1 The unevenness of the north Iberian crustal root, a snapshot
2 of an elusive stage in margin reactivation

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9 **ABSTRACT**

10 Crustal roots are identified in collision chains worldwide. Frequently mirroring
11 the summits of mountain systems, they elegantly encapsulate the concept of isostasy. The
12 rugged topography of northern Iberia results from convergence with the European plate
13 during the Alpine orogeny that formed the Pyrenean-Cantabrian mountain range. From
14 east to west, the range comprises three distinct parts: the Pyrenees, the Basque Cantabrian
15 region, and the Cantabrian Mountains. The identification of the Pyrenean root in the
16 1980s and the observation of a similar geometry beneath the Cantabrian range in the
17 1990s gave place to the current view of crustal thickening as a continuous feature,
18 resulting from the northward subduction of Iberian crust. Recent developments in rift
19 architecture have delivered a complex rifting template for the area prior to convergence,
20 and contrasting views based on two-dimensional restorations have led to a debate over its
21 evolution. A crucial geophysical constraint is Moho topography. Using two different data
22 sets and techniques, we present the most accurate Moho surface to date, evidencing

abrupt changes throughout the orogen. The complexity of hyperextended margins underlies the current Moho topography, and this is ultimately transferred to the nonuniform orogenic pattern found in northern Iberia.

CRUSTAL THICKNESS IN NORTH IBERIA

The physiography of northern Iberia results from its convergence with the European plate during the Alpine orogeny (Teixell et al., 2018, and references therein). From east to west, three differentiated systems can be distinguished: a continental collisional chain, the Pyrenees, which occupies the isthmus between Iberia and Europe; the Basque-Cantabrian Region (BCR), a deep Mesozoic inverted basin facing the Bay of Biscay; and the Cantabrian Mountains (CM), an east-west relief chain with south-directed thrusts onshore, which extend offshore in the form of a shortened continental platform and a well-developed accretionary wedge in the abyssal plain. The three systems constitute a roughly 1000-km-long, westerly trending, complex orogen (Fig. 1).

The ECORS profile (ECORS Pyrenees Team, 1988), a milestone in the seismic exploration of the European crust, provided the iconic image of the >50-km-deep crustal root beneath the Pyrenees. Earlier refraction and wide angle reflection (R/WAR) seismic models imaged the thickening along the axial zone (Gallart et al., 1981). The ECORS line depicted an interwedging of continental crusts, showing a northward bend of the Iberian lower crust protruded by the European plate. The root extends to the western end of the continental isthmus (Chevrot et al., 2014; Wang et al., 2016). When the European continental crust is no longer present, Iberia faces the Bay of Biscay crust. This aborted branch of the Atlantic Ocean opened in the Cretaceous, resulting in the individualization of two hyperextended magma-poor margins (Tugend et al., 2014[Tugend et al., 2014 is

46 **not in the reference list.]]**) with a limited amount of oceanic crust in their central part, a
47 highly thinned crust, and an exhumed mantle. The rift domain template shows a strongly
48 segmented rift, where the proximal domain is limited by the northwest-southeast–
49 trending Ventaniella fault (VF) (Cadenas et al., 2018). To the northeast, an irregular
50 necking domain gives way to westerly trending, hyperthinned, hyperextended areas, and
51 to a relatively rigid block, Le Danois High (Fig. 1), in between. Exhumed mantle
52 domains are common toward the BCR and the Pyrenees. The confluence of the Basque-
53 Cantabrian and the Bay of Biscay coetaneous rift systems occurs through the poorly
54 defined Santander transfer zone (STZ) (Roca et al., 2011; Tugend et al., 2014; Cadenas et
55 al., 2018; Lescoutre and Manatschal, 2020). The Alpine convergence reactivated the
56 southern margin, shortening the bay asymmetrically. Compressional deformation focused
57 on the weakened offshore domains, leading to their underthrusting (Cadenas et al., 2018).
58 At the western end, the oceanic crust initiated its subduction (Álvarez-Marrón et al.,
59 1997).

