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Title: The role of continental margins in the final stages of arc formation: Constraints from teleseismic tomography of the Gibraltar and Calabrian Arc (Western Mediterranean)

Article Type: Research Paper

Keywords: teleseismic tomography; upper mantle; Gibraltar Arc; Calabrian Arc; subduction zone

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Abstract: The deep seismicity and lateral distribution of seismic velocity in the Central Western Mediterranean, point to the existence under the Alboran and Tyrrhenian Seas of two lithospheric slabs reaching the mantle transition zone. Gibraltar and Calabrian narrow arcs correspond to the slabs. Similarities in the tectonic and mantle structure of the two areas have been explained by a common subduction and roll-back mechanism, in which the two arcs are symmetrical end members. We present a new 3-D tomographic model at mantle scale for the Calabrian Arc and compare it with a recently published model for the Gibraltar Arc by Monna et al. (2013a). The two models, calculated with inversion of teleseismic phase arrivals, have a scale and parametrization that allow for a direct comparison. The inclusion in both inversions of ocean bottom seismometer broadband data improves the resolution of the areas underlying the seafloor networks. This additional information is used to resolve the deep structure and constrain the reconstruction of the Central Western Mediterranean geodynamic evolution. The Gibraltar tomography model suggests that the slab is separated from the Atlantic oceanic domain by a portion of African continental margin, whereas the Calabrian model displays a continuous oceanic slab that is connected, via a narrow passage (~350 km), to the Ionian basin oceanic domain. Starting from the comparison of the two models we propose the following interpretation: within the Mediterranean geodynamic regime (dominated by slab rollback) the geometry of the African continental margin, located on the lower plate, represents a critical control on the evolution of subduction. As buoyant continental lithosphere entered the subduction zones, slab pull caused tears in the subducted lithosphere. This tectonic response in the final stages of arc evolution, strongly controlled by the paleogeography of the subducted plates, explains the observed differences between the Gibraltar and Calabrian Arcs.

Suggested Reviewers: Gideon Rosenbaum

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Expert of Mediterranean region. Expert in seismic tomography.

Rome, 21 March 2016

Paper: TECTO10726

Title: "The role of continental margins in the final stages of arc formation: Constraints from teleseismic tomography of the Gibraltar and Calabrian Arc (Western Mediterranean)"

Authors: A. Argnani, G.B. Cimini, F. Frugoni, S. Monna, C. Montuori

Dear Editor,

We are pleased to resubmit our revised paper to Tectonophysics. We have followed the reviewer's suggestions and modified the paper accordingly. We have also submitted our point-to-point answer (in italics) to the reviewer's comments (in bold). We thank the reviewer for the useful comments.

The submitting author certifies that all co-authors know of and concur with the submission of the manuscript.

Thank you very much for your attention.

Sincerely,

Andrea Argnani

The deep seismicity and lateral distribution of seismic velocity in the Central Western Mediterranean, point to the existence under the Alboran and Tyrrhenian Seas of two lithospheric slabs reaching the mantle transition zone. Gibraltar and Calabrian narrow arcs correspond to the slabs. Similarities in the tectonic and mantle structure of the two areas have been explained by a common subduction and roll-back mechanism, in which the two arcs are symmetrical end members. We present a new 3-D tomographic model at mantle scale for the Calabrian Arc and compare it with a recently published model for the Gibraltar Arc by Monna et al. (2013a). The two models, calculated with inversion of teleseismic phase arrivals, have a scale and parametrization that allow for a direct comparison. The inclusion in both inversions of ocean bottom seismometer broadband data improves the resolution of the areas underlying the seafloor networks. This additional information is used to resolve the deep structure and constrain the reconstruction of the Central Western Mediterranean geodynamic evolution. The Gibraltar tomography model suggests that the slab is separated from the Atlantic oceanic domain by a portion of African continental margin, whereas the Calabrian model displays a continuous oceanic slab that is connected, via a narrow passage (~350 km), to the Ionian basin oceanic domain. Starting from the comparison of the two models we propose the following interpretation: within the Mediterranean geodynamic regime (dominated by slab rollback) the geometry of the African continental margin, located on the lower plate, represents a critical control on the evolution of subduction. As buoyant continental lithosphere entered the subduction zones, slab pull caused tears in the subducted lithosphere. This tectonic response in the final stages of arc evolution, strongly controlled by the paleogeography of the subducted plates, explains the observed differences between the Gibraltar and Calabrian Arcs.

*Revision Notes
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Paper: TECTO10726

Title: "The role of continental margins in the final stages of arc formation: Constraints from teleseismic tomography of the Gibraltar and Calabrian Arc (Western Mediterranean)"

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Please note that the **reviewer's comments** are in bold while *our answer* are in italics. The parts of the text that are highlighted in yellow have been added in response to the Reviewers' requirements. We re sending a text with tracked changes (Argnani_et_al_Revisions) and a version without visible changes (Argnani_et_al_clean).

We thank the reviewers for the useful comments.

Reviewer #1: **The is an interesting paper that compares the seismic velocity structure of the upper mantle beneath the Gibraltar and the Calabrian arcs and interprets them tectonically.**

The paper makes use of tomography models from both regions that incorporate data from ocean bottom seismographs, giving the models better offshore resolution than previous models. The Gibraltar arc model has been published elsewhere recently, whereas the Calabrian arc model has not been previously published as far as I can tell. Given the large amount of recent work on the Gibraltar arc region and the western Mediterranean generally the paper is timely, and the addition of Atlantic OBS data is important and unique.

I was a bit disappointed that the authors did not include at least part of the large volume of land data for this region that is now available in their inversions, but that may have been beyond the scope of the project. The author's have done a reasonably good job of citing the relevant literature.

We agree with the reviewer. For the Gibraltar arc 3D model we used the data that was available to us at the time. We hope to improve our model by adding the new permanent network data and, if available, data from recent large experiments in the area, such as IberArray and PICASSO.

The paper's chief shortcoming is that it tends to be somewhat redundant, and the English needs to be reviewed by a native speaker. In a number of places it is difficult to understand the authors' meaning. It is for this reason that I recommend moderate revision. The author's should look to tightening the manuscript by removing redundancies and clarifying the English. I ended up with so many grammatical corrections and revised phrasing that it is not feasible to list them here, after a short while I quit attempting to keep track of suggested revisions Part of the paper's structural problem is that the authors are repeatedly skipping back and forth between the two arcs, which gets a bit tedious, and also results in some of the redundancy.

Yes, we agree. We have made several changes to make the paper more readable.

Various parts of the paper have been restructured (to see which parts please see version with annotated changes)

In particular:

1) We have deleted redundant parts

2) Section 2 has been shortend, leaving only the parts that are more relevant to our work.

2) We have included section 3.1 and 3.2 in sections 2.1 and 2.2, respectively, to (hopefully) make the paper more readable.

3) Some akward and possibly obscure phrases have been corrected/clarified.

Please be aware that with the changes old Section 4 is now Section 3 and so on.

Specific comments: Section 3: introduction: I would call the smallest scale tomography models regional rather than local, as they are still examining multiple tectonic domains. Local, as in local earthquake normally means on the scale of 100km.

We agree and have applied the reviewer's suggestion.

Line 418: The authors say that the intermediate-depth earthquakes provide information on the subjected slab beneath the Alboran basin, but then make only a vague statement about exactly what information it is they provide. I find this section to be a little vague. I think that the authors could make much more of the seismicity in both arcs, actually.

We have added more information in Sections 2.1 and 2.2 on the seismicity, in particular on the focal mechanisms and stress regime in the two slabs, and a new citation (Buforn et al., 2011).

All of the labels on my versions of figures 6 and 7 are unclear. As the authors base their interpretations on these two figures and several cross sections, they should make the labels larger and clearer.

We have enlarged the labels so that they are visible also in the pdf version

I don't quite understand their interpretation of the Gulf of Cadiz low velocity anomaly (GC-LVA) as thinned continental lithosphere. If the lithosphere was thinned by extension during the opening of the Atlantic then it should have re-equilibrated to a normal TBL lithosphere of ~100km thickness by now, similar to Atlantic oceanic lithosphere. If it thinned more recently due to the local GA tectonics, then I missed the explanation somehow. Please explain this.

The thinning of the continental lithosphere is related to the Mesozoic oceanic opening. We agree that the lithosphere has likely re-equilibrated to ca. 100 km thickness, but the crustal part of it remains thin and has a slower Vp with respect to the adjacent oceanic lithosphere.The lithospheric velocity structure just offshore Gibraltar appears different from that of the adjacent oceanic lithosphere in the Gulf of Cadiz, and, most important, it interrupts the continuity between the slab subducted underneath Alboran and the Atlantic oceanic lithosphere.

I think the authors should discuss their figures 11 and 12 in comparison to the results of van Hinsenbergen et al 2013 G3, which in my opinion is the clearest exposition on development of the Gibraltar Arc.

The focus of our paper was not to present a long-term evolution of the Gibraltar and Clabrian arcs, but rather to show how the nature of the crust and lithosphere in the subducting plate affected the finale stage of arc formation. To illustrate this aspect we used a couple of snapshots at Tortonian and present-day (figures 11 and 12). Nevertheless, we did mention that our results are more compatible with the model presented by Rosenbaum et al., 2002, Chertova et al. 2014, and now we have also taken into consideration van Hinsbergen et al 2014.

The author's have overlooked a paper by Thurner et al, 2014, G3, which to my eye most clearly shows the Alboran slab delamination under the Betics and Rif. I'm sure this was just an oversight, as the literature on the GA and CA is extensive.

Our paper suffered from a long gestation, during which several papers on the Alboran-Gibraltar region were published; it happened that we missed some references. However, the paper of Thurner et al, that we now acknowledge, is in line with many studies published more or less at the same time and resulting from the massive work carried out within the PICASSO and IberArray projects; we tried to take advantage of these recent results in our interpretation.

Reviewer #2: **This paper contrasts the seismic structure of two present-day subducted slabs that bracket the western-central Mediterranean and that are widely thought to have originated from what was initially a single slab. These are the Alboran and the Calabrian slabs. The analysis is centered on recent tomography models carried out using the same technique which facilitates the comparison. The main point that comes across is that the Alboran and Calabrian slabs are different in that further Alboran subduction was impeded by the entrance into the trench of African continental margin lithosphere.**

The paper is generally well written and illustrated although in my opinion it could be shortened without loss of clarity. More importantly, I think some of the literature is not referenced appropriately (see below).

There is, in my view, an issue that is very relevant to the central point of this paper that the authors do not

address: the role of the continental lithosphere of the Alboran domain. In some models [Faccenna et al., 2004; Bezada et al., 2013] the Alboran loses its lithospheric mantle by delamination as part of the Alboran slab. That is, the slab includes the Alboran mantle. These hybrid rollback/delamination models are not discussed in the introduction. More importantly, in this scenario the entrance into the trench of continental lithosphere did not stop subduction from proceeding, but rather resulted in delamination of the continental lithosphere and transfer of the crust to the overriding plate. If this was the case, then it would be interesting to sort out why the entrance of the Alboran into the trench was not able to stop rollback, but the arrival of the African continental margin was. Of course, the authors could argue that those models are wrong, and that this kind of delamination doesn't happen, but I think the possibility should be discussed. In any case, delamination of continental mantle lithosphere when a continental block enters the trench has been shown to be possible by numerical [e.g. Faccenda et al., 2009] and analog [e.g. Bialas et al., 2011] modeling. It is my opinion that the authors should engage with this issue in one way or another.

