AGU PUBLICATIONS

Tectonics

COMMENT
10.1002/2016TC004418

This article is a comment on Barnett-Moore et al. (2016), https://doi.org/10.1002/2015TC004019.

Key Points:
- Paleomagnetic data of Iberia are high-quality, reliable recorders of Iberia's plate kinematic history
- A new Apparent Polar Wander Path for Iberia is provided as key constraint on its plate kinematic history
- Eight independent seismic tomographic models image high seismic velocities around the Reggane anomaly

Supporting Information:
- Supporting Information S1
- Movie S1

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Citation:
van Hinsbergen, D. J. J., Spakman, W., Vissers, R. L. M., & van der Meer, D. G. (2017). Comment on "Assessing discrepancies between previous plate kinematic models of Mesozoic Iberia and their constraints" by Barnett-Moore et al. *Tectonics*, *36*, 3277–3285. https://doi.org/10.1002/2016TC004418

Received 14 NOV 2016
Accepted 9 MAY 2017
Accepted article online 4 NOV 2017
Published online 4 DEC 2017

Comment on "Assessing Discrepancies Between Previous Plate Kinematic Models of Mesozoic Iberia and Their Constraints" by Barnett-Moore Et Al.

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Abstract In their recent paper, Barnett-Moore et al. (2016) reflect on current models of Iberian plate motion in the Jurassic and Cretaceous as well as ongoing debates on the reliability of the various types of kinematic data that form independent constraints on Iberia's motion relative to Eurasia. They question the validity of various marine geophysical, seismic, tomographic, geological, and paleomagnetic data sets from the Bay of Biscay, Central Atlantic Ocean, and Iberia for kinematic reconstruction of Iberia and conclude that neither models invoking Aptian-Albian transtension, nor compression, are consistent with currently available data. An important element in their analysis is that they discard the large paleomagnetic data set from the Jurassic and Cretaceous from Iberia based on perceived limitations of that data set. In addition, they argue that seismic tomographic images exclude a scenario of subduction in the Aptian-Albian in the Pyrenees, and based on this "question the validity of current plate reconstructions, their constraints, and geodynamic scenarios, which are in support of this scenario [e.g., Vissers et al., 2016]." We welcome the discussion raised by Barnett-Moore et al. (2016) on the reliability and usefulness of paleomagnetic data as independent constraint for Iberia's plate motion in the Mesozoic. Taking these paleomagnetic data at face value, Vissers et al. (2016) recently showed that these are consistent with an ~40° counterclockwise rotation of Iberia in the Aptian, requiring up to 500 km of Aptian convergence across the Pyrenees, that is, through subduction. In this comment, we aim to critically assess whether and how the concerns on the quality of paleomagnetic data raised by Barnett-Moore et al. (2016) may allow for an alternative explanation, particularly one with a Mesozoic rotation of Iberia that is small enough so as to not requiring subduction. We also reassess whether seismic tomographic images indeed refute subduction scenarios, using 8 *S* wave and *P* wave tomographic models including those used in Barnett-Moore et al. (2016).

1. Paleomagnetic Data From Stable Iberia

Barnett-Moore et al. (2016) cast doubt on the existing paleomagnetic data from Iberia on the basis of a series of assertions expressed in the following quote: "Recent work highlights crucial limitations surrounding Cretaceous Iberian paleomagnetic data, including a paucity of precise radiometric dates, the low age resolution of sampling, the small number of sites and samples, an absence of conclusive field tests, poorly defined inclination corrections in sedimentary rocks, and unknown paleo-horizontal corrections in the case of igneous rocks (Neres et al., 2012). These authors also point out that the vast majority of Cretaceous paleomagnetic poles used to constrain Iberia are derived from Cretaceous sedimentary rock, which casts doubt on the validity of the poles due to documented remagnetisation associated with sedimentary rocks in several Iberian basins….". In addition, they suggest that "a component of [Iberia's] CCW [i.e. counterclockwise] rotation could be resolved during the absolute plate motions of Iberia, then a part of a larger North America, during Triassic times."

Many of the arguments of Barnett-Moore et al. (2016) are hence adopted from a paper by Neres et al. (2012), who used a very small selection of paleomagnetic data from Iberia, including only six paleomagnetic poles from the critical Upper Jurassic-Lower Cretaceous interval. While some of the limitations perceived by Neres et al. (2012) may have been valid for their limited database, the much larger set of all paleomagnetic data from stable Iberia provided by Vissers et al. (2016) was available to Barnett-Moore et al. (2016), including 39 poles from this critical interval. This database can straightforwardly be viewed and analyzed at www.paleomagnetism.org (Koymans et al., 2016). Quoting the perceived limitations of Neres et al. (2012),

