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Key Points:
- We image lithospheric cavities beneath the Middle Atlas and central HighAtlas
- We image the delaminated lithosphere of the Middle Atlas at ∼400 km depth
- We propose piecewise delamination of Atlas lithosphere

Supporting Information:
- Supplementary Information Text

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Piecewise delamination of Moroccan lithosphere from beneath the Atlas Mountains

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Abstract The elevation of the intracontinental Atlas Mountains of Morocco and surrounding regions requires a mantle component of buoyancy, and there is consensus that this buoyancy results from an abnormally thin lithosphere. Lithospheric delamination under the Atlas Mountains and thermal erosion caused by upwelling mantle have each been suggested as thinning mechanisms. We use seismic tomography to image the upper mantle of Morocco. Our imaging resolves the location and shape of lithospheric cavities and of delaminated lithosphere ∼400 km beneath the Middle Atlas. We propose discontinuous delamination of an intrinsically unstable Atlas lithosphere, enabled by the presence of anomalously hot mantle, as a mechanism for producing the imaged structures. The Atlas lithosphere was made unstable by a combination of tectonic shortening and eclogite loading during Mesozoic rifting and Cenozoic magmatism. The presence of hot mantle sourced from regional upwellings in northern Africa or the Canary Islands enhanced the instability of this lithosphere. Flow around the retreating Alboran slab focused upwelling mantle under the Middle Atlas, which we infer to be the site of the most recent delamination. The Atlas Mountains of Morocco stand as an example of large-scale lithospheric loss in a mildly contractional orogen.

Introduction

The Atlas Mountains form an intracontinental mountain chain stretching 2000 km from the Atlantic coast in Morocco to the Mediterranean coast in Tunisia (Figure 1b). These mountains are a structural inversion of Triassic-Jurassic grabens created during the opening of the Atlantic and the Alpine Tethys [e.g., *Frizon de Lamotte et al*., 2008, and references therein]. Contraction occurred in two distinct episodes during the Mid-Eocene and Pliocene-Quaternary [*Frizon de Lamotte et al*., 2000] and only produced modest amounts of shortening. Total shortening estimates are of 15–30% for the High Atlas [*Beauchamp et al*., 1999; *Teixell et al*., 2003] and 10% or lower for the Middle Atlas [*Gomez et al*., 1998; *Frizon de Lamotte et al*., 2009; *Teixell et al*., 2009]. Shortening estimates are consistent with the modest elevations found in the eastern Atlas (Saharan and Tunisian Atlas, Aures Mountains, Figure 1b), whereas the elevations in the Moroccan Atlas (High and Middle Atlas) are much higher (Figure 1b). These elevation differences occur in spite of the similar crustal thicknesses of the Moroccan and eastern Atlas, implying that the crust alone is not responsible for the high elevations of the Moroccan Atlas [*Ayarza et al*., 2005]. Additionally, the Moroccan Atlas are flanked by two young upwarps that locally reach elevations of 2000 m without significant Cenozoic deformation: the Moroccan Meseta, and the Anti-Atlas, located on the northern edge of the West African Craton [*Hefferan et al*., 2000; *Ennih and Liégeois*, 2001]. The eastern Atlas have no upwarps of similar magnitude. Given that the Moroccan and eastern Atlas share a common geologic history and crustal thickness [*Frizon de Lamotte et al*., 2009], and that much of the Moroccan Atlas elevation cannot be attributed to crustal tectonics, a mantle component of buoyancy is required to account for the high Moroccan Atlas elevations [*Ayarza et al*., 2005; *Teixell et al*., 2005; *Missenard et al*., 2006; *Frizon de Lamotte et al*., 2009].

Mantle buoyancy beneath the Moroccan Atlas requires a thinned lithosphere. This is consistent with the occurrence of Cenozoic magmatism with an alkaline, intraplate chemical affinity in Morocco that is absent from the eastern Atlas. A first pulse of magmatism occurred in the early Tertiary in eastern Morocco. After a 30 m.y. volcanic pause, this was followed by a significantly larger episode starting in the mid-Miocene (Figure 1a). This second episode was significantly more voluminous and erupted in the Middle Atlas and

Anti-Atlas domains (Figure 1a). Mid-Miocene magmatism also occurred in northeast Morocco (Figure 1a)