Perhaps the Reviewer is adopting a concept of Alboran as a continental microplate, which we believe is not likely (see for instance the reconstructions of Platt et al and van Hinsbergen et al where the Alboran domain is seen as an accretionary complex, floating above a retrating oceanic subduction zone. Delamination has affected the Iberian and African continental margin when the continental crust entered subdution, that is, in the final stage of arc formation.

Also with regards to this central point, a crucial aspect is the non-continuity of the subducted Alboran lithosphere with the Atlantic. A number of papers have been published suggesting that such a continuity does exist and exploring the implications. I don't think the authors currently engage sufficiently with those arguments [e.g. Gutscher et al., 2002; Duarte et al., 2013]. Note that even though these papers are cited, the arguments are not really addressed. At least this should be addressed in the introduction to provide necessary context.

The continuity of the slab inferred in published papers [e.g. Gutscher et al., 2002; Duarte et al., 2013] is not supported by evidence as there is a gap in geophysical data in the critical region between the Gulf of Cadiz and Gibraltar; this is the region from which we obtain good tomographic images thanks to the offshore OBS stations.

These guys seem to be in direct contraposition to Gutscher and those guys who talk of ongoing subduction of Atlantic beneath Gibraltar. They better address those papers.

We have extensively cited the papers by Gutscher and co-authors and we have clearly pointed out that our view is different.

Regarding the referencing of previous work, I noticed that some papers that present seismic tomography models as well as tectonic evolution [Spakman and Wortel, 2004; Bezada et al., 2013] models were only considered insofar as the tomography model is concerned, but the ideas about tectonic evolution that are presented were not included in the discussion. Also, citing Levander et al. [2014] Along with Platt and Vissers and Calvert et al. is not appropriate. The Levander et al. paper discusses a fundamentally different model for the tectonic evolution of the region. Finally, there are a couple of tomography models of the Gibraltar area that came out after the Bezada et al. model and should probably be referenced: [Bonnin et al., 2014; Villaseñor et al., 2015]

We mention that Wortel and Spakman proposed subduction rollback followed, in the final stage, by lithospheric tearing. In general we mentioned models that propose different solutions with respect to the removal of thickend continental crust/lithosphere in the Alboran region, and we acknowledged the point of Levander et al. on the role of these processes on recycling of continental material into the mantle. We also now consider the papers by Bonnin et al. (2014) and Villaseñor et al., 2015.

Other comments:

The variance reduction for the Calabrian Arc is fair, but for the Gibraltar Arc is poor. The authors should comment on why that may be.

While the method and parameterization for both arcs is the same, the ray density is not. The authors should comment on how this may affect the imaging in each case and the comparison of the two arcs.

These two questions are linked. The GA dataset contains a large percentage of bullettin arrival times , while the larger CA dataset has a small percentage of bulletin data. The difference in data quality is already evident in the starting RMS values of the two dataset, for CA 0.6 s^{-1} on 8600 arrival times, against 0.7 s^{-1} for GA on 6238 arrival times. The errors in the bullettin arrival times limit the amount of RMS reduction. The differences in resolution between the two datasets is proved by the checkerboard resolution test. This test shows that the synthetic anomalies are better reconstructed by the CA dataset than with the GA dataset. In fact, the CA model could be parametrized with a smaller grid (~80 km), but we have chosen the same parametrization as for GA (100 km) to better compare them. In any case, in both cases the parts that we intepret are in volumes of the models that are reliably reconstructed in the synthetic tests. We have added more information on this aspect in the text.

L135 states that the GA model resolves previously undetected features, but does not specify which features these are. Models that came shortly after this one [Bezada et al., 2013; Bonnin et al., 2014; Villaseñor et al., 2015] have the advantage of much greater station coverage in Spain in Morocco.

We have clarified this part in the text. The features that are better resolved in our model (with respect to other models) are the ones resolved by the OBS data, particularly the lithosphere-upper mantle structure of the Gibraltar Strait-Atlantic sector.

L154: in the Algerian sector,

We have implemented the suggestion.

L163: It would probably be appropriate to cite Spakman and Wortel 2004 here as well.

We agree, the reference was added.

L182: At least in American English, "sketchy" has a negative connotation. I understand the authors mean "oversimplified" or something like that.

Yes, we have changed "sketchy" into "oversimplified".

L195: The authors should consider justifying their judgement that the evidence is "rather poor".

The occurrence of a so called Alkapeca microcontinent is used in some palaeogeographic reconstructions, where a continental domain much wider than the Corsica-Sardina microcontinent is represented. This continental domain would be located in the upper plate with respect to the African and Betic subductions and it is difficult to envisage how it can be completely destroyed during the opening of the Western mediterranean backarc basins. So far, the evidence for the occurrence of thinned conetinental crust (not belonging to the Iberia and African margins) is lacking within the Western Mediterranean basins. In any case, we have deleted this part of Section 2 trying to comply to the Reviewers' suggestion to shorten the paper.

I think section two in general could be shortened without leaving out anything that is crucially relevant to this paper.

We agree. We have tried to apply this suggestion.

L351: What did you use to correct for the crustal structure.

This aspect is later described in Sections 4.1 and 4.2 (now 3.1 and 3.2), we have inserted this reference at this point.

L440: "mentioned at the beginning of this section" is confusing. The variance reduction is actually mentioned in the following paragraph.

We agree and we have deleted this misleading information.

L444-446: the regularization weights are generally relative to the number of observations. More observations require higher regularization to obtain the same amount of damping/smoothing because the relative weight of the data in the objective function is larger. Without some knowledge of the specifics of the implementation of regularization these numbers have very little meaning to the reader.

We have deleted this confusing sentence in L444-446 and added a reference (in the beginning of Section 4, now Section 3) to the governing equation where the damping and smoothing parameters are defined. The regularization is due to the ill-posed mathematical inversion problem. In the case of seismic tomography the amount of regularization is strongly dependent on the event-station geometry and the chosen Earth parametrization.

L499: An important point is whether these low velocities could actually be produced by unaccounted-for low velocities in the crust; for example, a very thick sedimentary package.

The crustal correction used for the Gulf of Cadiz includes a 6 km thick low-velocity (3.5 km/s) sedimentary layer (see Table 1 in Monna et al., 2013a). In spite of this strong correction we still observe the strong low-velocity anomaly GC-LVA. We have added this information in the text.

L520-523: There is some intermediate-depth seismicity occrurring in the slab, that much is clear. I think a more accurate statment is that seismicity is not restricted to the Slab or not even concentrated in the slab. Locally it does closely follow the slab.

We agree, this sentence can be confusing. We have rephrased this concept and linked the distribution of the overall seismicity to the diffuse plate margin. We are referring to crustal seismicity; this point has been rephrased.

Regarding Fig. 12: Why is the Tortonian particularly important? Is this figure really necessary?

Perhaps the reviewer is referring to Figure 11 (referring Tortonian time) ? Tortonian time is particularly important because at this time the GA subduction is finished while the CA subduction is just on its way. The reconstruction of Figure 11 complements the present-day setting illustrated in Figure 12, as we are comparing the two time slices, Tortonian and Present, that represent the completion of arc formation in Gibraltar and Calabria, respectively.

In the figure captions (at least in Fig 8) if not defining the HVA, LVA on the figure, plaase say "look in the text for the definition of the HVA, LVA" or something to that effect.

We agree. Now we have added an explanation of all acronyms in the figure captions captions.

References cited:

We have added most of the missing references suggested by the Reviewer.

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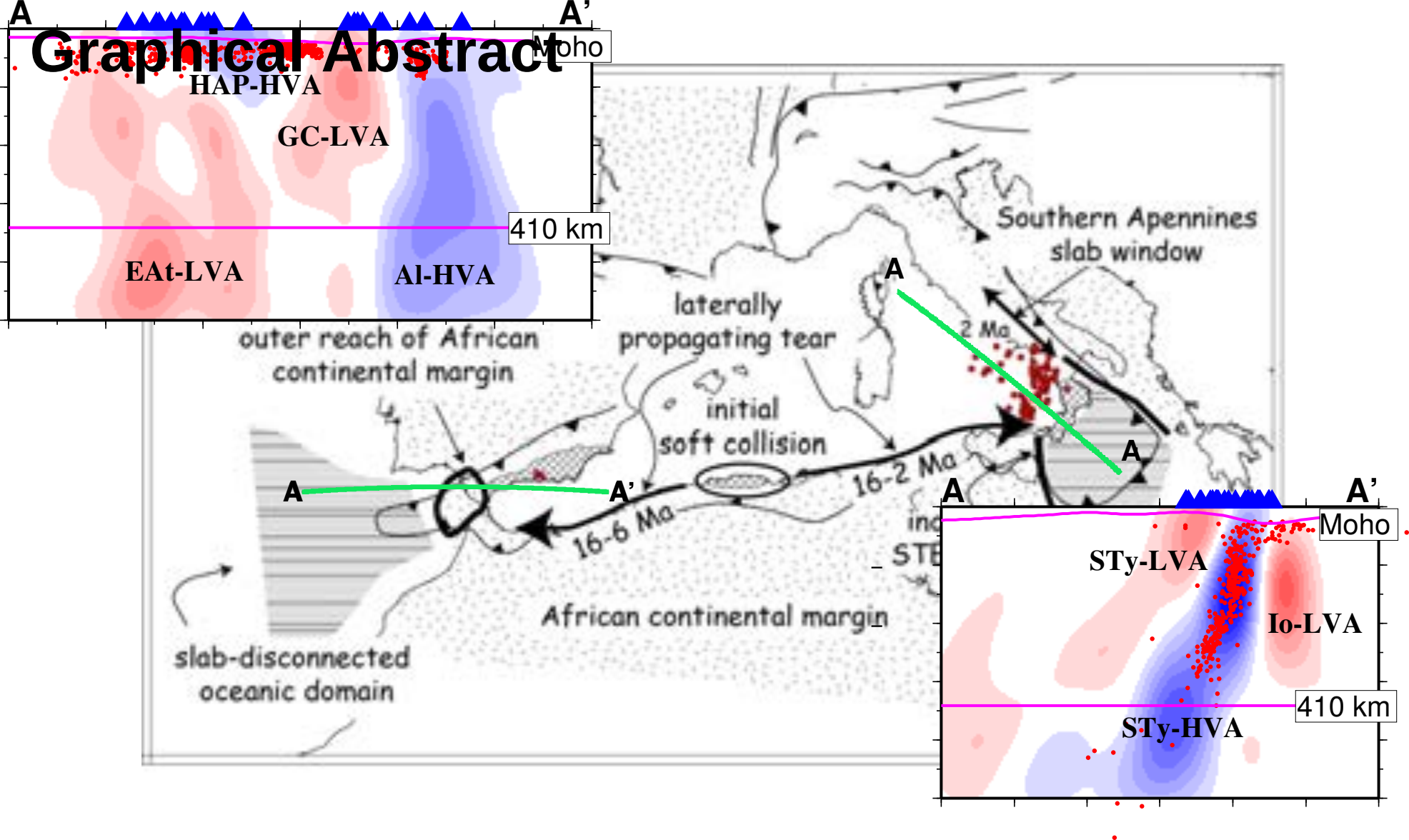
Villaseñor, A., S. Chevrot, M. Harnafi, J. Gallart, A. Pazos, I. Serrano, D. Córdoba, J. A. Pulgar, and P. Ibarra (2015), Subduction and volcanism in the Iberia-North Africa collision zone from tomographic images of the upper mantle, Tectonophysics, 663, 238-249, doi:10.1016/j.tecto.2015.08.042.