60 Regardless of those fundamental differences in the previous tectonothermal
61 history of the collision blocks, the images of the Iberian Moho beneath the CM showed a
62 thickening with a geometry similar to that in the Pyrenees (Pulgar et al., 1996). A seismic
63 reflection line, ESCIN-2 (**Estudio Sísmico de la Corteza Ibérica Norte project**), imaged
64 various kilometers of the northward bending of the Iberian lower crust, supporting the
65 lateral continuity of the large structure (Fig. 1). R/WAR-derived velocity models within
66 the BCR reinforced the continuity, despite limited sampling of the root zone (Pedreira et
67 al., 2003). Other geophysical surveys at larger wavelengths did not define the crust-
68 mantle boundary better, and even added ambiguity as a result of often reaching

69 limitations in resolution (Souriau et al., 2008; Chevrot et al., 2014; Diaz et al., 2016;
70 Palomeras et al., 2017). As the alleged thickening occurs around 50 km from the
71 coastline, geophysical data acquired offshore **were** included in this reassessment. The
72 onshore-offshore transition was probed by nonreversed land R/WAR profiles registering
73 marine air-gun shots. These lines, portraying typical passive margin profiles, showed
74 remarkable differences. In the west, crustal thickness varies from 32 km onshore to 20
75 km offshore. In the central section, two reflections with Moho characteristics were
76 imaged with anomalous velocities in the mantle wedge between them, and crustal
77 thickness varies from 45 km inland to 20 km offshore (Fernández-Viejo et al., 1998). The
78 interwedging of the marine and land Moho surfaces is geometrically unsolved and has
79 been interpreted to continue in front of the BCR (Ruiz et al., 2017).

80 The contrasting solutions obtained through evolution models based on two-
81 dimensional (2-D) reconstructions, i.e., Pedreira et al. (2015), Quintana et al. (2015), and
82 Pedrera et al. (2017), have led to quite a heated debate. However, the debate misses the
83 crucial observation that while one group of **researchers** restored the CM section (5°W),
84 the others restored the BCR (2°W), **and** the two sections **are** separated by the STZ in the
85 marine domain. Considering the extreme lateral heterogeneity of the rift system, these
86 solutions cannot really be compared with each other, and their lateral extrapolation is
87 heavily compromised. Orogenic shortening estimates based on the 2-D sections produced
88 values between 30 and 100 km. These reconstructions, based on surface geology, are
89 acceptable for the upper crust, but they face stronger limitations when used to infer
90 lower-crustal geometries (Quintana et al., 2015), where the main constraint is provided
91 by the available Moho data. The ductile component **in** crustal thickening during

compression can be invoked to explain observations, but the scarcity of geophysical input data to restore lower-crustal geometries allows for a great degree of freedom, and the contrasting solutions.

Our study offers a revision of the critical input data set and produces a Moho map with the highest accuracy obtained to date. This gives a reliable constraint for future geodynamical models, and it will hopefully help to focus the debate.

To determine the Moho surface, we first **reappraised** published R/WAR seismic data and integrated them into a new set of Moho points. These were extracted through autocorrelation (AC) procedures for ambient seismic noise acquired by portable seismic stations. The results consistently showed that the thickenings beneath the CM and the Pyrenees appear to be physically disconnected. This outcome implies that the current view of the crustal root as a continuous feature is no longer valid, questioning the lateral continuity of the orogen structure.

METHODS

~~To depict the Moho topography, we used:~~

Reassessment of the R/WAR Data

R/WAR seismic data are one of the most reliable sources for establishing the depth and extent of crustal interfaces, and they provide a first approximation of crustal composition based on the relationship between seismic velocities and lithology. Moreover, unlike other geophysical methods, model resolution is adequate to solve wavelength changes of an interface at the kilometer scale.

We retrieved the original record sections and 2-D models (Córdoba et al., 1987; Ayarza et al., 1998; Fernández-Viejo et al., 1998, 2000; Pedreira et al., 2003; Ruiz et al.,

2017) to analyze the phases and interfaces, and we extracted the segments that confidently sampled the seismic Moho and that fulfilled the following conditions:

- (1) The data showed both PmP and Pn phases (PmP—wide-angle reflection at the Moho; Pn—refraction in the upper mantle).
- (2) The velocity change across the interface was 1 ± 0.2 km/s (a typical crust-mantle boundary contrast).
- (3) The ray coverage sampled at least 10 km of the modeled interface, with interfaces where ray paths illuminated less than this distance being discarded.
- (4) Larger error bars were assigned to interfaces with no Pn, or an unreversed profile.

From the points extracted, we produced an interpolated surface that can be confidently regarded as the crust-mantle boundary (Fig. 2A). The points that fulfilled the above requirements are shown with a depth-dependent color scale. In total, 22% of original data was discarded.