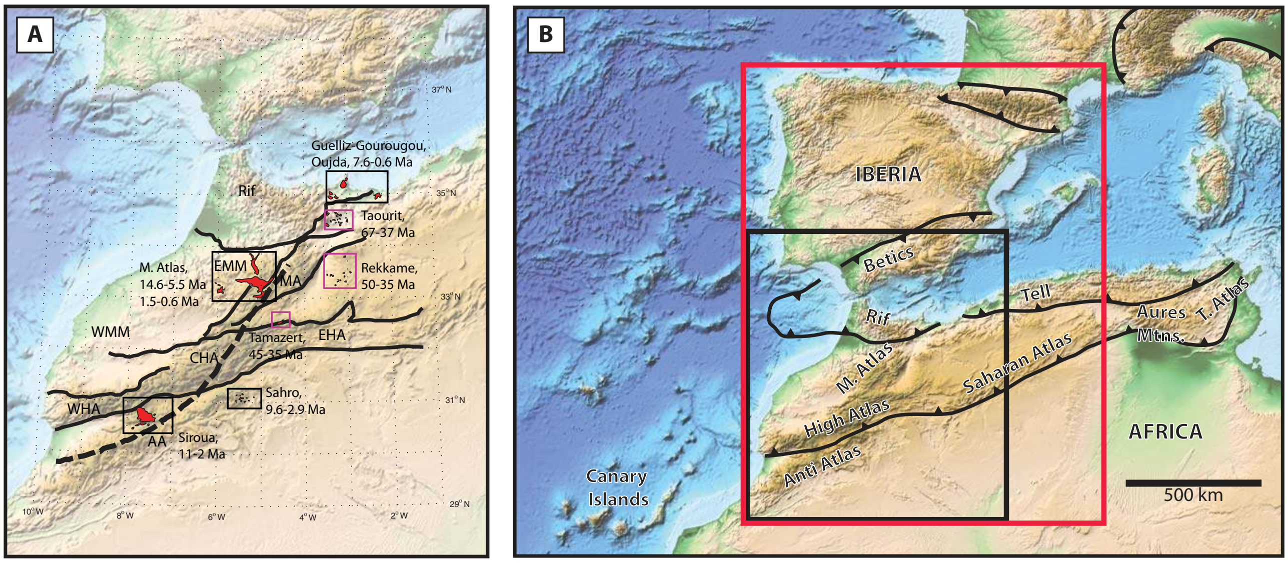

Figure 1. (a) Tectonic provinces and Cenozoic volcanic centers (red polygons) of Morocco that are discussed in the text (redrawn from *Teixell et al*., 2005]. Black and purple rectangles enclose mid-Miocene and Early Tertiary outcrops respectively. Solid lines show the boundary of tectonic provinces, thick dashed line shows the axis of lithospheric thinning as determined by *Missenard et al*. [2006]. WMM––western Moroccan Mesta; EMM––eastern Moroccan Meseta; MA––Middle Atlas; WHA––western High Atlas; CHA––central High Atlas; EHA––eastern High Atlas, AA––Anti-Atlas. (b) Regional map indicating relevant physiographic features. Black rectangle marks the location of Figure 1a as well as of the model slices shown in Figures 3–5. Red rectangle shows the location of Figure 2a.

although these magmas differ by having a chemistry typical of subduction. Both the intraplate and subduction-related magmas have trace element compositions that suggest a mixing of African lithosphere and sublithospheric mantle similar to that of the Canary Islands [*Duggen et al*., 2009].

Geophysical studies that combine geoid, gravity, heat flow, and topography data conclude that a roughly SW-trending elongate zone of lithospheric thinning (the "Morocco Hot Line") lies beneath western Morocco [*Frizon de Lamotte et al*., 2009]. Lithosphere in this zone is thought to be 60–90 km thinner than in surrounding areas [*Zeyen and Fernàndez*, 1994; *Teixell et al*., 2005; *Missenard et al*., 2006; *Fullea et al*., 2010; *Jiménez-Munt et al*., 2011] with the lithosphere-asthenosphere boundary (LAB) reaching depths as shallow as 90 km [*Fullea et al*., 2010] or even 60 km [*Missenard et al*., 2006]. Although estimates of its width and location vary between the different studies, this structure generally crosscuts the WSW-ENE structural trend of the High Atlas Mountains and has a width of 200–500 km. The central High Atlas and the Middle Atlas appear to have a thinner lithosphere than the western High Atlas [*Missenard et al*., 2006; *Fullea et al*., 2010]. These studies conclude that lithospheric thinning is responsible for a third of the elevation in western High Atlas [*Missenard et al*., 2006], most of the elevation in the Anti-Atlas [*Missenard et al*., 2006] and about a half of the elevation in the central High Atlas and Middle Atlas [*Teixell et al*., 2005; *Missenard et al*., 2006].

Fewer studies have explored Moroccan lithospheric structure seismologically. *Seber et al*. [1996] used teleseismic *P*-wave traveltime observations to infer that the lithosphere under the Atlas was abnormally thin, and *Calvert et al*. [2000] imaged a zone of high Sn attenuation and low Pn velocities under the Middle Atlas. A recent detailed surface wave study delineates a NNE-trending low *S*-wave velocity corridor extending under the eastern Moroccan Meseta, the Middle Atlas and central High Atlas [*Palomeras et al*., 2014]. This is interpreted as thin lithosphere with the LAB reaching a minimum depth of $\sim$50 km. In contrast, the lithosphere beneath the western High Atlas and the western Meseta appear not to be thinned. These results are generally in agreement with the gravity studies, although depths to the base of the lithosphere are systematically shallower in the surface wave study [*Palomeras et al*., 2014]. Additionally, mantle anisotropy measured by S and SKS splitting analyses indicates asthenospheric flow localized beneath the Middle Atlas and central High Atlas in a direction parallel to the trend of the mountain chains [*Miller et al*., 2013; *Miller and Becker*, 2014] and SP receiver functions show shallow LAB depths of $\sim$70 km in those same areas [*Miller and Becker*, 2014].