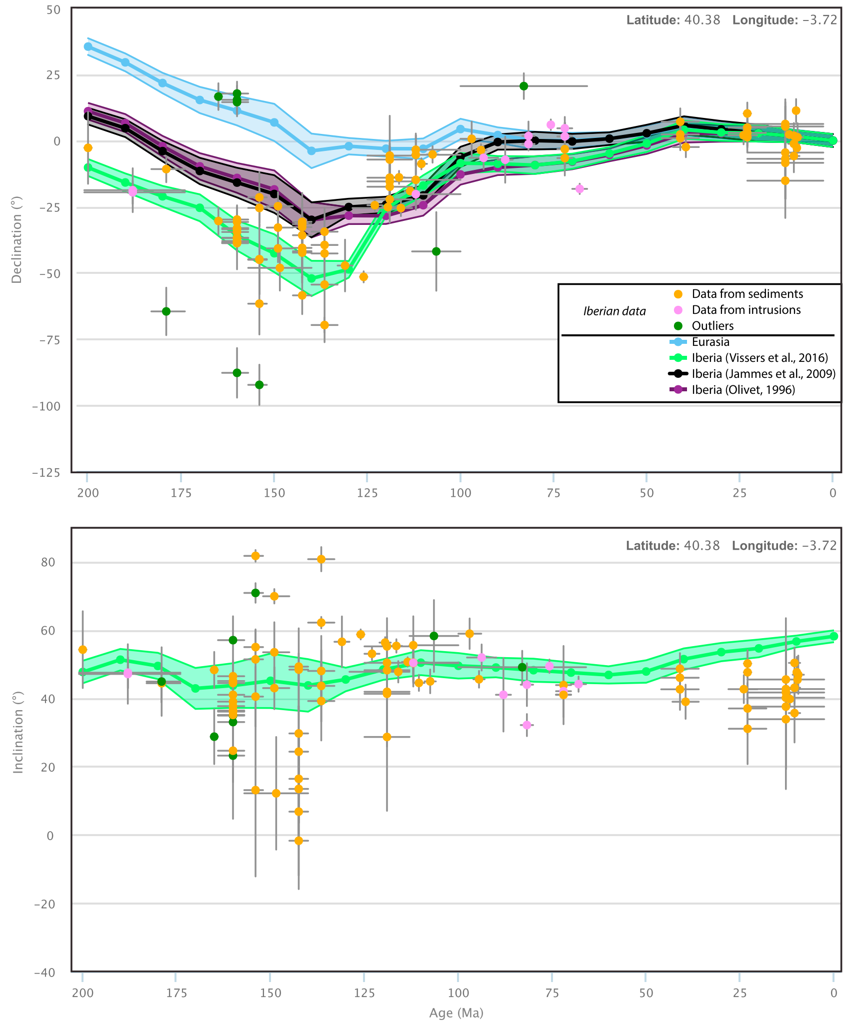

Figure 1. (a) Paleomagnetic declinations and (b) inclinations of Iberia as compiled in Vissers et al. (2016) and provided in their supporting information, compared to declinations predicted by the Global Apparent Polar Wander Path (GAPWaP) of Torsvik et al. (2012) in Eurasian, and Iberian coordinates, using Iberia-Europe rotation scenarios discussed in the text. Plotted on www.paleomagnetism.org (Koymans et al., 2016).

Barnett-Moore et al. (2016) discarded the conclusions of Vissers et al. (2016) without analyzing whether Neres' criticism applied to the much larger database. In this comment, we therefore evaluate one by one to what extent the above-quoted claims for the Iberian data set are valid and whether they allow for alternative explanations of the paleomagnetic measurements that would permit *k* scenarios with Aptian rotations much smaller than ~40°.

To illustrate the discussion below, we provide two figures showing the paleomagnetic constraints from Iberia. Figure 1 displays the paleomagnetic data from all available sites in Iberia. Figure 2 shows two Apparent Polar Wander Paths (APWPs) that we newly calculated for Iberia. These are constructed by a moving average in 10 Myr intervals with a 20 Myr sliding window, similar to the Global Apparent Polar Wander Path (GAPWaP) of Torsvik et al. (2012): one APWP average site averages ($APWP_s$), the other average paleomagnetic directions of those sites, thereby providing the largest weight to the sites constrained by the largest amount of individual directions ($APWP_d$).