Graphical Abstract



Highlights

- OBS data improve the resolution of mantle tomography in the Mediterranean region
- Comparison of lithosphere-astenosphere structure under Calabrian and Gibraltar arcs
- Geometry of continental margin can influence subduction and tectonic arc evolution

Title

The role of continental margins in the final stages of arc formation: Constraints from teleseismic tomography of the Gibraltar and Calabrian Arc (Western Mediterranean)

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Abstract

The deep seismicity and lateral distribution of seismic velocity in the Central Western Mediterranean, point to the existence under the Alboran and Tyrrhenian Seas of two lithospheric slabs reaching the mantle transition zone. Gibraltar and Calabrian narrow arcs correspond to the slabs. Similarities in the tectonic and mantle structure of the two areas have been explained by a common subduction and roll-back mechanism, in which the two arcs are symmetrical end members. We present a new 3-D tomographic model at mantle scale for the Calabrian Arc and compare it with a recently published model for the Gibraltar Arc by Monna et al. (2013a). The two models, calculated with inversion of teleseismic phase arrivals, have a scale and parametrization that allow for a direct comparison. The inclusion in both inversions of ocean bottom seismometer broadband data improves the resolution of the areas underlying the seafloor networks. This additional information is used to resolve the deep structure and constrain the reconstruction of the Central Western Mediterranean geodynamic evolution. The Gibraltar tomography model suggests that the slab is separated from the Atlantic oceanic domain by a portion of African continental margin, whereas the Calabrian model displays a continuous oceanic slab that is connected, via a narrow passage (~350 km), to the Ionian basin oceanic domain. Starting from the comparison of the two models we propose the following interpretation: within the Mediterranean geodynamic regime (dominated by slab rollback) the geometry of the African continental margin, located on the lower plate, represents a critical control on the evolution of subduction. As buoyant continental lithosphere entered the subduction zones, slab pull caused tears in the subducted lithosphere. This tectonic response in the final stages of arc evolution, strongly controlled by the paleogeography of the subducted plates, explains the observed differences between the Gibraltar and Calabrian Arcs.

Key words: teleseismic tomography, upper mantle, Gibraltar Arc, Calabrian Arc, subduction zone

1. Introduction

One of the outstanding and controversial features of the Mediterranean region is the presence of large-scale extensional basins within a convergent domain located between the African and European plates. Early studies recognized that the Central Western Mediterranean (CWM) extensional basins (Fig. 1) developed in a backarc setting (Dewey et al., 1973, 1989; Horvath and Berckhemer, 1982; Rehault et al., 1984), and also hypothesized that outward migration of subduction, due to slab sinking and retreat, was the most likely explanation for the observables (Malinverno and Ryan, 1986). Several papers stemmed from these early concepts, with progressive refinement of the timing and kinematics of backarc extensional and outward migration of the fold-and-thrust belt (e.g., Royden, 1993; Lonergan and White, 1997; Seranne, 1999; Argnani and Savelli, 1999).

A remarkable lateral variability in the character of the fold-and-thrust belts, timing of extension of backarc basins, and so on, is present in the Mediterranean orogen. Two main factors contributed to this result: i) non linear continental margins of the converging plates; and ii) gravitational instability of the subducted lithosphere.

The land-locked condition of the Mediterranean plate boundary, due to the presence of the Adriatic promontory, enhanced the effects of slab rollback (Le Pichon, 1982; Mascle et al., 1988). In fact, the collision of the Adriatic promontory with Eurasia around the Paleocene caused a slowdown in the Africa–Eurasia plate convergence, particularly for the N-ward component (Le Pichon et al., 1988; Dewey et al., 1989). This, in turn, promoted the activation of processes operating within the orogen, such as lithospheric root detachment, lithosphere delamination, lateral escape towards areas of depressed topography and rollback of dense oceanic slab, which are responsible for the origin of the Mediterranean extensional basins (i.e. Le Pichon, 1982; Dewey, 1988; Le Pichon et al., 1988; Otsuki, 1989; Argnani, 2000; Jolivet and Faccenna, 2000).

An additional important aspect is the interaction between lithospheric slabs and asthenosphere which could possibly result into slab breakoff or detachment and delamination of continental lithosphere. Lateral migration of slab breakoff has been proposed as a key factor for lithosphere dynamics in this region in the last 20-30 Ma, especially in the final stage of subduction (Wortel and Spakman, 1992, 2000; Carminati et al., 1998; Faccenna et al., 2004; Rosenbaum et al., 2008; Argnani, 2009). Within this setting, mantle flow possibly played a role in the deformation of the Gibraltar and Calabrian slabs (Gvirtzman and Nur, 1999; Faccenna et al., 2004; Baccheschi et al., 2008). Delamination of continental lithosphere is a process that likely operated within the Mediterranean orogens, following the subductional consumption of oceanic lithosphere (e.

g., Serri et al., 1993; Fillerup et al., 2010; Argnani, 2012; Levander et al, 2014). Although it is

known that continental rocks can experience subduction to depth over 100 km, before returning to shallow depth and becoming exhumed to the surface (e.g., Hacker et al., 2010; Butler et al., 2014), continental subduction is likely to be limited, both in extent and rate of subduction, as suggested by the overall stability of continents (Cloos, 1993). The tectonic evolution of the Mediterranean type orogen suggests that when a continental margin enters a retreating subduction zone (soft collision), the processes of subduction and slab retreat get to the end (e.g., Burchfiel and Royden 1991; Wortel and Spakman, 2000; Argnani, 2009).

The present structure and origin of the Gibraltar Arc-Alboran Basin system (GA) (Fig. 1) does not fit well in this unifying picture based on slab subduction and rollback, and alternative evolution scenarios have been proposed. Several authors do suggest that subduction of oceanic lithosphere (active or extinct) caused extension within the Alboran Basin in the Miocene by slab rollback (Royden, 1993; Lonergan and White 1997; Bijward and Spakman, 2000; Gutscher et al., 2002) or by slab detachment (Zeck, 1996). Alternatively, another group of authors presents an evolution for the Alboran basin initiating with lithospheric thickening during the Paleogene caused by the collision of Europe and Africa. The thickened continental lithosphere was later (ca. 25 Ma) detached by convective removal (Platt and Vissers, 1989) or by delamination (Calvert et al., 2000), leading to recycling of continental material (Levander et al., 2014). The collapse of this lithosphere caused extension of the Alboran and Algerian basins and uplift around the margin, edge delamination under the Betics and Rif margins and mixed continental-oceanic subduction (Booth-Rea et al., 2007; Duggen et al., 2005; Medaouri et al., 2014).

On the other hand, there is a general consensus that the Calabrian Arc-Tyrrhenian Basin system (CA) (Fig. 1) does fit well in the unifying picture: subduction with slab rollback has been the main factor in the opening of the Tyrrhenian Sea (Malinverno and Ryan, 1986), a well defined Wadati-Benioff zone is contained in a high seismic velocity body (Cimini and Marchetti, 2006, and references therein), and subduction-related magmatism is active under the CA (Barberi et al., 1974; De Astis et al., 2003).

Several tomography studies have concentrated on the Mediterranean mantle at different scales. They range from the global (e.g., Bijwaard and Spakman, 2000), to the European (e.g., Koulakov et al., 2009), to the Mediterranean scale (e.g., Piromallo and Morelli, 2003), down to a more regional scale (e.g., Cimini and Marchetti, 2006; Montuori et al., 2007; Bezada et al., 2013).

In this paper we focus on two tomographic P-wave velocity models of the upper mantle beneath the GA and CA regions, which give , with respect to previous models, a more resolved 3-D picture of the two subduction zones and surrounding asthenospheric mantle. Both tomographies take advantage of improved teleseismic-phase arrivals datasets obtained by integrating recordings from permanent national networks with recordings from recent dense deployments of temporary land and

marine (Ocean Bottom Seismometers - OBS) broad band arrays (Dahm et al., 2002; Monna et al., 2005; NEAREST project, http://nearest.bo.ismar.cnr.it). The teleseismic inversions were performed using a modern iterative technique (Rawlinson et al., 2006), by employing the same grid parametrization and depth extension (600 km) of the target volume, which allows for a direct comparison of the images. The GA tomography has been recently published (Monna et al., 2013a, 2015), while for the CA we present a new tomography model. Regarding the deep structure of GA the model shows features that were previously undetected or poorly resolved, in particular the lithosphere-upper mantle structure of the Gibraltar Strait-Atlantic sector, whereas for the CA the slab geometry and the surrounding asthenosphere are more accurately defined with respect to a previous models based on OBS data (Montuori et al., 2007). The inversion results are the starting point for a discussion and comparison of the two subduction systems within the geodynamic and tectonic framework of the Western Mediterranean region.

2 Geodynamic and tectonic evolution of the Central Western Mediterranean

Africa moved several 100's km towards Europe from the Cenomanian to the Chattian, and 200-300 km of convergence occurred in the Eocene-Oligocene time interval. Average N-S convergence between Africa and Europe slowed down since the Chattian, following the Alpine collision, and, as a result, rollback of subducted lithosphere initiated the opening of the backarc basins and the concomitant outward migration of the fold-and-thrust belts, that characterize the Western Mediterranean (Fig. 2) (Le Pichon, 1982; Dewey, 1988; Le Pichon et al., 1988; Argnani, 2000; Jolivet and Faccenna, 2000). The concomitant presence of calk-akaline volcanism along the European margin (Sardinia, offshore western Corsica, Provence) is an evidence that subduction of oceanic lithosphere occurred during the formation of these backarc basins (Argnani and Savelli, 1999).

The Balearic backarc basin was the first to open (Fig. 1) from late Oligocene to early-middle Miocene (Rehault et al., 1984; Chamot-Rooke et al., 1997; Faccenna et al., 1997) and extend to the western end of the Mediterranean, up to the Alboran basin (Watts et al., 1993; Booth-Rea et al., 2007). In the Algerian sector, the opening of the basin continued until late Miocene, possibly with oceanic crust emplacement in late Miocene (Mauffret et al., 2004; Booth-Rea et al., 2007; Medaouri et al., 2014). The Tyrrhenian backarc basin opened from Late Miocene to Pleistocene above the NW-dipping subduction of the Ionian lithosphere (Malinverno and Ryan, 1986; Kastens et al., 1988; Argnani and Savelli, 1999). Evidence from regional geophysics, arguments from plate kinematics and palaeo-reconstructions, suggest that the oceanic lithosphere, that subducted during the Tyrrhenian opening, belonged to a Triassic seaway (Argnani, 2005; Speranza et al., 2012).

The most striking feature in this process of backarc basin opening is the formation of the two tightly

arcuate features: the Gibraltar and Calabrian arcs (Fig. 1) (Horvath and Berckhemer, 1982; Faccenna et al., 2004; Rosenbaum and Lister 2004). The foreland of the Calabrian Arc fold-and-thrust belt faces the African plate (s.l.), although the nature of the lithosphere varies from oceanic in the apex of the arc to continental on either side. The foreland of the Gibraltar Arc fold-and-thrust belt, instead, covers both the African and Iberian plates; this plate boundary location contributes to additional tectonic complexity.

The large-scale models, that explain the Gibraltar and Calabrian arc subduction as coming from a single slab SE-ward retreat of the western Mediterranean (Faccenna et al., 2004; Carminati et al., 2012), may be too oversimplified to account for the geological complexity of the Alboran region. Other evolutionary models start with a shorter subduction zone, that is initially limited to the Balearic region (e.g., Lonergan and White, 1997; Rosenbaum et al., 2002; van Hinsbergen et al., 2014); this class of models seem to explain more satisfactorily the geological evolution of the Alboran region (Platt et al., 2013; Chertova et al., 2014).