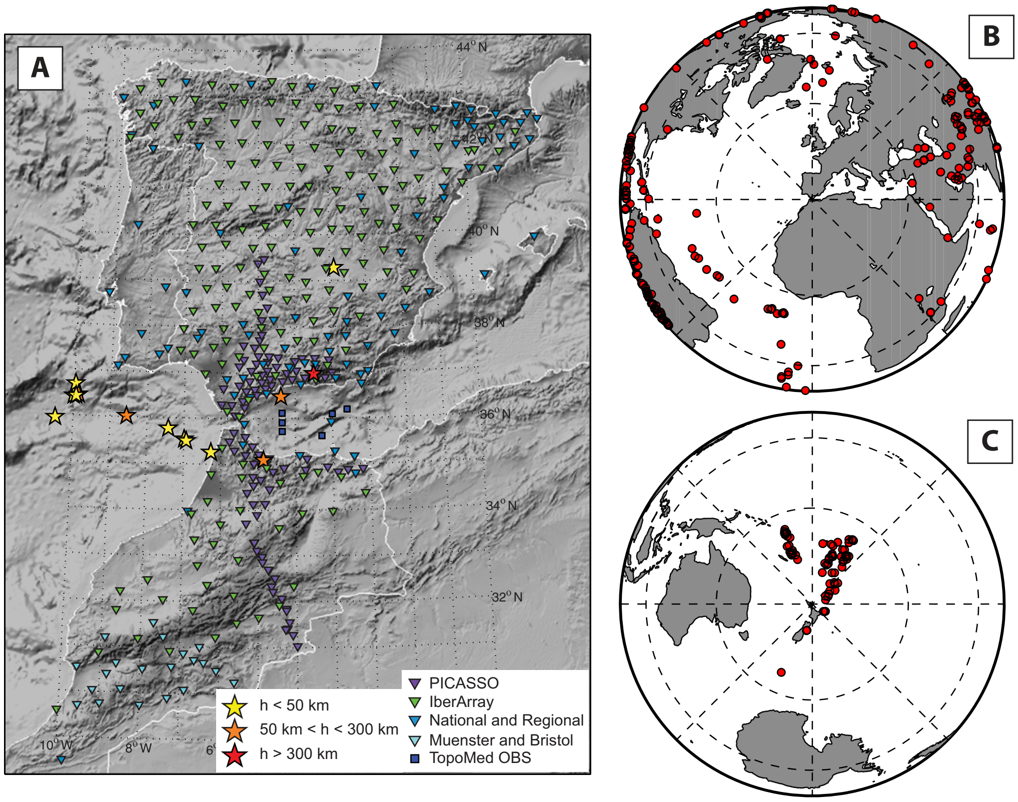

Figure 2. (a) seismic stations used in the study (inverted triangles) as well as local events (stars). Symbol colors represent station network affiliation and event depths as indicated in the legend. Location of teleseismic events used in the study (red circles), note the (b) good azimuthal coverage and (c) abundance of antipodal events.

In order to explain geochemical observations, *Duggen et al*. [2009] proposed that the elongate zone of thinned lithosphere in Morocco acts as a corridor, channeling anomalously hot mantle rising under the Canary plume toward the Mediterranean. In this interpretation, the sublithospheric corridor formed through the delamination of a thick lithospheric root underlying the Moroccan Atlas chain and its formation preceded and enabled inflow of plume mantle. Delamination of Atlas lithosphere is also proposed by *Ramdani* [1998] who cites the occurrence of intermediate-depth earthquakes under the Middle Atlas as additional evidence. We discuss these purported intermediate-depth earthquakes below.

Recognizing the need for mantle support of elevation, but noting that the Moroccan Hot Line trends obliquely to the structural trends, some authors favor a model in which lithospheric thinning results from the thermal erosion caused by a mantle upwelling. A "baby plume" mantle upwelling [*Teixell et al*., 2005; *Missenard et al*., 2006; *Fullea et al*., 2010] and flow caused by edge-driven convection [*Fullea et al*., 2010; *Missenard and Cadoux*, 2012] have each been suggested.

In this paper, we use seismic tomography of the upper mantle to suggest that lithospheric foundering (commonly referred to as delamination regardless of the mechanism) occurred in an irregular fashion beneath the Middle and High Atlas Mountains. We then use the tomography, regional uplift, and volcanic history to conclude that mantle upwelling induced by slab rollback beneath the Alboran Sea generated melt within an anomalously hot asthenosphere, and that this melt invaded the lithosphere and solidified as eclogite, triggering lithosphere delamination beneath the Middle Atlas.

2. Data Set and Method

Our tomography uses data from permanent networks and temporary deployments across the Iberian Peninsula and Morocco (Figure 2) consisting of delays from 398 events recorded over a period of almost 5 years. The data are mostly teleseismic P arrivals augmented with selected local events (Figure 2). Delays were

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determined by cross correlation of waveforms band pass filtered at frequencies of 1.0, 0.5, and 0.3 Hz. Over 76,000 delays were inverted using rays traced iteratively through laterally heterogeneous media, frequency-dependent sensitivity kernels, and damping and smoothing regularization as described in *Bezada et al*. [2013]. Local events were relocated after each iteration using a grid-search approach. Node spacing is 42 km in the interior of the model, increasing to 56 km in its outer edges. The surface wave model of *Palomeras et al*. [2014] served as starting constraint for the upper 150 km of the model: Shear wave velocities were converted to *P*-wave velocities using a constant Vp/Vs ratio and then expressed as anomalies from the mean at each depth. The final model produces a good fit to the data, with final residuals showing a variance reduction of ∼81% with respect to the measured delays.

3. Seismic Anomalies

The dense and extensive station covering (Figure 2a) enables improved imaging constraint. In this paper, we describe features beneath Morocco and avoid discussion of the Alboran slab which is the subject of *Bezada et al*. [2013]. Our velocity model (Figure 3) is an update of the *Bezada et al*. [2013] model that benefits from data recorded by additional stations deployed in that area.

The velocity structure shallower than 90 km is dominated by low-velocity anomalies. The general trend of these anomalies follows the Betics-Rif arc, and continues east to underlie the Guelliz-Gourougou volcanic fields. The Middle Atlas and the central High Atlas are also underlain by slow velocity anomalies. The central High Atlas anomaly is confined to the mountain chain and is visible as far down as ∼120 km depth, whereas the Middle Atlas anomaly has larger amplitudes, extends east under the western Moroccan Meseta, and persists to almost 200 km depth (Figure 3). The Anti-Atlas domain is underlain by neutral to weakly fast velocity anomalies. A slow anomaly is imaged in the SW part of our inversion domain near the Atlantic coast (where resolution is relatively poor), which is prominent at depths greater than 150 km and extends to depths greater than 400 km (Figure 3).

In addition to the very fast Alboran slab, three small, fast anomalies are imaged at depths of 350–450 km, generally under the Middle Atlas region. Two of the anomalies occur beneath the SW and NE ends of the Middle Atlas and a third one below the Atlantic coast of Morocco mostly offshore (Figure 3). A smaller fast anomaly is present deeper in the transition zone (530 km) between the Rif and eastern Moroccan Meseta both of which show weak slow anomalies at these depths (Figure 3).

4. Synthetic Tests

The interpretation of volumetrically small velocity anomalies in teleseismic tomography requires careful consideration. *Bezada et al*. [2013] tentatively interpret the fast anomaly near the top of the transition zone under the middle Atlas as delaminated Atlas lithosphere. To gain confidence on the authenticity of this structure we conduct a synthetic "squeezing" test.