Autocorrelation Functions

The ground motion at a seismic station contains information about the structure in the vicinity of the site, and the reflection response beneath a station can be retrieved by cross-correlating the ambient seismic noise using the same receiver as source and receptor. Recent studies have demonstrated the feasibility of this method to obtain body-wave reflections from the crust-mantle boundary (Tibuleac and von Seggern, 2012). We processed data from 44 stations (Fig. 1) and produced an independent Moho interface (Fig. 2B) (Acevedo et al., 2019). A detailed description of the procedure can be found in the Supplemental Material¹.

DISCUSSION

138 The interfaces obtained by both methods **were** combined to build a three-
139 dimensional (3-D) image of the Moho topography (Fig. 3). The crustal root is constrained
140 to an area of 350 km² that lies between 5.5°W and 4.5°W and extends from the coastline
141 to 43°N. The thickening decreases to the east, increasing again at the Pyrenees. Beneath
142 the CM, the Moho attains a depth of more than 45 km locally, but it diminishes to less
143 than 40 km within the BCR. The Duero Basin and the Galicia Variscan basement fall to
144 30–32 km. Local increases occur toward the Iberian range in the southeast and a small
145 area in the southwest. In Figure 2B, the extent of the surface is limited to the stations'
146 deployment area, but the thick crust remains confined to the same area.

147 Previous crustal depth estimations used the same pool of R/WAR data we
148 reassessed plus receiver functions (Diaz et al., 2016). Others used seismic ambient noise
149 (Chevrot et al., 2014; Palomeras et al., 2017), joint geoid and elevation modeling (Torné
150 et al., 2015), or even estimations of the Curie depth point as a crustal thickness proxy
151 (Andrés et al., 2018). A few imaged a shallowing around the BCR (Torné et al., 2015;
152 Palomeras et al., 2017; Andrés et al., 2018), but none of them openly challenged the
153 continuity. The main reason for not doing so was that these estimations either involved a
154 significant interstation distance and smoothing or a reduced pool of stations compared to
155 the number employed in this study.

156 This revised Moho topography requires us to consider the nature of the crusts
157 involved in the Pyrenean-Cantabrian orogeny at the time of convergence. In the past
158 decade, several studies about rifted margins have produced valuable insights into the
159 nature of their structure and their subsequent reactivation, particularly in the Bay of
160 Biscay (Roca et al., 2011; Tugend et al., 2014; Cadenas et al., 2018; Lescoutre and

161 Manatschal, 2020). At BCR longitudes, and limited to the west by the STZ, the
162 convergence reactivated the hyperextended crust, including the exhumed mantle. These
163 extremely thin domains could be underthrust without producing a major crustal root.
164 This area, considered the junction of the Pyrenean and Cantabrian rift systems, evolved
165 from a particularly complex rift template in two phases (Lescoutre and Manatschal,
166 (2020): first, the underthrusting of the hyperextended domains of Iberia to the north, and,
167 next, the collision of necking domains governed by thick-skinned deformation, which
168 later produced a doubly vergent orogen, **such as that in** the Pyrenees bounded by the
169 North Pyrenean frontal thrust and the South Pyrenean frontal thrust. The North Pyrenean
170 frontal thrust disappears in the STZ, and the compressional front jumps northward 70 km,
171 becoming the **Biscay wedge front**. This jump implies a flip in the direction of
172 underthrusting. This affects the upper plate onshore and the process of crustal thickening;
173 at the longitude of the CM, the rifted crust underthrust the continent to the south. The root
174 is absent west of 5.5°, which is approximately the longitude of the VF (Fig. 3). Crucially,
175 this is **where** the downward-moving, thinned crust presumably encounters the strong
176 Iberian basement, which is barely affected by extension and its associated thermal
177 weakening. As an Alpine structure, the VF partially overprints an outstanding
178 lithospheric boundary, which, in addition to **constituting** a seismological boundary (Fig.
179 3) (Viejo et al., 2014; López-Fernández et al., 2018), corresponds to a major Mesozoic
180 rift structure (López-Gómez et al., 2019). Our data suggest that the extrapolation of
181 steadily diminishing shortening to the west is more complex than previously
182 acknowledged, and a clear rearrangement occurs at the STZ. The local root beneath the
183 eastern CM could either be composed of the underthrust material, and therefore it

could **be** an indenter with delamination of the Iberian lower crust (Gallastegui et al., 2016), **or it could be a response to** ductile lateral transfer of the lower crust from the BCR during compression.