In both figures, the predicted declination or inclinations are indicated by the Global Apparent Polar Wander Path (GAPWaP) of Torsvik et al. (2012) in Eurasian coordinates, as well as in coordinates of Iberia using Iberia-Europe Euler poles as inferred from the reconstruction of Vissers et al. (2016), Olivet (1996), and

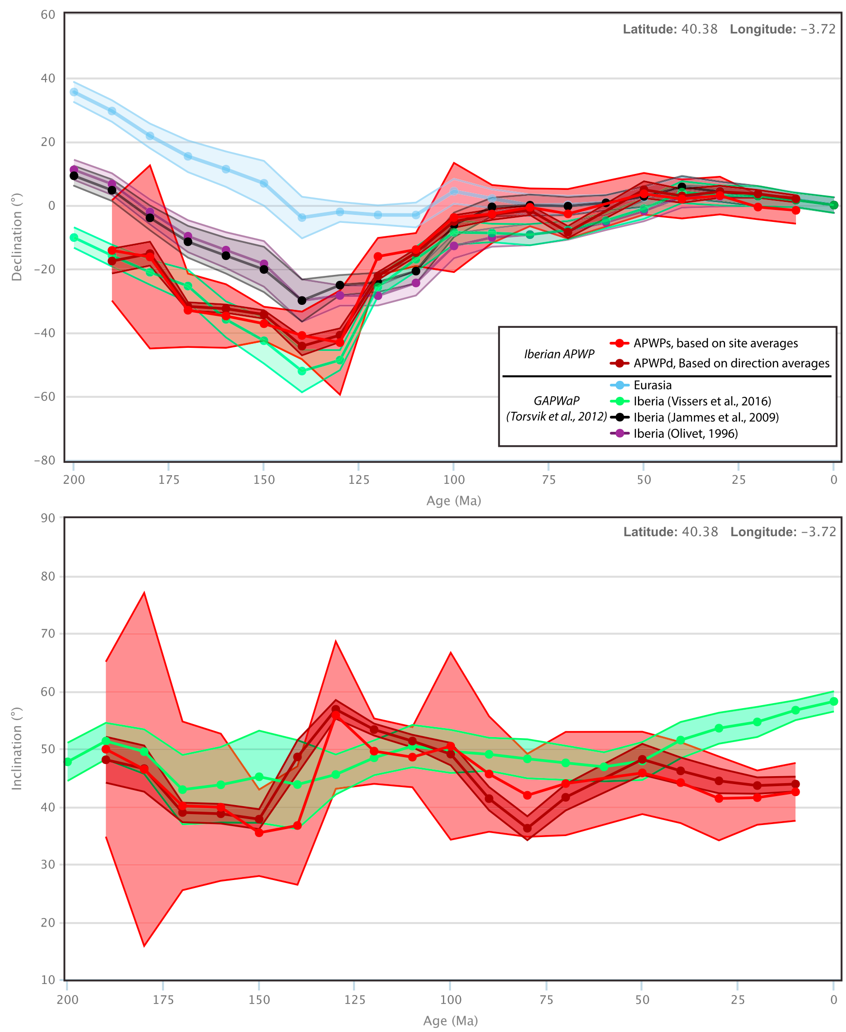

Figure 2. (a) Paleomagnetic declinations and (b) inclinations predicted from the Apparent Polar Wander Paths of Iberia based on sample and direction averages of Iberian paleomagnetic data (see Table 1), plotted against declinations predicted by the Global Apparent Polar Wander Path (GAPWaP) of Torsvik et al. (2012) in Eurasian, and Iberian coordinates, using Iberia-Europe rotation scenarios discussed in the text.

Jammes et al. (2009). The reconstruction of Vissers et al. (2016) involves some ~40° CCW Iberia-Europe rotation and is based on predictions of marine magnetic anomalies from the Central Atlantic Ocean and the Bay of Biscay when interpreted as isochrons (which is challenged, see, e.g., Nirrengarten et al., 2016) and passive margin fits. The reconstruction of Jammes et al. (2009) invokes only ~20° rotation so as to allow for Aptian-Albian plate divergence in the Pyrenees. Below, we discuss the perceived limitations of the Iberian paleomagnetic database as listed in Barnett-Moore et al. (2016):

1.1. A Paucity of Precise Radiometric Dates: The Low Age Resolution of Sampling

Age constraints on paleomagnetic poles, frequently biostratigraphic in nature, are indicated in Figure 1 (and in the plot of Figure 3 of Vissers et al., 2016). Age uncertainties of the paleomagnetic poles demonstrate both sufficient abundance and sufficient age resolution to distinguish between various propositions of Iberian rotation. From this, it follows that the relative absence of precise absolute radiometric dates and the perceived low age resolution of sampling are not crucial limitations. To interpret at most ~20° rotation of Iberia relative to Eurasia (Jammes et al., 2009; Olivet, 1996), the age of Lower and Middle Jurassic sites should have been consistently overestimated, by 10–30 Myr, whereas the bio- and magnetostratigraphic resolutions for the published sites are much better constrained than that (Figure 1) (Gradstein, 2012). For the Upper Jurassic and Lower Cretaceous sites, which are the most critical to determine the timing of rotation, assuming an older or younger age will in all cases increase the amount of Iberian rotation relative to Eurasia. Age uncertainties are thus unlikely to yield a significantly smaller rotation of Iberia allowing for Aptian-Albian extension.