2.1 Gibraltar Arc-Alboran Basin

The Atlantic sea-floor magnetic anomalies (Srivastava et al., 1990) indicate that the Iberia plate experienced a complex kinematics within the Africa-Eurasia convergence. Iberia was part of Africa from Late Cretaceous to Early Oligocene, whereas from Late Oligocene to present it became part of Europe, following the Pyrenean collision. As an alternative, recent reviews of the magnetic anomalies (Vissers and Meijer, 2012) allow for some 50-70 km convergence between Africa and Iberia for the Late Cretaceous-Middle Eocene time span. The west-ward arc propagation of the Betic-Rif fold-and-thrust belt is larger than the 200-250 km N-S convergence between Africa and Iberia, as suggested by the length of the east-dipping subducted slab imaged by high-resolution seismic tomography (e.g., Bezada et al., 2013; Palomeras et al., 2014). This propagation has been modelled with a substantial westward slab rollback (e.g., Royden, 1993; Lonergan and White, 1997; Gutscher et al., 2002; Rosenbaum et al., 2002). The internal Betics and Rif units (Fig. 2a) have a continental substrate of Palaeozoic age with a Mesozoic-Cenzozoic sedimentary cover, and have been affected by Palaeogene HP/LT metamorphism (Platt et al., 2013). These internal units have been also recovered in the Alboran Sea, defining the so-called Alboran Domain. The external Betics and Rif units are characterized by successions derived from the Iberian and African passive continental margins that were emplaced during the opening of the Alboran basin (e.g., Blankenship, 1992; Wildi, 1983). The sediments of the Flysch basin were thrusted by the Alboran Domain units that were moving west-southwest-ward during the Oligocene-Early Miocene (Fig. 2a; Wildi, 1983). The basement of the Flysch basin domain was likely oceanic and could correspond to the oceanic slab imaged by tomography under the Alboran basin. Most of the vertical-axis rotation and arc

211 formation in the Rif and western Betics was accomplished by the early Pliocene, as indicated by
212 paleomagnetic data (e.g., Platt et al., 1995; Platzman et al., 1993; Krijgsman and Garces, 2004;
213 Cifelli et al., 2008; Fig. 2a).
214 The Alboran Sea basin, which was formed in the Neogene as a result of extensional tectonics, is
215 currently floored by thinned continental crust, 13-20 km thick (Watts et al., 1993), and by
216 magmatically accreted arc-type crust in its eastern sector (Booth-Rea et al., 2007).
217 Recent tectonic models try to account for the details of the geological evolution of the Alboran
218 region. Platt et al. (2013), following their previous work, propose a NW-ward Paleogene subduction
219 that originated the Alboran Domain, followed (during the Early Miocene) by orogenic collapse and
220 a new subduction on the Iberian side of the Alboran Domain. As an alternative explanation, Vergés
221 and Fernandez (2012) propose a continuous southward subduction of the Iberian plate, with slab
222 rollback and slab break-off, that would account for both the Paleogene and Miocene subduction
223 events. This reconstruction which describes the evolution of the Betics, requires the occurrence of a
224 major transform boundary that separates the Betics (northward polarity) from the eastern
225 Maghrebides (southward polarity) subduction segments, and implies some difference in the tectonic
226 evolution of the Maghrebian belt of north Africa, for which there is not much evidence in the field.
227 Finally, a recent reconstruction (Van Hinsbergen et al., 2014) assumes that the Alboran terranes
228 mostly formed along an oblique subduction zone located south of the Balearic islands, partly
229 building on the reconstruction of Rosenbaum and Lister (2004). Here, the early Miocene heating
230 and exhumation affecting the peridotite mantle and overlaying Alboran terranes occurred within a
231 forearc setting, with the Alboran terranes subsequently dispersed across the western Mediterranean
232 during backarc opening.
233 A number of tomographic studies have been performed in the last decade to image the deep seismic
234 velocity structure of the GA. These studies agree on the presence of a high-velocity body under the
235 Alboran Sea, down to mantle depths (Blanco and Spakman, 1993; Bijwaard and Spakman, 2000;
236 Calvert et al., 2000). Very recent high-resolution tomography studies (Bezada et al., 2013;
237 Palomeras et al., 2014; Thurner et al., 2014; Bonnin et al., 2014; Villaseñor et al., 2015) confirm the
238 presence of a slab-shaped high velocity body, seen from the surface down to the bottom of the
239 transition zone. The GA slab has a small curvature radius, similarly to the CA, but it does not show
240 a Wadati-Benioff plane. In fact, sub-crustal seismicity (Figs. 3 and 8) is mostly located near the
241 Strait of Gibraltar within 120 km depth and distributed in a very narrow north-south oriented
242 vertical band (Seber et al., 1996), with a mixture of focal mechanisms showing both compression
243 and extension (Buforn et al., 2004). Deep earthquakes (depth > 300km) are rare and occur at the
244 bottom of the transition zone (~630 km depth) under southern Spain in the Granada area, and show
245 dip-slip motion with a vertical north–south plane and a nearly horizontal plane with the pressure

axis dipping 45° to the east (Buforn et al., 2004, 2011).

The large amount of geophysical and geological data for this area confirms a complex geodynamic evolution, and in fact the high velocity anomaly below the Alboran has been interpreted as a continuous subducting slab (Gutscher et al., 2002; Piromallo and Morelli, 2003), as a broken-off slab (Blanco and Spakman, 1993), and as lithosphere which has undergone delamination (Calvert et al., 2000), or convective removal of the root (Platt and Vissers, 1989).

One of the open problems for the GA has been the interaction between the Atlantic and Alboran domains, west and east of the Gibraltar Strait. Although global scale tomography studies cover both regions, they do not have the capability to resolve the finer details. On the other hand, in spite of the increase in available data, the great majority of the higher resolution (regional scale) tomography models do not image the mantle below the Atlantic region west of the Gibraltar Strait due to a lack of station coverage at sea. A recent regional scale tomography model (WMGC-OBS) based on OBS data which includes both domains, has been proposed by Monna et al. (2013a). A relevant aspect of model WMGC-OBS is that there is a separation of the two lithospheres of the two domains, thus excluding the existence of a single continuous slab coming from the Atlantic side and subducting eastward below the Alboran.

2.2 Calabrian Arc-Tyrrhenian Basin

The Calabrian Arc connects the Sicilian Maghrebides and Southern Apennines and is characterized by a stack of basement units, coming from different levels of a Hercinian continental crust (Fig. 2b) (Bonardi et al., 2001). A thick forearc sedimentary succession crops out in the Ionian side of Calabria, supporting the accretion of the Calabrian Arc terranes within a subduction system (Bonardi et al., 2001). The wide accretionary complex of the External Calabrian Arc extends into the Ionian Sea and is confined to the NE and SW by the Apulian and Malta Escarpments, respectively (e.g., Biju Duval et al., 1982; Argnani and Bonazzi, 2005; Argnani, 2006).

The evolution of the Calabrian Arc is strictly related to the opening of the Tyrrhenian backarc basin (Malinverno and Ryan, 1986; Patacca et al., 1993) and is marked by a progressive narrowing of the subducted slab. Palaeomagnetic data support the saloon-door opening of the Tyrrhenian basin (Cifelli et al., 2007), as the structural units of the Southern Apennines experienced a counter-clockwise rotation of 60° during Middle-Late Miocene (Gattacceca and Speranza, 2002), whereas the structural units of the Sicilian Maghrebides show a large clockwise rotation of ca. 70° between Langhian and Late Tortonian (Channell et al., 1990; Speranza et al., 1999).

The Tyrrhenian Basin is located on the wake of the Apennines and Sicilian Maghrebides. The amount of extension is greater in the southern basin which, in fact, is characterized by a thin crust (less than 10 km) and high heat flow (Kastens et al., 1988), with possibly wide stretches of

exhumed mantle (Prada et al., 2014). A girdle of volcanic islands, the Aeolian Islands, located north of Sicily represents the volcanic arc of the Tyrrhenian subduction, with calc-alkaline activity that spans from 1 Ma to the Present (Fig. 2b) (Barberi et al., 1974; De Astis et al., 2003). The rocks of the Campania Magmatic Province (Fig. 2b), that includes the Campi Flegrei high potassium calcalkaline (2.0 - 1.6 Ma), the Campi Flegrei, Ischia and Procida shoshonites (100 ka - Present), and the Vesuvio leucitite and leucitite basanite (1 Ma - Present), also show affinity with island arc magmatism. Magmatic rocks from Campania and the Aeolian volcanic arc have comparable geochemical features, suggesting a similar Oceanic Island Basalt mantle source, enriched by components derived from subducted oceanic lithosphere (Serri, 1990).

The onshore Calabrian Arc has been affected by major uplift in the last 0.8 Ma, with rates up to 2.0 mm/yr (Westaway, 1993; Bordoni and Valensise, 1998), and presents extensional grabens filled by Late Pliocene-Quaternary sediments, trending both parallel and perpendicular to the arc (Tortorici et al., 1995). This active tectonic regime is supported by extensional focal mechanisms (e.g., Vannucci et al., 2004). To the west of the central Aeolian Islands, earthquake focal mechanisms indicate that active compressional deformation occurs offshore northern Sicily (Pondrelli et al., 2004; Argnani et al., 2007; Serpelloni et al., 2007), although the seismogenic structures have not been properly identified. This compressional boundary has been considered as part of a kinematic rearrangement that occurred about 2 Myr ago (Jenny et al., 2006).

For the CA there is a wide consensus that subduction of oceanic lithosphere below the southern Tyrrhenian is taking place. In the tomographic images the subduction is represented as a narrow arc-shaped high velocity body which flattens in the transition zone at the 660 km discontinuity between upper and lower mantle (Cimini, 1999; Piromallo and Morelli, 2003; Spakman and Wortel, 2004; Montuori et al., 2007). The existence of subduction and overlying mantle wedge for the CA is confirmed by other geophysical and geochemical observations, such as, for example, the presence of a volcanic arc (Barberi et al., 1974; De Astis et al., 2003). Furthermore, the spatial distribution of the deep events (Figs. 3 and 9) (Frepoli et al., 1996) shows a Wadati-Benioff zone dipping ~70° NW beneath the southern Tyrrhenian, down to about 600 km depth (Cimini and Marchetti, 2006, and references therein). The focal mechanism P-axes show steep down-dip compression at intermediate depths (between 160 and 370 km). The deepest events (below 370 km) have P-axes with shallower dip (Frepoli et al., 1996).

The tomographic models have been interpreted as representing the final result of a subduction with rollback process which has caused the opening of the Tyrrhenian Sea in the last ~13 Ma (Wortel and Spakman, 2000; Piromallo and Morelli, 2003).

The tomographic images show that there is not a continuous slab under the Italian peninsula, as it is interrupted by a low-average velocity volume below the central-southern Apennines at lithospheric

depths. Other distinct high velocity bodies are found below the Northern Apennines and the Alps (Spakman and Wortel, 2004; Piromallo and Morelli, 2003; Giacomuzzi et al., 2012). This distribution in space of the high velocity bodies, prompted several authors to hypothesize the existence of an original single slab which had undergone one or more slab tears and/or detachment (e.g., Wortel and Spakman, 1992; 2000; Amato et al., 1993; Spakman and Wortel, 2004).