The southward underthrusting continues as far as Galicia, where the involvement of oceanic crust forms an embryonic subduction **zone**. Neither volcanism nor a crustal root is observed onshore, suggesting that the slab did not descend below 60 km (Ayarza et al., 2004). The halting of this incipient subduction coincided with the southward transfer of the strain localization of the Iberian/European plate boundary to the Azores-Gibraltar fracture zone during the Miocene (Roest and Srivastava, 1991).

The convergence across the northern edge of the Iberian plate translates into a different orogenic architecture depending on the crustal inheritance. Where previously hyperextended rift domains are involved, we find tectonic features that are not included in the classic plate-tectonics boundaries of ocean-ocean, ocean-continent, and continent-continent collisions. We propose the concept of the short-lived “hyperextended continental crust convergent boundary.” The formation of this subtype of destructive plate boundary would be favored in compressive microplate scenarios with a young oceanic crust, or in the presence of an exhumed mantle and a limited time lag after hyperextension and reactivation. The tendency of a hyperextended crust to be the locus of plate failure (Lundin and Dore, 2011) means that while present during the earliest stages of the reactivation of margins, it is obliterated when the oceanic lithosphere is dragged into the subduction zone. The interruption of the convergence in north Iberia enabled the preservation of this furtive stage in plate collision evolution.

CONCLUSIONS

Autocorrelation functions from ambient noise seismic data combined with a reappraisal of R/WAR seismic data have allowed us to determine the Moho topography interface in northern Iberia with precision.

Both methods independently imaged a similar result, supporting the validity of using AC to infer the crust-mantle boundary. Collaterally, the combined methods illustrate the importance of restricting velocity-model interpretations to segments that have been sampled confidently regardless of their length.

The crustal root in northern Iberia outside the Pyrenees is essentially limited to the CM, slightly offset toward the coast. The BCR did not undergo enough thickening to produce a crustal root. This may have been related to the extremely thinned crusts on both sides prior to convergence. The new data set encourages a revision of evolutionary models and a refinement of shortening estimates throughout the orogen that used the orogenic root.

The initial reactivation of hyperextended margins constitutes an elusive stage in the destruction of lithosphere that is only produced under favorable conditions. In northern Iberia, the migration of the effective plate boundary to the Azores-Gibraltar fault zone at an early stage allowed the preservation of this ephemeral, but probably not uncommon, convergent architecture.

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FIGURE CAPTIONS

Figure 1. Tectonic map of the Pyrenean-Cantabrian orogen showing refraction and wide angle reflection (R/WAR) profiles and stations used to perform autocorrelation (AC) functions. BWF—Biscay wedge front, STZ—Santander transfer zone, VF—Ventaniella fault, NPFT—North Pyrenean frontal thrust, SPFT—South Pyrenean frontal thrust,

CMF—Cantabrian Mountains front. Inset: Rift domains in Bay of Biscay. **[[Spell out seismic survey names in the caption; e.g., ECORS—Etude de la Croûte Terrestre en France par Méthode Sismique; IAM, etc.]]**
[[Figure edits: In legend, spell out Mesozoic and use American English spelling of Paleozoic.]]

Figure 2. (A) Moho topography after reevaluating refraction and wide angle reflection (R/WAR) data. Circles indicate the subset that complies with the resolution criteria. (B) Moho topography from autocorrelation (AC) results. Circles indicate stations. (C) Example of ACs in four stations. Left panels: Filtered ACs (2–4 Hz) and their envelopes. Right panels: Amplitude-normalized second derivative of envelope. Gray band represents expected time window for Moho reflections based on calculated lag times from previous receiver function (RF, red) and seismic data (R/WAR, blue) determinations (Díaz et al., 2016) ± 1.5 s lag time uncertainty. New identified Moho reflections are dashed black (AC) and green lines (R/WAR). **TWT—two-way traveltime; CM—Cantabrian Mountains; BCR—Basque-Cantabrian Region. See Figure 1 for other abbreviations.**

Figure 3. Views from the (A) south, (B) east, and (C) north of composite 3-D Moho undulations with digital elevation model (DEM) superposed. Red circles indicate seismicity. **[[Please specify coordinate system in the caption.]]**
[[Figure edit: Fix spelling of Refraction in all panels and delete plural 's' in autocorrelation Moho (all panels).]]

385 ¹Supplemental Material. [\[\[Please provide a brief caption here.\]\]](#). Please visit
386 <https://doi.org/10.1130/XXXXXX> to access the supplemental material, and contact
387 editing@geosociety.org with any questions.