1.2. Small Number of Sites and Samples

The paleomagnetic data compilation of stable Iberia shown in Vissers et al. (2016) (and here in Figure 1) includes results from 28 studies, comprises a total of 99 paleomagnetic poles (most consisting of multiple sites) that are based on a total of 5,668 paleomagnetic directions. The average directions and poles in 10 Myr intervals with a 20 Myr sliding window for Iberia based on these data are constrained in the critical Late Jurassic-Early Cretaceous period (160–120 Ma) by 8 to 26 sites, or 300 to 1,350 paleomagnetic directions per average. For comparison, the GAPWaP of Torsvik et al. (2012) in the same period is constrained by 9 to 28 poles per 10 Myr average. In other words, the Iberian APWP has a statistical power that is equivalent to the global reference against that we test. The argument that the APWP is based on too few sites and samples is thus difficult to defend, and no argument is provided by Barnett-Moore et al. (2016) on how even more data would dramatically shift the APWP in Figure 2.

1.3. Poorly Defined Inclination Corrections

Inclination shallowing is a common feature, particularly in clastic sediments (e.g., Tauxe & Kent, 2004). Shallowing of the inclination due to compaction, however, does not influence the declination, and on a plate as small as Iberia will only marginally influence declinations when transferring the data to a reference point (here Madrid, 40.38°N, 3.72°W, Figure 1). Moreover, there is no systematic shallowing bias in inclinations predicted by $APWP_s$ or $APWP_d$ that are calculated from the carbonate-dominated Jurassic to Cretaceous rocks of Iberia (Figures 1 and 2). Only the paleomagnetic data from Cenozoic, frequently fine-grained clastic rocks that postdate the Iberian rotation, appear to have undergone a significant compaction-induced inclination shallowing (Figure 2). Correcting for inclination errors will therefore not significantly change Vissers et al.'s (2016) conclusions on the Iberian rotation.

1.4. Unknown Paleohorizontal Correction in the Case of Igneous Rocks

A total of 11 of the 99 sites incorporated in the compilation of Vissers et al. (2016) come from intrusive rocks. Nine of these are from the coastal areas of Portugal, all but one postdating the major Aptian rotation of Iberia (violet dots in Figure 1), and all of them are consistent with declinations from sedimentary rocks. Two studies collected samples from the major lowermost Jurassic Messejena dyke that cuts Iberian crust over hundreds of kilometers. The results from this dyke are consistent with the results from Jurassic sedimentary rocks and demonstrate ~40° Iberian rotation. Excluding the data from the Lower Jurassic and Cretaceous intrusive rocks therefore does not change the amount of paleomagnetically required Aptian rotation of Iberia.

1.5. Remagnetization

An important element of paleomagnetic analysis is establishing that the paleomagnetic signal is of primary origin. Barnett-Moore et al. (2016), as well as Neres et al. (2012), argue that "absence of field tests" and "widespread Cretaceous remagnetization" cast doubt on the validity of the poles, citing a series of papers that demonstrated remagnetization. Remagnetized sites identified as such by the original authors have been excluded in the compilation of Vissers et al. (2016). Where field tests are absent, establishing whether a remagnetization occurred is more challenging and can be done based on rock magnetic criteria, as performed by Gong, Langereis, et al. (2008) and Gong, Dekkers, et al. (2008). Remagnetization has been recognized in basins in northern Iberia, not regionally simultaneously, but basin per basin (Gong et al., 2009). These authors actually showed that remagnetization occurred at different times during Iberia's Aptian rotation and that remagnetized directions are also consistent with 35–40° of counterclockwise rotation of Iberia. No remagnetization has been demonstrated for the Cretaceous sites in Portugal that show the same gradual Aptian rotation as the nonremagnetized sites in northern Iberia, and the Middle Jurassic sites, including those used for magnetostratigraphy and hence clearly not remagnetized, unequivocally demonstrate a 35–40° rotation (Figure 1). Finally, it is not clear how a remagnetization could lead to a declination that is considerably *larger* than the original declination and at the same time leave a set of