In recent years, thanks to the improvement of the Italian National Seismic Network, regional tomography studies could resolve finer details of the CA lithosphere-asthenosphere structure (e.g., Chiarabba et al., 2008). Furthermore, inversion of the 3-D attenuation structure (Chiarabba et al., 2008; Monna and Dahm, 2009) has added independent constraints, which are especially helpful in distinguishing the role of chemical composition and temperature as causes for seismic velocity anomalies.

3. Teleseismic tomography models of GA and CA based on OBS data

In this section we describe 3-D P-wave velocity models computed for the upper mantle of GA and CA. The CA images are derived from the new tomographic model presented in this work The GA images are derived from model WMGC-OBS presented in two recent papers (Monna et al., 2013a, 2015). To calculate both models we used accurate time picks of teleseismic waveforms recorded by the integrated arrays shown in Fig. 4 at epicentral distances between 25° and 95° (P phases) from worldwide Mw ≥ 5.5 earthquakes. The time picks were corrected for station elevation/bathymetry, Earth's ellipticity, local crustal structure (see sections 3.1 and 3.2), and then reduced to relative arrival time residuals using the ak135 global velocity model (Kennett et al., 1995). We applied the iterative nonlinear tomography method developed by Rawlinson et al. (2006) to map these residuals into 3-D P wave velocity anomalies. We note that inversion of relative traveltime residuals produces only 3-D velocity perturbations with respect to an average (usually 1-D) Earth model modified for the appropriate crustal structure. In the inversion scheme, the calculation of teleseismic wavefronts and the traveltimes from the base of the model volume to the array of receivers on the surface is performed with the fast marching method (FMM) (Sethian and Popovici, 1999). For both study regions, the bottom of the 3-D model was set at 600 km depth and the grid spacing used for the parametrization of mantle structure was 60 km. Outside the model volume the Earth is assumed to be spherically symmetric, which allows the use of a 1-D global reference model to rapidly compute the traveltimes from the distant sources to all grid nodes at the bottom. For a detailed description of the technique and the inversion equation we refer the reader to Rawlinson et al. (2006). In both cases, the nonlinear inversion was performed by testing different values of the maximum iteration number, to check the overall stability and performance in modeling the residual data. The tomographic images displayed in the following subsections describe the velocity field

computed at the third iteration, as only minor improvements in the data fit (<1%) and small structural changes in the velocity patterns were observed, for both cases, with successive inversion steps. Since the parametrization for the two models is the same, their direct comparison is possible. In general, the images for the CA show stronger anomalies, which explains the different scale of the color palettes in Figs. 6-10, +/- 0.2 km/s for the GA and +/- 0.3 km/s for the CA, in spite of the stronger regularization applied in the CA inversion. The difference in the amplitude of the anomalies could be explained by differences in accuracy of the two datasets and in the RMS reduction, but also by a greater heterogeneity of the CA upper mantle with respect to GA. With respect to previous tomographic studies at the same scale (e.g., Montuori et al., 2007; Giacomuzzi et al., 2011) the CA inversion we present has greater resolution and coverage of the oceanic areas. A comparison between the resolution of the GA and CA models is performed using the "checkerboard tests" displayed in Fig. 5. In this test the input velocity model is formed by alternating regions of fast and slow anomalies (with added gaussian noise to account for errors in the data; Monna et al., 2013a). The recovered pattern provides information on the well resolved areas of the models. We note that the CA model could be parametrized with a smaller grid (~80 km), but we have chosen the same parametrization as for GA (100 km) to better compare them. In any case, in both cases the parts that we intepret are in volumes of the models that are reliably reconstructed in the synthetic tests. We have clarified this aspect in the text.

3.1 Gibraltar Arc (GA) model

The information on the GA model that we present in the following is an updated summary of the results presented in Monna et al. (2013a, 2015). The teleseismic data set for the GA model is composed by 152 events recorded in the period 2007-2009 by the permanent networks of Spain, Portugal, and Morocco, and by the NEAREST OBS array (Carrara et al., 2008) deployed in the Gulf of Cadiz from August 2007 to August 2008 (in total 111 seismic stations; Fig. 4; left). This data set provided 6238 residuals for the tomography. The OBS array (25 seafloor broad band stations) recorded waveforms from 67 events. Other waveforms were collected from two land stations operating in SW Portugal installed during the experiment, and from the European Integrated Data Archive (EIDA; http://eida.rm.ingv.it). To improve ray coverage, arrival times extracted from the ISC bulletin (http://www.isc.ac.uk) were also added. The average time pick error was estimated in 0.43s. A crustal correction was applied based on four models which take into account up-to-date information available from published studies. These four models represent the Atlantic Ocean Domain, the Iberian Peninsula, Betics and Rif, and Atlas (see Table 1 in Monna et al., 2013a).

The GA-Alboran Basin model lateral extension (Fig. 3; left) spans 12.0° in latitude (from 31.0°N to

43.0°N), and 16.0° in longitude (from 15.0°W to 1.0°E). The 3-D velocity grid comprises 5544 nodes at 60 km spacing in all three dimensions (depth, latitude, longitude). The tomographic inversion was carried out with damping and smoothing parameters of 5.0 and 2.5, respectively. The three-step inversion reduced the data variance by 26% from 0.53 to 0.39 s^2 (Monna et al., 2013a).

We now briefly describe the main features found in the GA model as represented in Figs. 6 (maps) and 8 (cross-sections). Further details on the velocity pattern imaged in the Atlantic portion of the GA model can be found in Monna et al. (2015). The tomographic images show:

1) A high velocity body with arcuate geometry under the Betics-Alboran Sea area (Al-HVA). This fast structure depicts an L-shaped slab steeply dipping from the uppermost mantle to the transition zone where it becomes less curved.

2) A high-velocity body under the Horseshoe Abyssal Plain in the Atlantic region (HAP-HVA).

3) A diffuse low velocity anomaly (EAt-LVA) present in the Eastern Atlantic region south of the Gloria fault, down to the mantle transition zone.

4) A prominent low velocity anomaly below the Gulf of Cadiz (GC-LVA) which separates the two high-velocity bodies found under the Alboran (Al-HVA) and Atlantic regions (HAP-HVA).

Al-HVA extends from the surface to the base of our model (Figs. 6 and 8), and its maximum width is ~300 km in the EW direction below the Granada region (AA'). The AA' profile, which crosses the southern tip of the Iberian peninsula, shows the transition from the Atlantic to the Alboran domain, and the width of the slab (100–200 km). Section BB' crosses the Alboran Sea and shows the north-south extension of Al-HVA (approximately 300 km). Subcrustal seismicity is distributed along an arc-shaped belt with the deeper events contained in the uppermost part of the Al-HVA. These intermediate-depth earthquakes have a distribution which is not typical of subduction zones, in contrast with the clear Benioff zone of the Calabrian Arc (Fig. 9). Nevertheless, they provide information on the subducted oceanic slab beneath the Alboran basin, as their occurrence is usually linked to dehydration reactions in subducting oceanic lithosphere (e. g. Hacker et al., 2003).

GC-LVA extends from the top of the model down to ~250 km depth in (AA'). Below the NEAREST OBS array, roughly under the Horseshoe Abyssal Plain, the model shows HAP-HVA down to a depth of ~240km (Fig. 6). From profile AA' we obtain an east-west extension for HAP-HVA of ~250 km. This feature has been interpreted as a developed subduction process in the Gorringe Bank region (Monna et al., 2015).

3.2 Calabrian Arc (CA) model

The teleseismic events were collected from the Italian National Network (managed by INGV) and from temporary experiments performed both at sea (TYDE (Dahm et al., 2002) and NEMO-SN1 (Favali et al., 2013) and on-land (SAPTEX (Cimini et al., 2006) and SeSCAL (Frepoli et al., 2011))

during the last decade. The integrated network used in this study includes 209 stations (Fig. 4; right). The dataset spans the years 2000-2008 and consists of 276 events for a total of 8635 residuals. Crustal corrections of traveltime residuals were performed on the basis of two models (Monna et al., 2013b), one for the continental part (Sicily and Apennines) and one for the oceanic part (southern Tyrrhenian and Ionian Seas). Differently from the GA data set, the CA data set comes all from very accurate handpicked arrival times with an estimated average error of 0.16s which is almost 1/3 of the GA time pick error. The high quality of the CA data led to a solution model which is associated to a significant reduction of the residual variance.

The CA-Tyrrhenian Basin model lateral extension (Fig. 3; right) spans 8.0° in latitude (from 36.0°N to 44.0°N), and 12.0° in longitude (from 9.0°E to 21.0°E). The 3-D velocity grid comprises 3344 nodes spaced apart, 60 km in all the three directions, as for the GA model.For the CA model we obtained a variance improvement of over 51%, from 0.41 to 0.20 s^2.

The main features found in the CA model, represented in Figs. 7 (maps) and 9 (cross-sections), are:

1) A high velocity body with slab-like shape under the Tyrrhenian Sea area (STy-HVA).

2) A high-velocity body under the Apennines (Ap-HVA).

3) A high velocity anomaly visible below the Adratic Sea (Adr-HVA) adjacent to the Ap-HVA visible below 300 km depth.

4) A diffuse low velocity anomaly (STy-LVA) adjacent to Sty-HVA and Ap-HVA, found down to ~350 km depth. In the depth interval ~100-300 km, STy-LVA and the prominent low velocity zone imaged in the Ionian side (Io-LVA) join in a continuous belt surrounding the main fast structures.

5) A low velocity anomaly (Ap-LVA) at lithospheric depths below the central and southern Apennines, down to 120 km depth. Ap-LVA interrupts the lateral continuity of Ap-HVA, suggesting that the Apenninic slab has been subjected to tearing and slab window formation processes. Its geometry is clearly defined by the NW-SE profile shown in Fig. 10 (cross-section CC').

The deep seismicity delineates a well defined Wadati-Benioff plane, which is included in the volumes with the highest velocity perturbations, and is mostly concentrated in the 100-350 km depth range (Figs. 7 and 9). The high velocity slab shows a remarkable horseshoe shape in the 100-300 km interval. STy-HVA extends from crustal depths down to the bottom of the model (the lower part of the transition zone), and its lateral extension is about 350 km (Fig. 9, BB'). Ap-HVA appears from uppermost mantle depths down to ~120 km depth, as two distinct anomalies, one under the central (CAp-HVA) and the other below the southern Apennines (SAp-HVA). Ap-HVA seems to merge with Sty-HVA from 180 km depth down to the bottom of the model (Fig. 7).

The pattern of low P-wave velocity perturbations visible around Sty-HVA (Fig. 7), is recognizable also in the PM0.5 model by Piromallo and Morelli (2003) at 150 and 200 km depth.

4. Discussion

The aim of this discussion is not to tackle the reconstruction of the long-term evolution of the Western Mediterranean region, which has been described in several papers, but rather to focus on the final stages of arc formation in the Western Mediterranean and, in particular, on the interaction of the subduction system with the portions of continental margin that are approaching the subduction zone. Some key features of the Gibraltar and Calabrian subduction systems are compared and contrasted on the basis of the two presented tomographic models and other geophysical and geological data. We first describe and compare the lithosphere-asthenosphere structure of the two arcs, then their seismicity and active tectonics, and finally we focus on the slabs evolution.

Lithosphere-asthenosphere structure

There are two main high velocity anomalies (HVA) evident in the horizontal layers (Figs. 6 and 7), that underlie the Alboran (Al-HVA) and the Tyrrhenian (STy-HVA) basins. Both HVAs reach the mantle transition zone down to at least 600 km depth, the bottom of our models. While the STy-HVA presents a more evident arcuate shape, the Al-HVA is thicker, and the stronger part of the anomaly is blob-like, especially in the top 300 km. Moreover, the STy-HVA mostly underlies the Tyrrhenian basin, whereas the Al-HVA is mostly located below the Betics and the Granada area, where the scarce deep seismicity is found.