The first step of our squeezing test is to invert the data under the constraint that no positive anomalies exist at depths greater than 200 km, except those directly associated with the Alboran slab (see supporting information for details). The residuals from this inversion contain any delays that can't be explained by the constrained model. These unexplained delays are used as data for a second inversion. If a deep fast anomaly under the Middle Atlas is required by the data, the second inversion should reproduce it.

As expected, in the "squeezed" model there are no positive anomalies between 350 and 450 km depth in the region under the Middle Atlas and Moroccan Meseta (Figure 4). The slow anomalies to the south of the study area at these depths are largely unchanged except for small amplitude and geometry differences.

After inverting the residuals from the squeezed case, the only prominent anomaly at 390 km depth in the resulting model is SW-NE trending fast anomaly (∼1.5%) located under the Middle Atlas (Figure 4). This test indicates the fast velocity anomaly that underlies the Middle Atlas near the top of the mantle transition zone is required in order to fit portions of the data. Given this information and the location of the anomaly in correspondence with important surface and subsurface features, we conclude that this is a real feature and not an artifact created by the inversion.

The slow velocities surrounding the Alboran slab are a prominent feature in our model. Since slow rims around fast anomalies are a common artifact of seismic tomography inversions, we verify that this is not

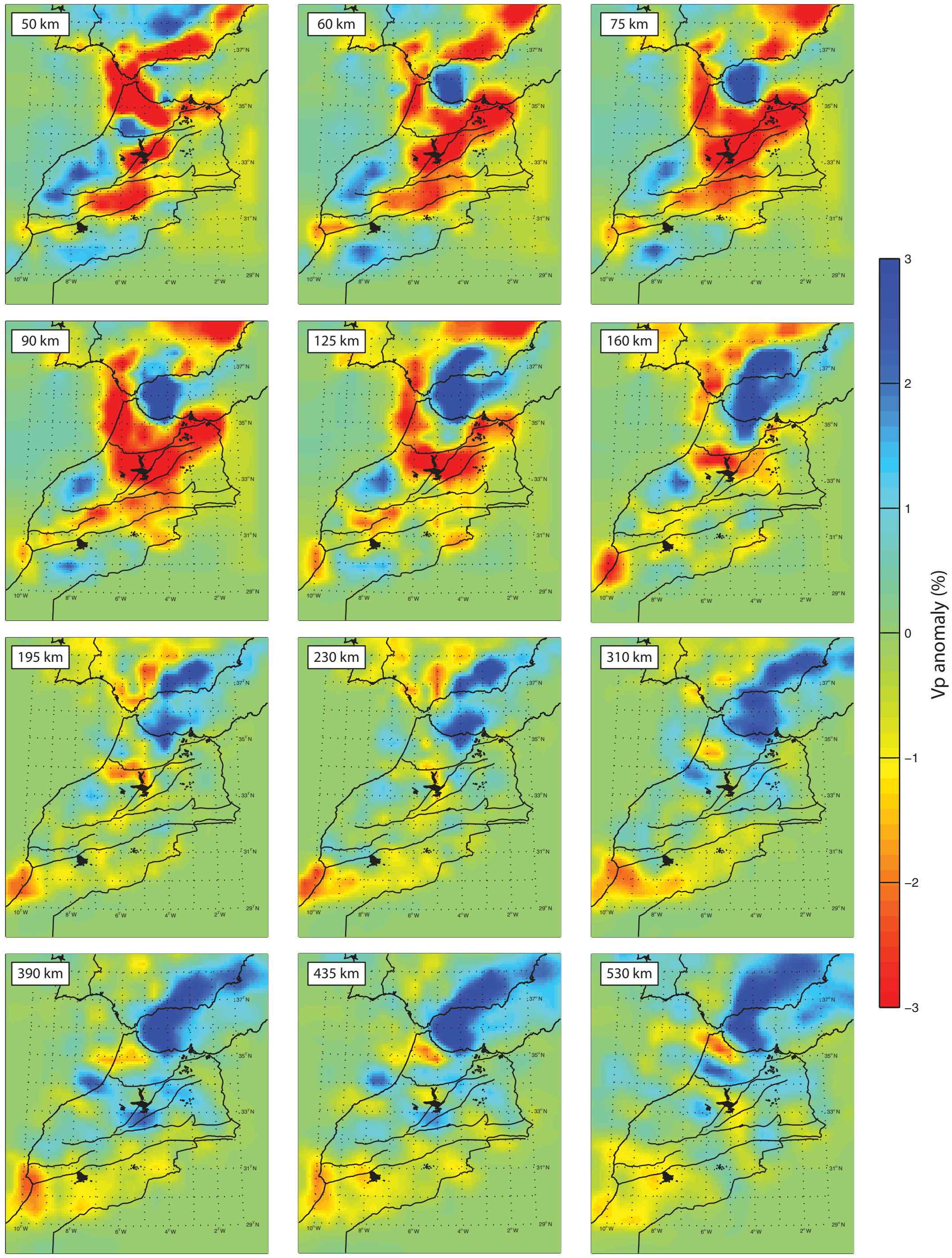

Figure 3. Horizontal slices through the final model at different depths as indicated on each plot. Volcanic centers and tectonic boundaries from Figure 1a are overlaid on the model slices for spatial reference. Aside from the Alboran slab, above 160 km the model is dominated by slow anomalies; below 300 km, spatially small fast anomalies occur beneath the Middle Atlas region.

the origin of our anomalies with a second synthetic test. The prescribed velocity model for this test consists exclusively of a fast anomaly that simulates the Alboran slab. After eight iterations, the inversion recovers the geometry of the prescribed anomaly very well. While there is a faint, thin rim of low velocities around the fast anomaly, this artifact is much smaller in amplitude and lateral extent than the anomalies we image in our final model (Figure 5). We conclude that the slow anomalies around the Alboran slab are an authentic feature and not an artifact of the inversion procedure.