Table 1
Apparent Polar Wander Paths of Iberia Using Site or Direction Averages

Iberian APWP: Averaging sites				
n	λ	ϕ	A95	Age
13	74.2	181.5	3.8	10
15	73.5	178.0	3.5	20
6	73.2	166.5	5.4	30
4	75.4	169.1	5.5	40
3	76.5	162.3	5.8	50
6	75.2	185.7	7.0	70
8	73.8	178.3	5.4	80
6	76.5	186.7	8.1	90
4	80.3	196.0	14.6	100
16	74.3	226.8	4.5	110
18	73.6	233.9	5.0	120
8	56.3	273.6	13.1	130
17	50.0	248.8	7.0	140
26	52.1	244.2	5.0	150
15	55.8	245.7	9.2	160
12	57.2	244.0	10.6	170
3	71.6	227.8	25.2	180
3	75.0	230.6	13.5	190
Iberian APWP: Averaging samples				
n	λ	ϕ	A95	Age
47	71.8	233.5	3.4	190
108	72.3	225.8	3.3	180
1,328	57.5	241.5	1.2	170
1,289	56.9	242.1	1.2	160
1,356	55.2	243.2	1.2	150
299	52.6	263.6	2.5	140
385	58.4	274.3	1.7	130
769	71.2	253.1	1.0	120
561	75.4	235.9	1.0	110
226	78.8	199.5	1.7	100
317	73.2	185.5	1.5	90
261	69.7	180.4	1.4	80
173	72.1	202.0	1.7	70
293	78.1	155.0	2.3	50
455	76.9	164.6	1.9	40
717	75.3	161.0	1.7	30
1,377	74.8	163.8	1.1	20
1,238	75.2	169.0	1.0	10

Note. The APWP is constructed as a moving average with a 20 Myr sliding window in 10 Myr intervals. n = number or sites or directions; λ = pole latitude, ϕ = pole longitude, and A95 is the Fisher (1953) 95% cone of confidence around the pole.

magnetic polarity reversals in Jurassic rocks consistent with biostratigraphy. Figure 1 clearly shows that the declinations measured in Middle to Upper Jurassic and Lower Cretaceous rocks can only have been acquired if Iberia rotated ~40° relative to Eurasia after the Early Cretaceous. A remagnetization could only have imprinted northerly declinations suggesting smaller rotations.

1.6. Absolute Plate Motion Effects

Finally, Barnett-Moore et al. (2016) argued that part of the counterclockwise rotation of Iberia could be resolved by absolute motion of Iberia and Europe together relative to the spin axis. While such motions have indeed resulted in rotations, as shown in Figures 1 and 2, the relative net declination difference between Iberia and Europe is consistently the same throughout the Jurassic and Early Cretaceous and thus shows a relative rotation between these two continents of approximately 40°: motion of Eurasia relative to the spin axis is thereby taken into account.

In summary, when carefully evaluating the criticism on the quality of paleomagnetic data pertinent to the region as listed by Barnett-Moore et al. (2016), we find that none of these limitations appear to actually apply to the Iberian paleomagnetic data set compiled by Vissers et al. (2016), and we do not see how these limitations would provide a means toward an alternative explanation of the data. Discarding these data based on these perceived limitations is therefore in our view not warranted.

1.7. New APWPs Testing Iberian Rotation Models

The APWPs we calculated for Iberia (Figure 2 and Table 1) can thus serve to test predictions of existing models and may also serve as a basis for an independent model. First, the predicted rotation in the scenario of Vissers et al. (2016) based on (debated) marine magnetic anomaly patterns in the Bay of Biscay and Atlantic Ocean predicts an APWP for Iberia that for the entire Mesozoic is largely within error to $APWP_s$ and $APWP_d$ (Figures 2 and 3). On the other hand, the scenarios of Jammes et al. (2009) and Olivet (1996) are for the entire Late Jurassic-earliest Cretaceous significantly different from, and mispredict, the APWP calculated from Iberian paleomagnetic data by 15–20° (Figures 2 and 3). When taken at face value, the APWP calculated from Iberian paleomagnetic data would suggest that 5–10° of the rotation of Iberia may have occurred between 150 and 130 Ma and that 30–35° rotation occurred during the Aptian. This prediction of the rotation over a larger time interval than the Aptian may, however, be the result of the applied 20 Myr sliding window used to construct the APWP that would smooth the sharp cusp. In any case, the amount of Aptian rotation is significantly more than the 20° angle that exists between the strike of the Pyrenees and the Armorican margin (see Figure 2 in Vissers et al., 2016 or Figure 1 in Barnett-Moore et al., 2016). A rotation exceeding that angle inevitably involved contraction in the Pyrenees during the rotation of Iberia, around an Euler pole in the eastern Bay of Biscay. Shifting that Euler pole eastward to create extension in the Pyrenean realm in the Aptian inevitably leads to overlaps of Iberia and Africa and can be readily excluded. Such limitations on geometry and kinematics dictate that the paleomagnetic constraint requires up to 500 km of subduction in the Pyrenees during the Aptian (Vissers et al., 2016) (Figure 2). We note that reconstructing the rotation of Iberia from paleomagnetic data does not require interpretations of the M0 anomalies (126 Ma) but does predict the alignment of the M0 anomalies and of ocean-continent transitions on either side of the Bay of Biscay as well as the Central Atlantic Ocean (Vissers et al., 2016).