In both areas there are strong LVAs that surround the slab. In the Calabrian Arc the LVA underlies the Tyrrhenian basin (STy-LVA) and the oceanic crust of the Ionian Sea (Fig. 9) . The lithosphere-asthenosphere structure under the Ionian side is only partially resolved due to the lack of long term broadband OBS deployments in the Western Ionian Sea. Continuity of the slab is inferred only from indirect evidence (e.g., slab geometry and seismicity). On the contrary, the lithosphere-asthenosphere structure below the Gulf of Cadiz (GC-LVA, Fig. 8) is well resolved and represents the key feature separating the two high velocity anomalies underlying the Atlantic and the Alboran, respectively (Monna et al., 2013a). We are confident that GC-LVA is not an effect of low velocity uppermost crustal layers smeared down the upermost mantle, given the strong crustal correction we applied that includes a thick low-velocity sedimentary layer (see Table 1 in Monna et al., 2013a).

Seismicity and active tectonics

Comparison of vertical profiles in Figs. 8 and 9 also clearly shows a very different spatial distribution of sub-crustal seismicity, with a typical Wadati-Benioff zone for the CA and a belt of intermediate-depth seismicity (<120km) for the GA. While for the CA seismicity is included in the

volume with the largest positive velocity anomalies, for the GA seismicity is concentrated on top of the HVA. Profiles BB' give a measure of the width of the two slabs, which is about 300 km for Al-HVA and 350 km for STy-HVA.

The different patterns of sub-crustal seismicity in the Gibraltar and Calabrian Arcs, suggests that a different tectonic regime is active in the two arcs (Fig. 3). It is noteworthy that only limited seismicity occurs offshore in the CA accretionary prism, but remarkable seismicity with large earthquakes, mostly hystorical but also instrumental, characterizes the onshore, uplifted region of the arc, continuing into the southern Apennines. Focal mechanisms of crustal earthquakes indicate orogen-perpendicular extension (Vannucci et al., 2004; Frepoli et al., 2011). In the GA almost no seismicity occurs in the outer accretionary prism; instead, seismicity (found also down to ~60 km) is present in the Gorringe Bank-Horseshoe Abyssal Plain (e.g., Geissler et al., 2010), where it is associated to a high velocity subducting lithosphere (Monna et al., 2015). No relevant seismicity is present at the apex of the GA, whereas some seismicity is related to the right-lateral strike-slip regime found in the eastern Betics, and a remarkable crustal seismicity is present in the Alboran basin (Serpelloni et al., 2007; Stich et al., 2006; 2010), along the Trans-Alboran shear zone (Alvarez-Marron, 1999). The distribution of crustal seismicity appears to reflect the occurrence of a diffuse plate boundary deformation that shifts from the Gloria Fault-Gorringe-SW Iberia system to the Maghrebides of north Africa; this southward shift occurs just across the Alboran basin (Fig. 3) (Serpelloni et al., 2007).

Evolution of the two subduction systems

The evolution of the Mediterrenean subduction is strongly controlled by the paleogeography of the African margin (lower plate), and in particular by the location and extent of its oceanic domains. A tectonic reconstruction at Tortonian time (Fig. 11) shows the different stages in the formation of the Gibraltar and Calabrian arcs. This time is crucial since the Tyrrhenian basin was in its initial stage, and the Calabrian Arc formed subsequently, driven by the subduction and rollback of the Neotethyan ocean located between Africa and Adria. On the contrary, the Gibraltar Arc was almost completely defined.We propose an interpretation that is summarized in Fig. 12.

During the evolution of the retreating Mediterranean subduction, the soft collision of the outward-migrating orogen with the African margin first occurred in the Magrebides (e.g., Lonergan and White, 1997; Rosenbaum and Lister, 2004). The soft collision was followed by a slab breakoff, marked by a change from orogenic to anorogenic magmatism (Maury et al., 2000; Abbassene et al., 2016), that disrupted the originally continuous subducted slab, and propagated laterally both eastward and westward (Fig. 12), to originate the Calabrian and Gibraltar Arcs, respectively

(Wortel and Spakman, 2004). Slab tearing focussed trench retreat, favouring the formation of tightly arcuate subduction zones (e.g., Schellart et al., 2007). The narrow CA subducted slab (Fig. 9; BB') is discontinuous on either side, underneath Sicily and southern Apennines. The lack of high velocity bodies underneath western Sicily is likely a result of progressive lithospheric tearing. Tearing propagated eastward along the north African continental margin, removing the slab, during the Tyrrhenian opening from 10 to 2 Ma (Carminati et al., 1999; Faccenna et al., 2004; Goes et al., 2004; Argnani, 2009). An interruption of the slab or slab window underneath the Southern Apennines (Fig. 12) is visible in the tomography models as a low velocity anomaly at lithospheric depths (Fig. 10). The presence of a slab window is consistent with abundant volcanic products younger than 2 Ma in the Campania Magmatic Province, which supports the tapping of deep mantle reservoirs (Serri, 1990).

The low mantle velocity underneath Calabria (e.g., Mele, 1998) suggests a decoupling of the slab from the overlying lithosphere, that can be partly responsible for the recent uplift of Calabria (Gvirtzman and Nur, 1999; Argnani, 2000). A role of toroidal mantle flow dynamically sustaining the Calabrian topography has also been inferred (Faccenna et al., 2011), although the contribution of dynamic topography is likely a minor one (Molnar et al., 2015). The existence of lithospheric tears located on either side of the Calabrian Arc is supported also by local earthquake and seismic velocity distribution. Some authors have inferred the occurrence of north-west-trending tears, that are supposed to favor the south-eastward drift of Calabria (e.g., Neri et al., 2012). The seismicity gaps and reduced seismic velocities presented by Neri et al. (2012), however, seem to outline discontinuities that propagated parallel to the trench, which are difficult to reconcile to north-west-trending lithospheric tears that would allow displacement perpendicular to the trench. In this last case, in fact, the tomographic model should suggest slab segments that are laterally shifted in the north-west-direction with respect to each other, a feature that is not observed (Fig. 7). In fact, the only discontinuity perpendicular to the trench is an incipient, ca. north-south-trending, lithospheric tear (STEP fault) (Govers and Wortel, 2005) which is located offshore eastern Sicily (Figs. 2b and 11) (Argnani, 2009).

As described in the following, we infer that the portion of continental lithosphere defined by our tomography (Fig. 6) may have played a role in preventing a further evolution of the Gibraltar Arc. In the Gibraltar system the narrow (ca. 300 km wide) high velocity body is not a typical subducting slab, given its seismicity and its blob-like shape underneath the Betics (Fig. 6). Recent studies show that underneath most of the Betics the subducted slab is partly torn off its adjacent continental margin, whereas underneath the Rif it is still attached to the crust (e.g., Levander et al., 2014). In particular, observations from seismic tomography (Bezada et al., 2013; Palomeras et al., 2014) and receiver function analysis (Mancilla et al., 2015; Thurner et al., 2014) are consistent with the

presence of continental crust that was removed from the continental margins and is now part of the slab.

Both slabs below the Alboran and Tyrrhenian basins are thought to belong to narrow oceanic basins. The original oceanic domain belonged to the Alpine Tethys and Neotethys for the Calabrian subduction (e.g., Stampfli and Borel, 2002; Argnani, 2005), and to the Alpine Tethys and Central Atlantic for the Gibraltar subduction (e.g., Gutscher et al., 2012). However, the physical connection between Alpine Tethys and the Central Atlantic proposed by several authors (see Section 2.1) can be questioned. In fact the occurrence of an arcuate structure underneath the Gibraltar Arc, with a seismic velocity pertaining to continental lithosphere, suggests the presence of a possible continental domain located just west of Gibraltar in the GA model (Figs. 6 and 8; Monna et al. (2013a, 2015)). Recent tomography models (Bonnin et al., 2014; Villaseñor et al., 2015) show a low velocity anomaly at lithospheric depths just west of the Gibraltar Strait, which agrees very well with our GC-LVA.

The existence of possibly Jurassic oceanic crust in the Gulf of Cadiz has been documented by refraction data (Sallares et al., 2011), but the refraction profile is located further to the west of the low-velocity anomaly that we attribute to continental lithosphere (Fig. 2a), and recent refraction data across the Gibraltar Strait show a continental crustal structure (Gil et al., 2014). The boundary between continental and oceanic mantle domain is placed just east of Gibraltar Arc (Morais et al, 2015) through receiver function analysis, and the continuity of the thickened crust along the Gibraltar Arc (Mancilla et al., 2015) seems to support the occurrence of a substrate of continental nature. Although Mancilla et al (2015) propose an oceanic connection between the Atlantic and the subducted slab, their receiver functions data are also compatible with our hypothesis, as their data do not constrain the nature of the crust in the western offshore of Gibraltar.

The presence of a portion of continental lithosphere that has limited the Alpine Tethys to the west, and that is now choking the subduction underneath the Alboran basin, fits well with other recent high resolution tomography models (Bonnin et al., 2014; Palomeras et al., 2014; Villaseñor, 2015). These tomography images can be explained by a process of ongoing delamination, with a sinking oceanic slab pulling and thinning the lithosphere of the Betics and Rif.

In our interpretation, continental lithosphere is entering subduction in the Gibraltar Arc from the west, and due to its positive buoyancy it contrasts the slab pull effect, favoring slab break-off, delamination, and limiting asthenosphere wedging west of the Gibraltar Arc, and thus limiting uplift and extension. Active extensional tectonics and recent uplift, in fact, have not been observed at the apex of the Gibraltar Arc; recent uplift occurs mostly in the Sierra Nevada (Perez-Pena et al., 2010; Braga et al., 2003). On the contrary, in the CA, subduction of oceanic lithosphere is well documented, with the slab connected to the oceanic Ionian lithosphere (Fig. 11) (Argnani, 2005;

Speranza et al., 2012). The slab pull, which is still active, favored the wedging of asthenospheric mantle and ensuing uplift (Gvirtzman and Nur, 1999). The uplift, in turn, promotes gravitational collapse towards the topographically low Ionian Sea and possibly triggers the extension which is ongoing in Calabria (Argnani, 2000; D'Agostino et al., 2011).

5. Summary and Conclusions

The Western Mediterranean subduction system was active mostly during the Neogene, creating the arcuate mountain belts and deep basins that characterize the Mediterranean orogen. Slab sinking and trench retreat contributed to the opening of the Balearic and Tyrrhenian basins. Although the main driving force is likely given by trench retreat of oceanic subduction within a low plate-convergence setting, additional complexities came into play throughout the evolution of the Western Mediterranean, the major factor being the interaction between the European subduction in the Alps and the African subduction in the Apennines (e.g., Argnani, 2012). In this paper we focus on the origin of the two tight loops of the Gibraltar and Calabrian Arcs using two teleseismic tomography models. These two arcuate features have been often described together and considered as typical of the Western Mediterranean evolution (Horvath and Berckhemer, 1982; Rosenbaum and Lister, 2004; Faccenna et al., 2004). The fact that trench retreat has overtaken convergence throughout the Neogene evolution of the Mediterranean implies that the nature of the lower plate lithosphere may strongly affect the geodynamic balance of the system. In fact, the arcuate orogenic belts were mostly formed in the final stages of the Western Mediterranean evolution and, apart from trench rollback, they were affected in an important way by the geometry of the continental margins. In the Gibraltar Arc both slab rollback and gravitational potential of a thickened orogen have been driving forces for the emplacement of the Alboran units in the early Miocene.