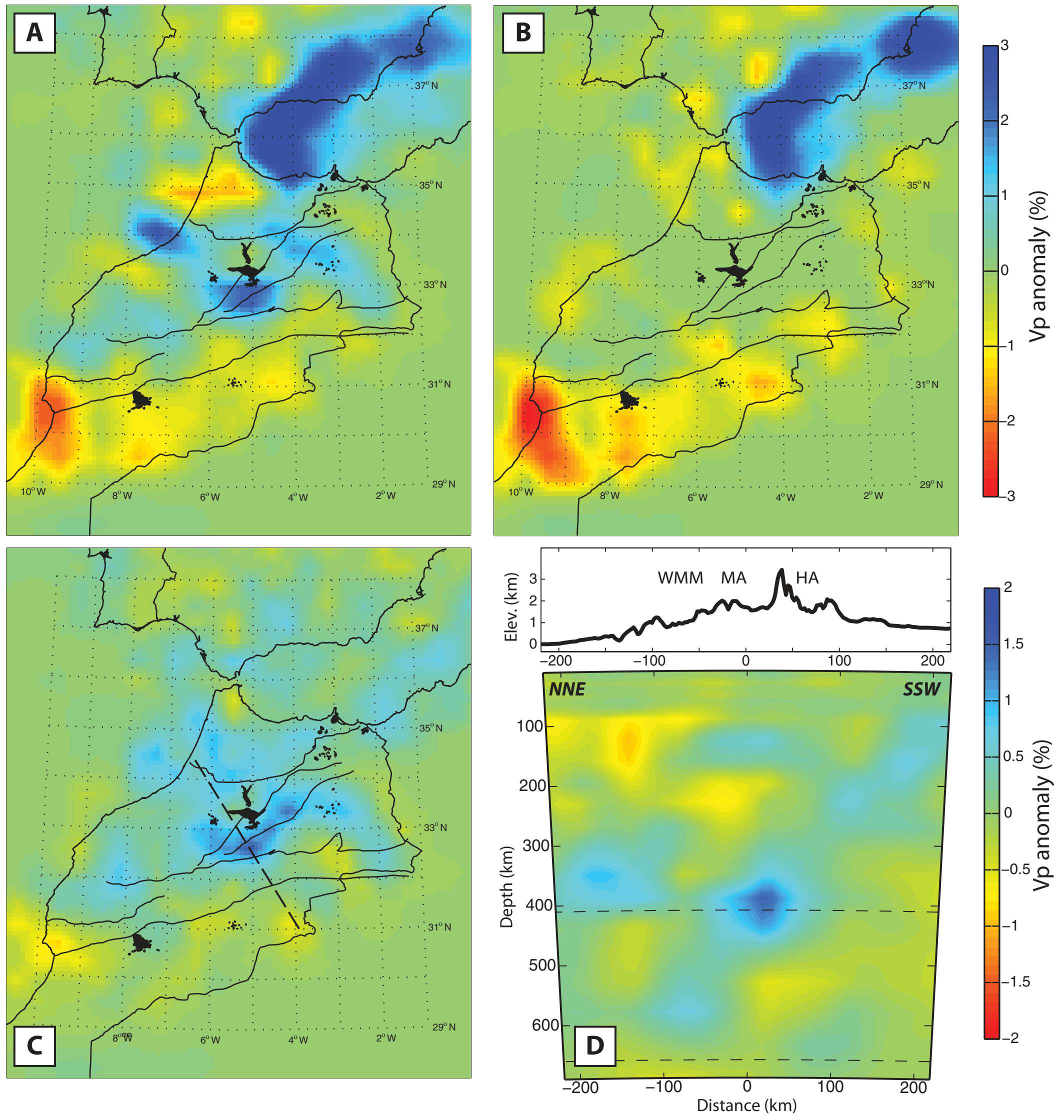

Figure 4. Results of the squeezing test. (a) Horizontal slice through final velocity model at 390 km depth. (b) Horizontal slice through constrained velocity model at 390 km depth, note the absence of fast anomalies other than those related to the Alboran slab. (c) Horizontal slice through residual model at 390 km depth; we recover a fast anomaly beneath the Middle Atlas from the residuals of the constrained inversion. (d) Vertical cross section through the residual model and corresponding elevation profile (location indicated with a dashed line in Figure 4c). The fast anomaly at ~400 km depth is located slightly south and east of the Middle Atlas. WMM––western Moroccan Meseta; MA––Middle Atlas; HA––High Atlas. Note the different color scale for the top and bottom plots. Volcanic centers and tectonic boundaries from Figure 1a are overlaid on the model slices for spatial reference.

The slow features at lithospheric depths in our model do not connect to the Atlantic in the west or underlie the Siroua and Sahro fields in the Anti-Atlas as was inferred by gravity and geochemical studies [*Missenard et al*., 2006; *Duggen et al*., 2009] and might be expected given the location of the magmatic centers. We conduct a third test to investigate if the absence of this anomaly could be a product of inadequate coverage in the southern end of the array.

In this test we generate synthetic delays from a prescribed model that incorporates a 200 km wide, 5% slow corridor that connects the Middle Atlas anomaly with the Atlantic, following the trend defined by *Missenard et al*. [2006] (Figures 1 and 6). When we invert these delays, the resulting model successfully recovers the full extent of the prescribed slow corridor, including the areas where the real tomography image does not show slow anomalies (Figure 6). The results of this test suggest that, rather surprisingly, the lithosphere under the Anti-Atlas is not thinned.