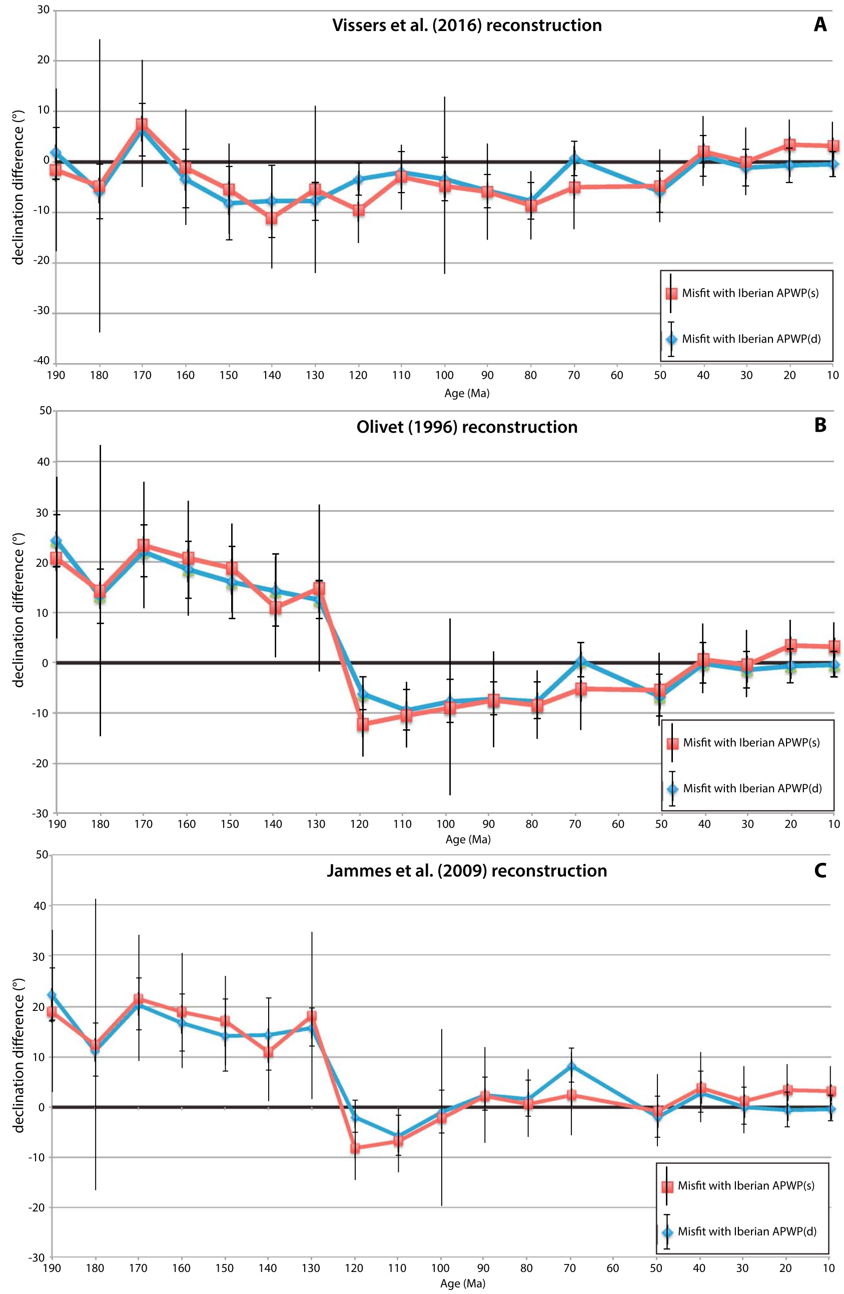

Figure 3. Plots of the misfit between the $APWP_s$ and $APWP_d$ calculated from Iberian paleomagnetic data (Table 1 and Figure 2) and the Global APWP rotated into coordinates of Iberia using reconstructions of (a) Vissers et al. (2016), (b) Olivet (1996), and (c) Jammes et al. (2009). Models B and C would allow for a scenario without Iberian subduction but mispredict Iberian paleomagnetic declinations in the Jurassic and Early Cretaceous by 15–20°. The Pyrenean subduction model (Figure 3a) is consistent with Iberian paleomagnetic observations.

2. Mantle Tomography

Such predicted subduction in the Pyrenees invited our testing against tomographic models in Vissers et al. (2016) and van der Meer et al. (2017), who interpreted a small anomaly in the lower mantle below Algeria as a potential relict of this subduction. Barnett-Moore et al. (2016) show images from four global seismic tomography models of the lower mantle below Northern Africa and conclude there is a "lack of correlation between this and any fast seismic velocity anomaly that could potentially fit the geometric description of the Reggane anomaly (Vissers et al., 2016)" …and "argue that we cannot clearly identify tomographic evidence in support of Cretaceous subduction along the IEPB."