The continuity of oceanic subduction represents the major difference between the Calabrian and Gibraltar arcs. In the Gibraltar Arc the continental margin domain is entering subduction. The GA tomography model suggests that the Gibraltar Arc was docking into a portion of thinned continental crust, located just west of Gibraltar (Fig. 12). This buoyant lithosphere was likely responsible for the end of trench retreat, and its related extension in the Alboran basin. As the subduction of the oceanic lithosphere was progressively completed, the continental margin lithosphere of Africa and Iberia entered into the subduction zone and was pulled down by the sinking oceanic slab, leading to ongoing continental delamination underneath the western Rif and the Betics and slab breakoff (Bezada et al., 2013; Levander et al., 2014; Thurner et al., 2014; Mancilla et al., 2013, 2015). Active deformation in the region is reflected in the location of the roughly east-west-trending Africa-Iberia plate boundary. This boundary shifts from the southwest Iberian margin to north Africa just across the Alboran Sea, mostly ignoring the arcuate structures of the Gibraltar Arc, and

confirming that subduction is not the main operating mechanism at the moment (Zitellini et al., 2009).

In the case of the Calabrian Arc, the slab is connected to the Ionian basin that is likely floored by oceanic lithosphere (Argnani, 2005; Speranza et al., 2012). The opening of the southern Tyrrhenian basin caused a soft collision of the outward migrating fold-and-thrust belt into the continental margins of Adria (southern Apennines) and Africa (Sicilian Maghrebides). This soft collsion was followed by a trench-parallel slab break-off in both the southern Apennines and Sicilian Maghrebides (Fig. 12). This process produced the slab window visible, in our CA tomographic model (Figs. 7 and 10). The window underneath Sicily is much wider because the slab was progressively torn off at the African margin during the Tyrrhenian backarc opening (Argnani, 2009), whereas the slab window under the Southern Apennines formed in the last 2 Ma and extends for about 300 km along the chain (Fig. 12). A choked subduction, at much reduced rates, of a narrow oceanic slab continued underneath Calabria. The pull exerted by the sinking oceanic lithosphere, narrowed after slab breakoff on either side of the arc, promoted the initiation of lateral tears (or STEP fault) (Govers and Wortel, 2005), particularly on the western Ionian side and along the north-south branch of the Aeolian Islands (Argnani and Bonazzi, 2005; Argnani et al., 2007; Argnani, 2009). The sinking Ionian slab decoupled from the overlying Calabrian orogen and released the upper plate from compressional stresses, favouring the wedging of asthenosphere, as indicated by reduced upper mantle Pn velocities (Mele et al., 1998) and confirmed by seismic attenuation measurements (Chiarabba et al., 2008; Monna and Dahm, 2009); this last process, in turn, promoted uplift and extension in the Calabrian Arc.

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Figure 1

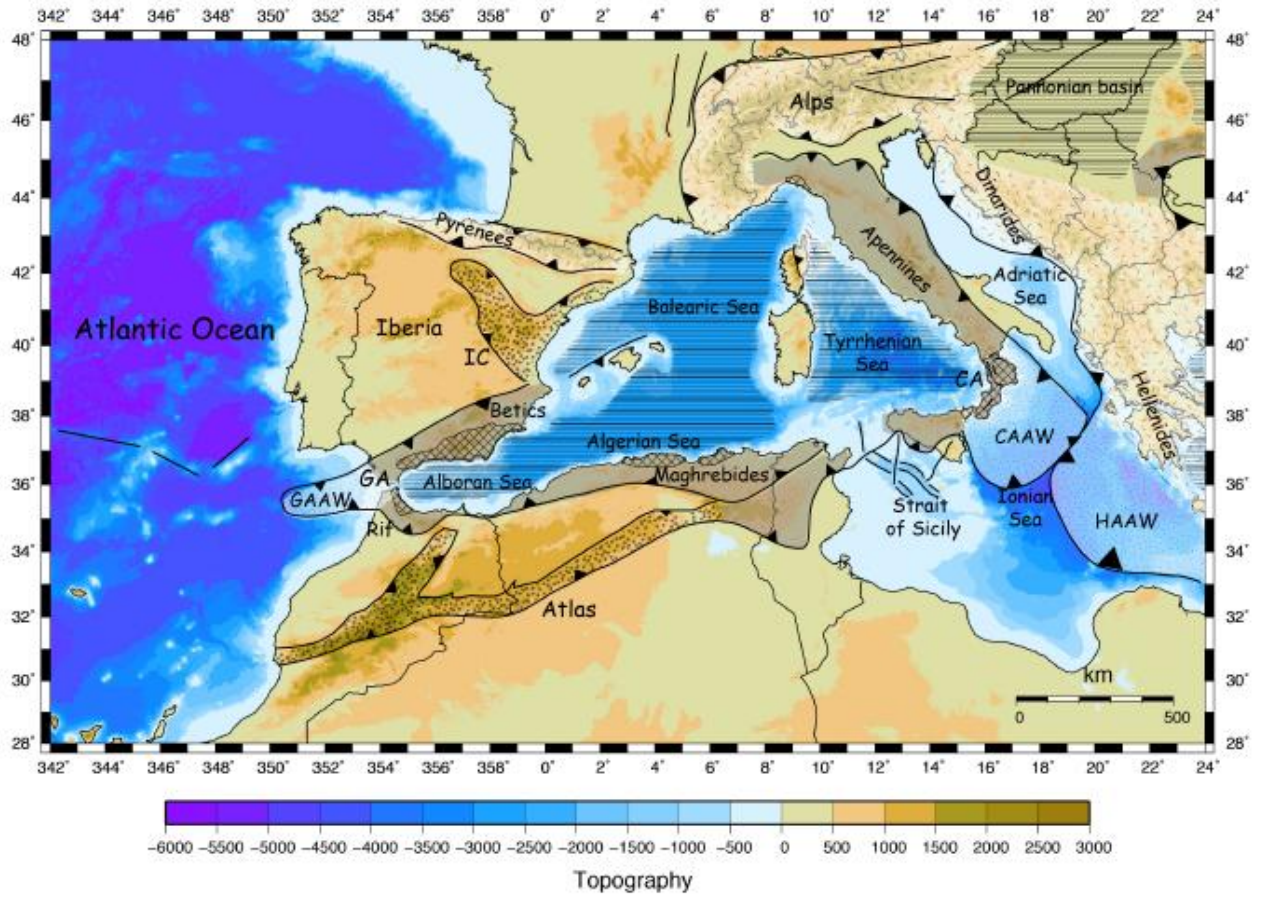


Fig. 1. Simplified geological map of the CWM region. The system of fold-and-thrust belts, indicated in gray, formed from Late Oligocene to Pliocene, during the opening of the backarc basins (horizontal rules; also including the volcanic arcs). The accretionary wedges related to oceanic subduction are indicated with fine dots (GAAW: Gibraltar Arc Accretionary Wedge; CAAW: Calabrian Arc Accretionary Wedge; HAAW: Hellenic Arc Accretionary Wedge). The units belonging to the internal domain are shown with cross hatching. The collisional belts are indicated with random dashes, whereas the Atlas and Iberian Chain (IC) intracontinental belts are indicated with coarse dots. BF: Bradanic foredeep basin; GCF: Gela-Catania foredeep basin.

Figure 2a

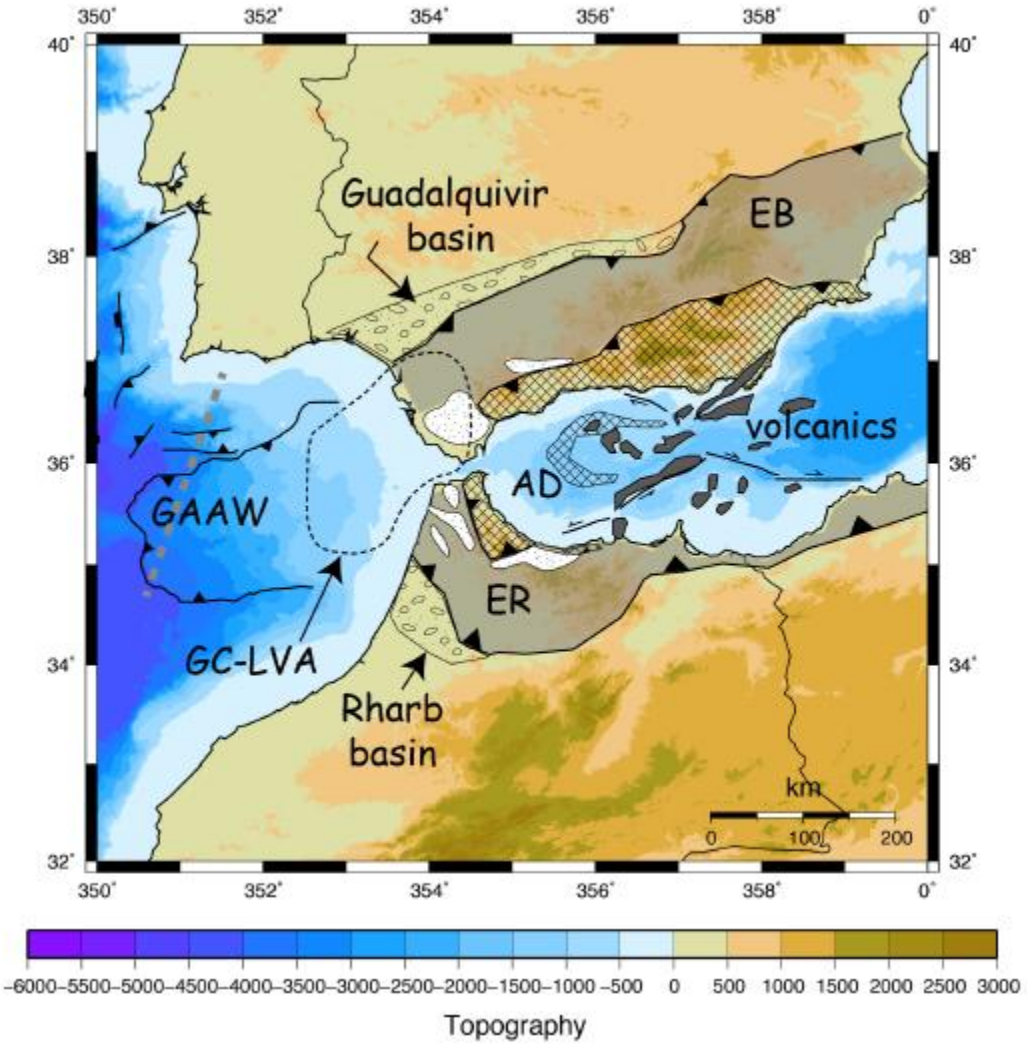


Fig. 2. Simplified geological maps of the two study regions. **a)** Gibraltar-Alboran region (after Alvarez-Marron, 1999; Platt et al., 2013; Gutscher et al., 2012; Duarte et al., 2013). The Alboran Domain (AD), that includes the Internal Betics and Internal Rif, is indicated by cross hatched pattern. The External Betics (EB in gray pattern) includes the Subbetic and Prebetic, and the External Rif (ER in gray pattern) includes the Intrarif and Mesorif. The white field with dotted pattern represents the Flysch belt, and the volcanics are indicated in dark gray. GAAW: Gibraltar Arc Accretionary Wedge; GC-LVA: approximate location of the low-velocity anomaly (from 100 to 200 km depth). Trace of seismic refraction profile (Sallares et al., 2011) indicated by thick gray dashed line. (After Monna et al., 2015).