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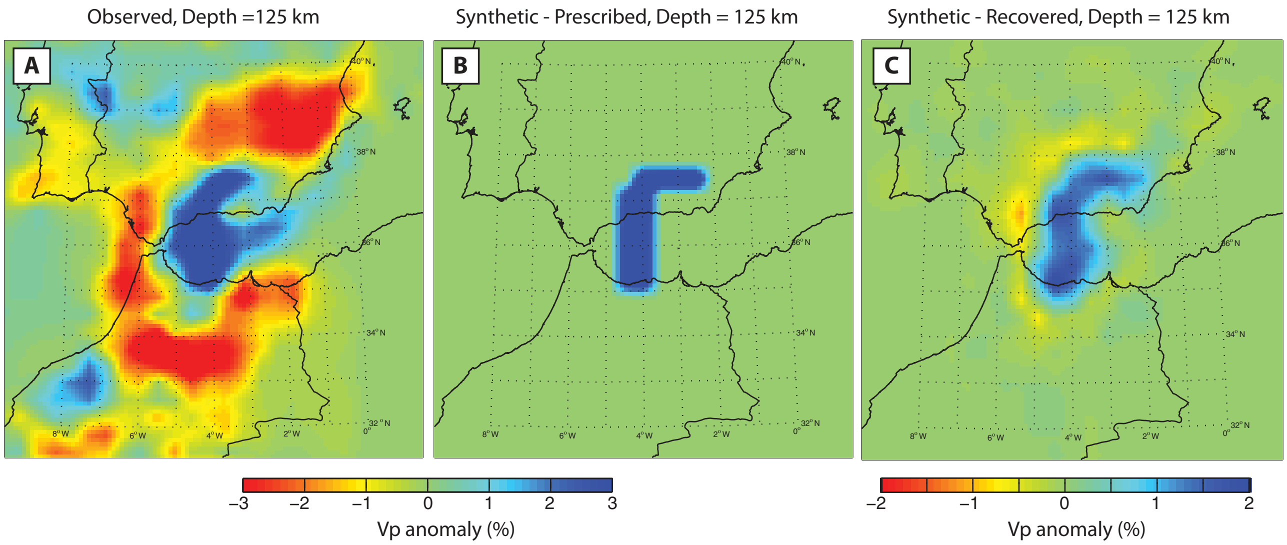

Figure 5. Results of synthetic test. The three plots show horizontal slices at 125 km depth from (a) the final tomography model, (b) the prescribed velocity model with only a fast velocity slab, and (c) the model recovered by the inversion of delays generated from the prescribed model. Note that artificial slow anomalies located around the fast slab in the recovered model are much smaller in amplitude and extent than the slow anomalies in the final tomography model.

5. Interpretation of Structures

There are three main structures in our velocity model that are relevant to the mantle-driven uplift in the Moroccan Atlas region.

At shallow sub-crustal depths, low seismic velocities are localized under the Middle Atlas and the central High Atlas (Figure 3). In their shallowest expression, these structures correlate spatially with the mountain ranges as well as the areas of thinnest lithosphere inferred from multi-parameter geophysical inversion

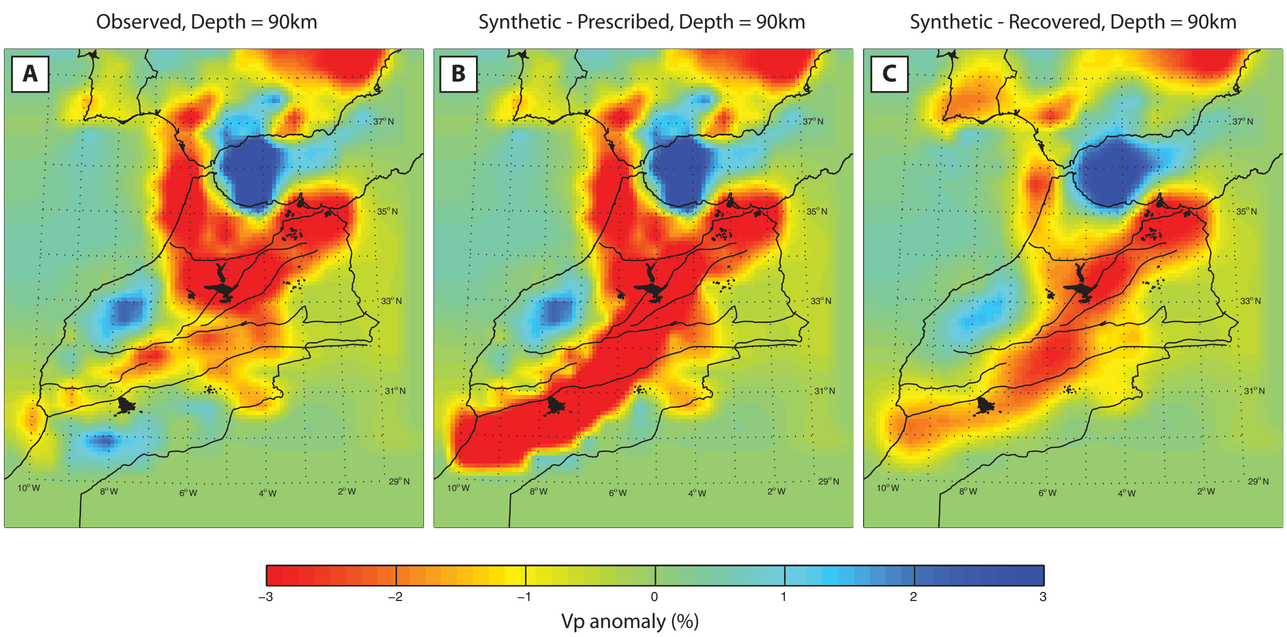

Figure 6. Results of synthetic test. The three plots show horizontal slices at 90 km depth from (a) the final tomography model, (b) the prescribed velocity model with a through-going thinned-lithosphere corridor connecting to the Atlantic, and (c) the model recovered by the inversion of delays generated from the prescribed model. Note that the inversion of the synthetic delays successfully recovers the entire lithospheric corridor, including the zone beneath the Anti-Atlas that is absent from the final tomography model. Volcanic centers and tectonic boundaries from Figure 1a are overlaid on the model slices for spatial reference.

