extends outward from the southern part of the eastern flank (Fig. 10b). As shown in Figs. 9b-c, it also overlies the stack of slump deposits that accumulated at the base of the northern part of the eastern flank. The stacking arrangement of lenticular bodies beneath the pink landslide indicates that the slumps get older in the following order: orange, blue, green, and purple. In the south, the relative age of the deeper (red) slump beneath the pink landslide is not clear, except that it occurs at a similar stratigraphic level above Fault E as the deepest deposits to the north (Figure 9b). To first order, slump size appeared to increase with time, although detailed volumes have not been calculated.

Although our timing constraints are somewhat limited, the quantity and distribution of slumps and landslides suggests that slope failure may have accompanied much of the exhumation and uplift of the PR. That the smaller bodies lie at the bottom of the stack of deposits suggests that the initial slope failures may have been relatively small. Perhaps slump size correlated with the
height of the PR. If so, as the PR rose, larger and more extensive slumps developed, burying earlier ones. There is no clear pattern in the distribution of slumps from north to south, suggesting that PR uplift may have been relatively uniform across the area, or that differential uplift did not strongly influence the mechanisms of slope failure. A more likely factor is the development of fault E and the splay fault above it, which cut through the eastern flank. These structures seem to have served as a detachment surface upon which many of the slumps slid. Fault E’s size, depth, and gradual loss of amplitude with depth suggest that it formed early in the PR’s development, perhaps soling into still-partially-ductile mantle. In addition to accommodating PR uplift and related slope destabilization, active faults such as E and its splay may have served as fluid conduits, locally enhancing the serpentinization of the flank, further weakening the overlying materials, and facilitating slope failure.

This series of inferences leads us to a potential sequence of events to explain the PR’s flank morphology:

1. During or after the PR’s complete uplift, fault E formed, cleaving off the outer section of the PR’s eastern flank. This created a hydration pathway, promoting internal serpentinization.

2. Other smooth, concave faults splayed off of E, cutting the cleaved-off section into lens-shaped slump blocks that slip over and past one another.

3. Landslides on the surface of each flank translated material to the base of each slope, leaving behind arcuate fault scarps. The deformed and displaced material accumulated in fan-like bodies, which experienced compression and thrusting at their distal toe.

4. Sedimentary strata accumulated above the PR. As recently as the Miocene, small periodic displacements continued on slip surfaces in the northeast sector (in this area) of the PR, offsetting the overlying sedimentary strata. Differential compaction above the arcuate fault scarps on the west flank, and elsewhere produced smaller-offset faults.
This model is not definitive. In essence, it posits that the deformation of the PR began near the center of the structure and progressed outward. Although this fits with many of the observations made in this study, an outward progression of deformation would seem to imply that the surface of the PR initially remained intact, while the deeper parts of its flanks were being deformed. This seems counter-intuitive, particularly in light of the fact that serpentinization (requiring hydration and low temperatures) would have been a downward- (or inward-) progressing process in the context of the PR. This may underscore the significance of fault E occurring early in the PR’s development, rapidly hydrating the eastern flank from within.

Finally, it is worth restating that this well-processed, high-resolution seismic volume covers 20 km of a 65-km-long segment of a 250-km long feature. Therefore, any sweeping “north vs. south” or “west vs. east” comparisons — and inferences based on them — should be considered in context. Henning et al. (2004) demonstrated that the morphology of the PR changes dramatically just over the span of segments R2 and R3 (Fig. 3). This study, compared to Borgmeyer’s (2010) interpretation of reflectors E and W as a single feature (Fig. 4), highlights the error of extrapolating too far beyond the limits of a dataset. Future seismic surveys of the PR, and of the ridges to its west, will answer whether or not the mass wasting phenomena observed here are characteristic of the Galicia exhumed mantle domain at large.

Despite the uncertainties in the sequence of events interpreted from the seismic volume over the PR, and questions about how representative it is of the Galicia Margin at large, the data reveal clear evidence of a complex history of mantle uplift and deformation that is well-preserved beneath the post-rift strata. Future studies, including possible ocean drilling expeditions, now have clear targets to pursue to resolve such questions.
6 CONCLUSIONS

The transitional zone between oceanic and continental crust along the Galicia margin is defined by a long, margin-parallel, segmented Peridotite Ridge (PR), thought to represent exhumed mantle. Taking advantage of the recently available Galicia3D PSTM reflection seismic dataset, this study describes a variety of structures and seismic facies within a 20-km section of the PR.

The outer section of the eastern flank is separated from the core of the ridge by a major landward-dipping normal fault, E, which features prominent downslope-dipping undulations ~10 km wide. The depth of fault E, its size, and its potential connection to the regional detachment fault S, among other factors, suggest that it formed during or soon after the PR's uplift.

The material above fault E is cut by smaller, concave faults that splay off of it. These define the basal slip surfaces for a series of overlapping, lenticular, smoothly-bounded rotational slump blocks. These slumps young vertically upward and laterally to the northeast, suggesting that the lowest and southernmost lens detached first, then another just north of it, and finally an irregularly-shaped unit that overlies them. The slump lenses are overlain by a large, finely-layered unit of what may be foliated serpentinites in the north, and by a wide, translational landslide deposit in the south. The landslide has a thin upslope extensional domain and a thick downslope compressional domain, in the form of two fan-like bulges of chaotic material, cut by thrust faults, at the base of the flank. These lie directly beneath the earliest post-rift sediments in this region, placing a lower bound on their age (Hauterivian, 134 Ma). A smaller but similar landslide deposit lies at the base of the western flank, and corresponds to an arcuate, scoop-like fault scarp it likely left behind. Other such scarps, found only on the west flank, do not have a corresponding bulge at their base, for reasons unknown.

The western flank of the PR has its own laterally continuous reflector, W, which separates a discontinuous but highly reflective upper layer from the PR's low-amplitude, mostly structureless core. Unlike E, this reflector is rough, lacks any grooves or lineations, and does not offset (or
approach) the surface of the PR. It is therefore interpreted as a discrete serpentinization front, on which slip was limited or never initiated.

Apart from Reflector W and one other reflector lying just beneath the surface, the west flank is largely devoid of structure compared to the east. The reason for this may have to do with the fact that fault E breaches the surface of the PR, whereas Reflector W does not. By creating a hydration pathway into the eastern flank, fault E would have facilitated serpentinization of the underlying peridotite, which may have weakened the slope, and enabled slope failure. Without a similar hydrating fault, the western flank may have undergone less serpentinization, limiting slope failure.

The post-rift sedimentary strata overlying the PR are cut by a series of normal faults, most of which dip away from the PR. Most of these faults nucleate above irregularities in the PR’s flanks, such as fault E’s offset of the eastern flank and the landslide scarps on the west. The latter, with small consistent offsets, were most likely caused by differential compaction, which is a common phenomenon above basement highs in sedimentary basins. The former, with much greater offset and growth packages in the hanging-wall, may have been formed by recent slip on underlying faults within the PR – whether on fault E or on one of its splay faults.

Mass wasting, likely facilitated by serpentinization, has played a major role in shaping the PR over an extended period of time, probably initiating with mantle exhumation and continuing into the Miocene. Slope failure and mass wasting have shaped the PR over time, and may explain its striking sharpness: it seems plausible that a wider, more ‘domal’ crest of mantle was initially unroofed, and then sharpened through mass wasting into its present shape. The consistent downslope-dipping texture on both flanks of the PR and the large, bowl-shaped basins of chaotic reflectivity on either side of it support this possibility.
REFERENCES


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