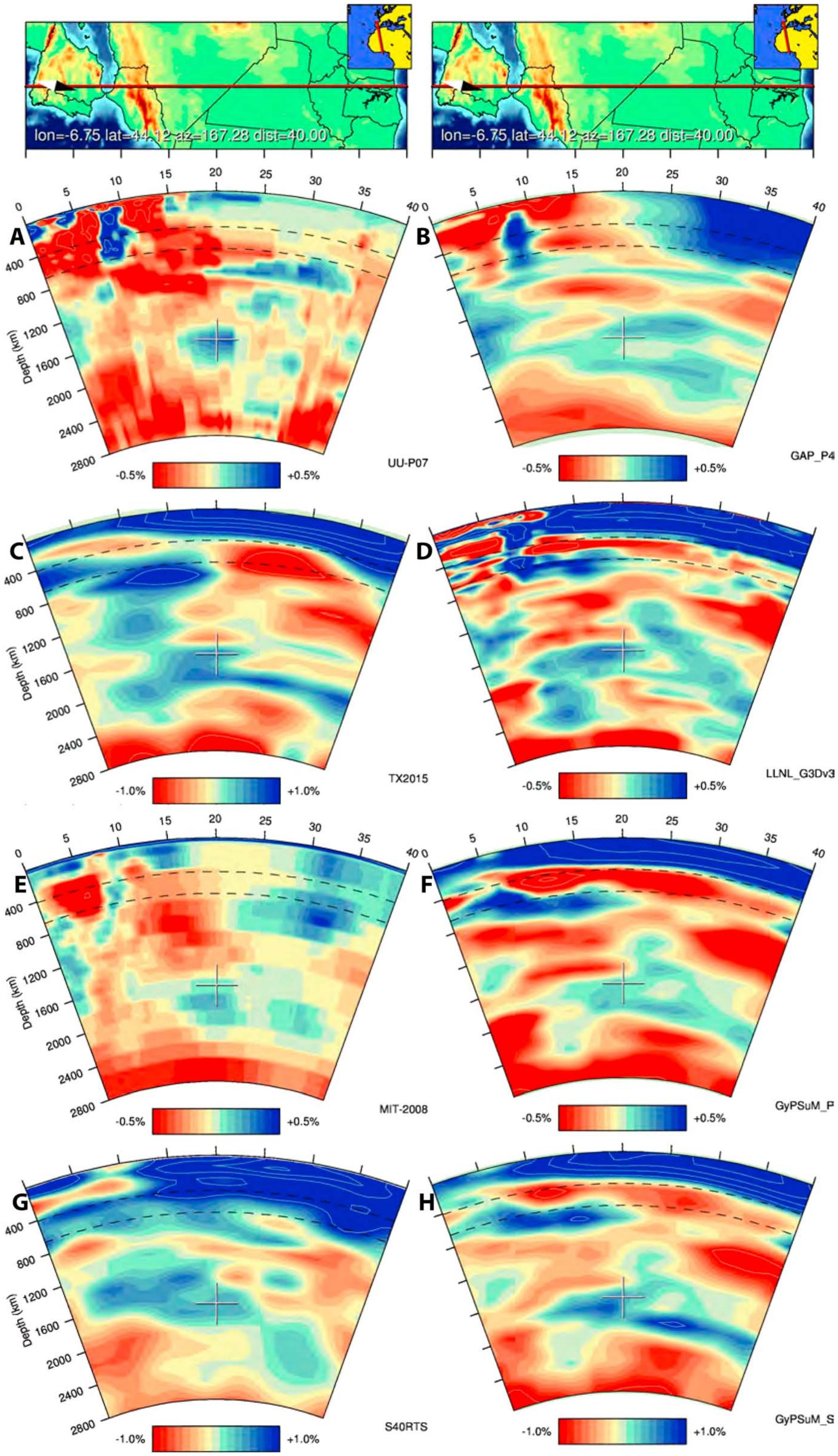

Figure 4. Comparison between eight tomographic models showing all of these image positive seismic wave speed anomalies at the Reggane anomaly identified by Vissers et al. (2016), which they based on the UUP-07 and S40RTS models. Also included are the MIT-2008, GyPSuM-P, and GyPSuM-S models used by Barnett-Moore et al. (2016) to argue against evidence for Aptian subduction in the Pyrenees. The location of the Reggane anomaly is indicated as a cross in all images. Movies of these eight models are available in the supporting information. Models include the following: (a) UU-P07 (Amaru, 2007; van der Meer et al., 2010), (b) GAP-P4 (Obayashi et al., 2013), (c) TX2015 (Lu & Grand, 2016), (d) LLNL-G3Dv3 (Simmons et al., 2012), (e) MIT-2008 (Li et al., 2008), (f) GyPSuM_P (Simmons et al., 2010), (g) S40RTS (Ritsema et al., 2011), and (h) GyPSuM_S (Simmons et al., 2010).