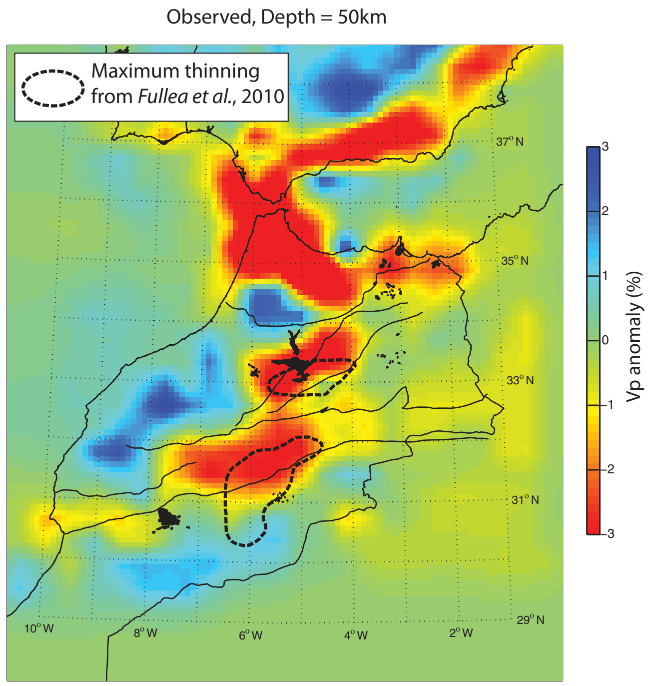

Figure 7. Comparison of a model slice at 50 km depth with the areas maximum thinning found by *Fullea et al.* [2010] indicated by thick, dashed lines. Note the good agreement with the location of slow anomalies beneath the Middle Atlas and central High Atlas.

(Figure 7). We interpret these volumes of slow mantle as asthenosphere filling lithospheric cavities. Thermal erosion of the lithosphere by conductive heating alone would produce diffuse anomalies with gradational boundaries. The sharp-edged anomalies we image suggest instead that the lithosphere was lost advectively, and thus, that the lithospheric cavities we image were formed by a delamination process. The apparent large-scale removal of lithosphere probably occurred by some form of wholesale delamination or vigorous drip-like convection. We loosely refer to any of these as delamination. This interpretation is in conflict with reports of intermediate-depth earthquakes within what we consider to be asthenosphere [e.g., *Hatzfeld and Frogneux*, 1981]. Using our 3-D velocity model to relocate two such events that occurred during our deployment, we find the observed arrival times are much better fit by shallow (<5 km) depths than the reported depths of >80 km (Instituto Geográfico Nacional, Spain). See supporting information for details.

An alternative interpretation for the shallow low-velocity anomalies is the existence of a thick crustal root beneath the Middle Atlas and central High Atlas. We reject this possibility on the basis of evidence from recent receiver function and active source studies that all point to crustal thicknesses of 30–40 km in these regions [*Thurner et al*., 2011; *Ayarza et al*., 2013; *Miller and Becker*, 2014].

Beneath the Middle Atlas, we image a relatively small, fast (cold) volume of mantle that we interpret as delaminated lithosphere. Its location and size suggests that it represents only the lost lithosphere of the Middle Atlas. If so, the lithosphere that once filled the imaged cavities was not lost coherently in a single episode, but rather in multiple delamination events.

The Alboran slab is surrounded by very slow mantle at depths from 60 to 160 km (Figure 3). Mantle this slow (>4%) probably results from partial melting, and partial melting below 100 km probably involves anomalously hot mantle. The volume of very slow mantle is present where flow driven by slab rollback would drive asthenospheric ascent in conjunction with toroidal flow around the slab and it is absent where slab motion would entrain asthenosphere down [see *Funiciello et al*., 2006; and *Piromallo et al*., 2006 for a general treatment; *Alpert et al*., 2013 for discussion of the western Mediterranean]. The straightforward interpretation of this very slow seismic feature is decompression melting of anomalously hot mantle driven to flow upward by slab rollback.

6. Discussion

Crustal thickening created by tectonic shortening is not sufficient to explain the elevation of the Atlas Mountains of Morocco and surrounding areas**.** There is a wide consensus that a mantle component of uplift is required, but the origin of this mantle buoyancy––either lithospheric foundering or plume emplacement––is debated.

The Atlas fold and thrust belts are the dominant structural features in the area that has experienced young (post-Miocene) mantle-driven upwarping. This suggests a genetic link between the tectonic structures and the dynamic process. A possible relation is that convergence and the resulting forced downwelling of mantle lithosphere initiated delamination of a mantle root beneath the fold and thrust belt [e.g., *Ramdani*, 1998; *Duggen et al*., 2009]. Some authors, however, point to the facts that shortening across the Atlas is small, that uplift extends into areas that experienced no shortening (e.g., the Moroccan Meseta and Anti-Atlas), and that the eastern Atlas experienced a similar shortening history but show no evidence for mantle-derived uplift [*Teixell et al*., 2005; *Missenard et al*., 2006; *Frizon de Lamotte et al*., 2009; *Fullea et al*., 2010]. These observations, they argue, make it unlikely that lithospheric shortening is the sole cause of delamination.

Thermal erosion of the lithosphere by hot, upwelling mantle stands as an alternative explanation for sub-crustal buoyancy. The plume-like chemistry of the young lavas [*Duggen et al*., 2009] suggests the presence of anomalously hot asthenosphere in the region, perhaps related to the Canary hotspot [*Duggen et al*., 2009] or to different regional [*Ebinger and Sleep*, 1998; *Lustrino and Wilson*, 2007] or local [*Missenard and Cadoux*, 2012] upwellings.

With sound evidence supporting each of these possibilities, and with the aid of upper mantle seismic imaging, we prefer an explanation that incorporates elements of each hypothesis. Based on our imaging, we infer a patchy set of recent delaminations in a region underlain by unusually hot asthenosphere.

We propose that the presence of hot mantle enabled the foundering of intrinsically unstable lithosphere from beneath the Middle Atlas and central High Atlas. Delamination proceeded in a discontinuous, piece-wise fashion and did not result in the throughgoing removal of the entire Moroccan Atlas lithosphere as envisioned by *Duggen et al*. [2009]. Each of the processes under consideration (lithospheric shortening and impingement of hot mantle) would enhance lithospheric instability, especially in areas where asthenosphere upflow generated melt that would freeze as eclogite within the lithosphere, thus tending to make the process self-sustaining.