In Figure 4, we show for three of the tomographic models that Barnett-Moore et al. (2016) inspected as well as for five more models that, in contrast to these authors, we have no problem identifying tomographic evidence for positive seismic wave speed anomalies consistent with the Reggane anomaly identified in Vissers et al. (2016) that can result from Cretaceous subduction within the predicted mantle window. Two movies from the tomographic models used in Figure 4 are provided in the supporting information.

To avoid confusion, we clarify the essence of the rationale of Vissers et al. (2016). Previously, Souriau et al. (2008) and Chevrot et al. (2015) argued that absence of a slab in the present-day upper mantle below the Pyrenees would demonstrate that there was no Aptian subduction. First, Vissers et al. (2016) pointed out that one should not look in the upper mantle under the present-day Pyrenees for a detached Cretaceous slab but take the absolute plate motion of Iberia relative to the mantle as well as slab sinking into account. This predicts that such a slab should rather be looked for in the midmantle below northwest Africa—a point Barnett-Moore et al. (2016) agree with. Second, Vissers et al. (2016) aimed to falsify the hypothesis of subduction using seismic tomography. This hypothesis would have been falsified if no positive wave speed anomalies would be present near the predicted depth and near the predicted location. The falsification attempt failed when tested against various tomographic models (Vissers et al., 2016; Figure 4) and section P2 in Figure 4 of Barnett-Moore et al. (2016). The resolution of this "Reggane" anomaly in the UUP07 model was shown sufficient (appendix to Vissers et al., 2016) to detect an anomaly on the scale of the proposed Pyrenees slab but not sufficient to produce a sharp image. Generally, structure in the mantle of northern Africa is rather poorly constrained by seismological data for lack of African seismological stations and occurrence of earthquakes. In support, the Reggane anomaly could also be associated with positive seismic wave *S* wave speed anomalies in the independent tomographic model S40RTS (Ritsema et al., 2011), as shown in the appendix to Vissers et al. (2016). Irrespective of having identified a potential candidate, Vissers et al. (2016) limited their conclusion to the illustrated fact that seismic tomography of the present-day mantle under the Pyrenees, or below northwestern Africa, cannot be used to exclude Aptian subduction in the Pyrenees.

Barnett-Moore et al. (2016) note that not all of the tomography models they tested show the same size and shape of the "Reggane" anomaly, or its connectivity to adjacent anomalies. We first note that tomographic models cannot be readily compared in detail without knowing the spatial resolution of each model. This is why Vissers et al. (2016) limited their analysis to demonstrating that independent tomographic models show positive seismic anomalies at the predicted mantle window. None of the inspected models in Figure 4 exclude subduction in the Pyrenees. We note that due to the different tomographic methodologies, seismological data sets inverted, and model regularization applied, one cannot expect to obtain similar images in a mantle region that is generally poorly sampled (as mentioned above). Not finding an anomaly that corresponds exactly to the physical size of the Cretaceous slab that according to paleomagnetism must have subducted below the Pyrenees is therefore by no means evidence against a subducted slab, and the remnant of Pyrenean subduction would be part of these variably blurred images.

3. Conclusion

Our analysis of limitations of Iberian paleomagnetism as perceived by Barnett-Moore et al. (2016) leads us to conclude that none of these limitations can discard paleomagnetic data. We conclude that Barnett-Moore et al.'s (2016) discarding of the large paleomagnetic data set of Vissers et al. (2016) as input for Iberia reconstructions is insufficiently argued by them. We analyzed these concerns and provide arguments that particularly paleomagnetic data provide a strong and conclusive source of information to constrain the convergence history in the Pyrenees independent from geological or marine magnetic anomaly constraints. If Barnett-Moore et al. (2016) prefer a model without subduction in the Pyrenees, we look forward to their explanation for the significant misfit between small-rotation models that would not require subduction (e.g., Jammes et al., 2009; Olivet, 1996) and the Iberian APWP (Figures 2 and 3).

In addition, we believe that the tomographic data support Vissers et al. (2016) in their conclusion that seismic tomography of the present-day mantle under the Pyrenees, or below northwestern Africa, cannot be used to exclude Aptian subduction in the Pyrenees.

Acknowledgments

D.J.J.v.H. acknowledges ERC starting grant 306810 (SINK) and NWO Vidi grant 864.11.004. W.S. acknowledges support from the Research Council of Norway through its Centers of Excellence funding scheme, project number 223272. The paleomagnetic database used for the construction of Figures 1, 2, and 3 was provided as online appendix to Vissers et al. (2016) and can also be downloaded from www.paleomagnetism.org.

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