The most conspicuous delamination event occurred beneath the Middle Atlas. There, we image a large volume of very slow mantle extending up to near the Moho, indicating a focused area of mantle upwelling. The only well-resolved structure that appears to be delaminated lithosphere is the relatively small high-velocity body residing at ~400 km depth, also beneath the Middle Atlas, and both the shallow slow and deep fast anomalies underlie a region of vigorous recent magmatism (Figure 3). This volume of delaminated lithosphere is too small to account for all the lithosphere that would have occupied the imaged cavities (Figures 3 and 4). Thus the Middle Atlas event seems to represent only the most recent delamination.

Delamination under the High Atlas may have occurred in a similar manner to the Middle Atlas delamination but at an earlier time, or it may have proceeded in a more progressive fashion: for instance, lithosphere foundering could have started in the central High Atlas and progressed east and west through a series of small-scale downwellings rather than the wholesale delamination of a coherent body as seems to be the case in the Middle Atlas. In either of these cases, the lost lithosphere of the High Atlas would be more difficult to image given that it would deeper in the mantle, broken up into smaller pieces, or both.

The inferences made above are based largely on robust observations of uplift, local tectonic history and upper mantle seismic imaging. To address the underlying causes of delamination, we consider the regional setting and published results of geodynamic modeling. Several factors combined to make the Atlas lithosphere unstable and more vulnerable to delamination than the surrounding areas. Tectonic shortening would have produced some lithospheric thickening, forcing lithospheric protrusions into the asthenosphere that would tend to make these locations the sites of initial foundering, and thereby giving a structure to the downwelling. Perhaps most important, eclogite loading associated with basaltic magmatism would have created a compositionally dense lithosphere [*Elkins-Tanton and Hager*, 2000; *Krystopowicz and Currie*, 2013]. Early basalt intrusion probably occurred during Mesozoic rifting beneath the grabens that would become the Cenozoic Atlas mountain ranges. Further eclogite loading during the Eocene magmatism (Figure 1a, purple rectangles) would have contributed to densifying the Atlas lithosphere, as would magmatism that occurred in the last ~11 m.y. (Figure 1a, black rectangles). The younger magmatism may have helped initiate convective instability. In addition to these destabilizing processes, presence of anomalously hot asthenosphere would have further increased the instability of Atlas lithosphere. Unusually hot mantle seems to underlie much of the circum-Mediterranean region [*Spakman and Wortel*, 2004] and probably is involved in the production of anorogenic volcanism throughout the region [*Lustrino and Wilson*, 2007]. While the origin of the hot asthenosphere is speculative, various possible sources include diapiric upwellings [*Lustrino and Wilson*, 2007], the north and east Africa domes [*Ebinger and Sleep*, 1998] and the Canary plume [*Duggen et al*., 2009].

The dynamics of mantle flow around the retreating Alboran slab helped focus upwelling mantle beneath the Middle Atlas, where the imaged low-velocity anomalies are stronger (Figure 3). Toroidal flow around the slab seems to have directed hot mantle toward the Middle Atlas, and the vertical component of this slab-driven flow is expected to be strongest beneath the region of the Middle Atlas. The onset of delamination may have then helped to organize the mantle upwelling, further focusing it there.

Delamination of the Atlas lithosphere provides a means of understanding much of the dynamic uplift in Morocco as well as an interesting example of wholesale lithosphere loss in a mildly contractional orogen. The uplift of the Anti Atlas domain and the magmatism in its northern margin remain enigmatic, as there is no clear indication from the velocity structure or the mantle anisotropy of a thinned lithosphere [*Miller et al*., 2013; *Palomeras et al*., 2014, this study]. Edge-driven convection, perhaps as a south-propagating delamination or drip, is a possibility [*Missenard and Cadoux*, 2012]. Regardless, the young uplift and magmatism, and the occurrence of low seismic velocities penetrating a volume of what is thought to be Archean craton (Figure 3), appear to document the destruction of parts of this cratonic lithosphere.

7. Conclusions

We image a strongly heterogeneous mantle structure in the upper few hundred kilometers beneath Morocco, which indicates a vigorously active uppermost mantle (Figure 3). However, the structure is complex. We interpret the young uplift of Morocco as due to a series of lithospheric delaminations of an intrinsically unstable Atlas-area lithosphere that currently is largely underlain by hot, plume-like asthenosphere, the Atlas lithosphere having been destabilized by a variety of mechanisms acting in different regions. Delamination resulted in the formation of lithospheric cavities, but not a continuous sublithospheric corridor from the Atlantic to the Mediterranean (Figures 3 and 6). Intermediate-depth earthquakes reported to have occurred in these asthenosphere-filled cavities are actually crustal in nature (supporting information).

For the Middle Atlas and eastern Meseta, we attribute the apparent lithospheric cavity, and young magmatism and uplift, to a delamination of the local lithosphere. We appear to image this lost lithosphere at a depth of $\sim$400 km (Figures 3 and 4). The connection between the large volume of slow mantle that nearly surrounds the Alboran and the slow mantle under the Middle Atlas and eastern Moroccan Meseta (Figure 3) suggests that return flow around the retreating slab helped focus mantle upwelling under this part of the Atlas Mountains. Low velocities beneath the High Atlas from 60 to 125 km suggest a delamination of this lithosphere as well, although the velocities are not as strongly anomalous. This suggests the possibility of an older (but not old) delamination of this lithosphere or a more slowly progressing delamination style different from that of the Middle Atlas. For both of these regions, the lithosphere was made unstable by some combination of eclogite loading during Mesozoic rifting and Cenozoic magmatism (Figure 1a), and lithospheric convergence and thickening. Anti-Atlas uplift, with its young magmatism distributed along its northern margin, is more difficult to explain, but perhaps involves edge-driven convection along the margin of the West African Craton.

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