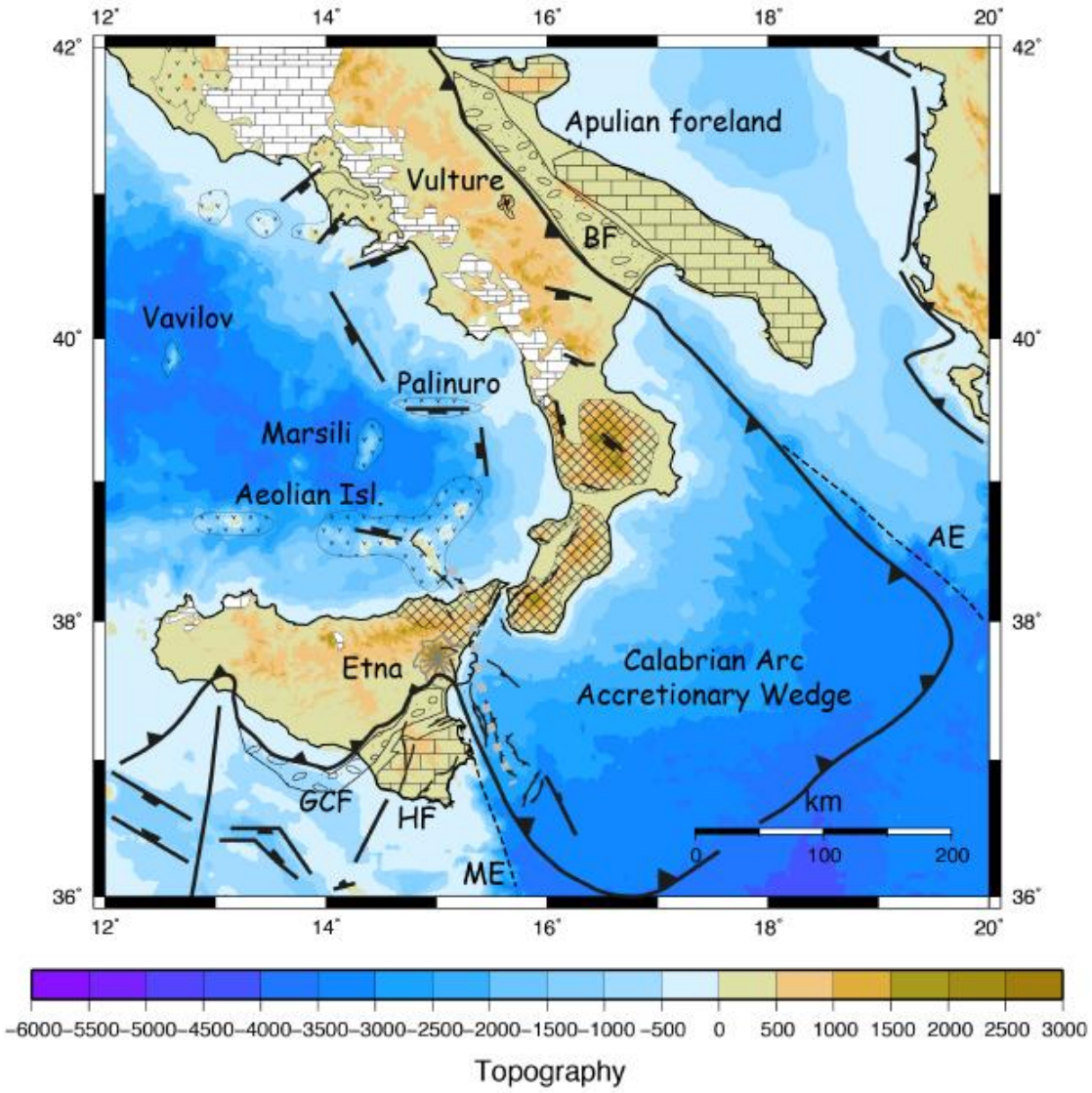


Figure 2b Calabrian Arc-Southern Tyrrhenian region (after Bigi et al., 1990; Argnani, 2005). The outcrops of Apulian and Hyblean (HF) foreland are indicated with large brick pattern, whereas the carbonate units encased within basinal units of the Southern Apennines-Maghrebides are indicated as white fields with brick pattern. The conglomerate pattern indicates the Bradanic (BF) and Gela-Catania (GCF) foreland basins. The mostly crystalline units of the Calabrian Arc are shown with cross hatching. The V pattern indicates Pliocene-Quaternary volcanics, including the Campania Magmatic Province. The Malta and Apulia Escarpments (ME and AE, respectively) are also indicated with a dashed line. The thick, gray dashed line offshore eastern Sicily marks the approximate location of the incipient lithospheric tear (after Argnani, 2009).

Figure 3

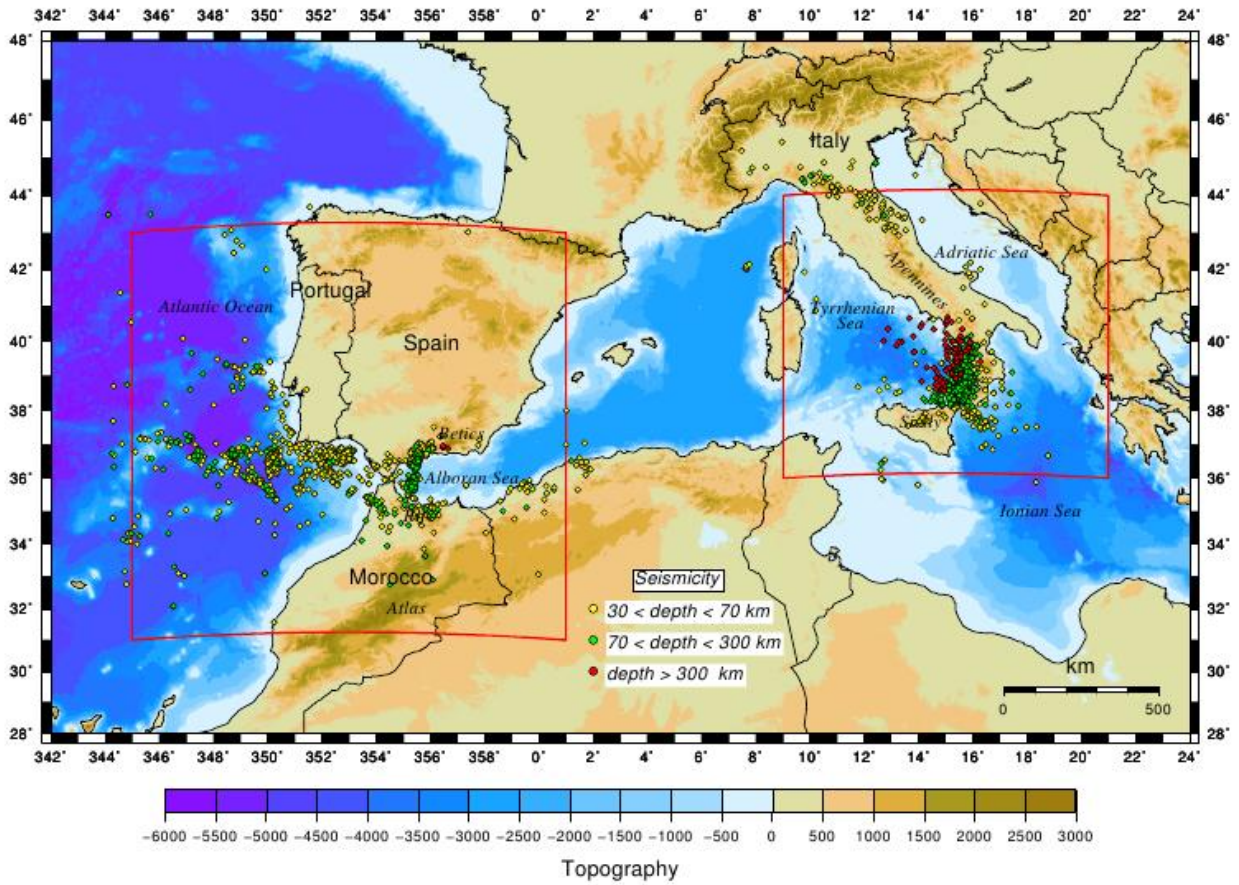


Fig. 3. Map of the CWM region with the two study areas. Colored circles show the sub-crustal seismicity (M>= 3) which occurred in the years 1990-2013. Hypocentral parameters from IGN catalogue and INGV bulletins. Topography/bathymetric profiles are from the Global-Integrated-Topo/Bathymetry Grid (GINA) (Lindquist et al., 2004).

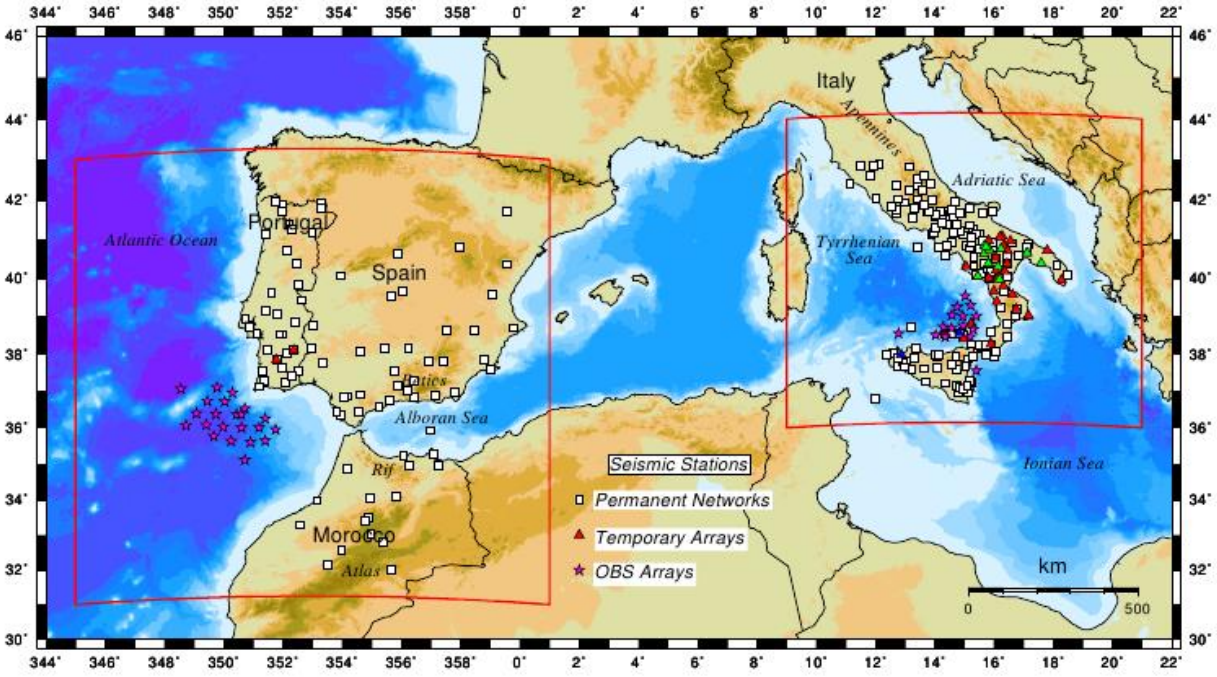
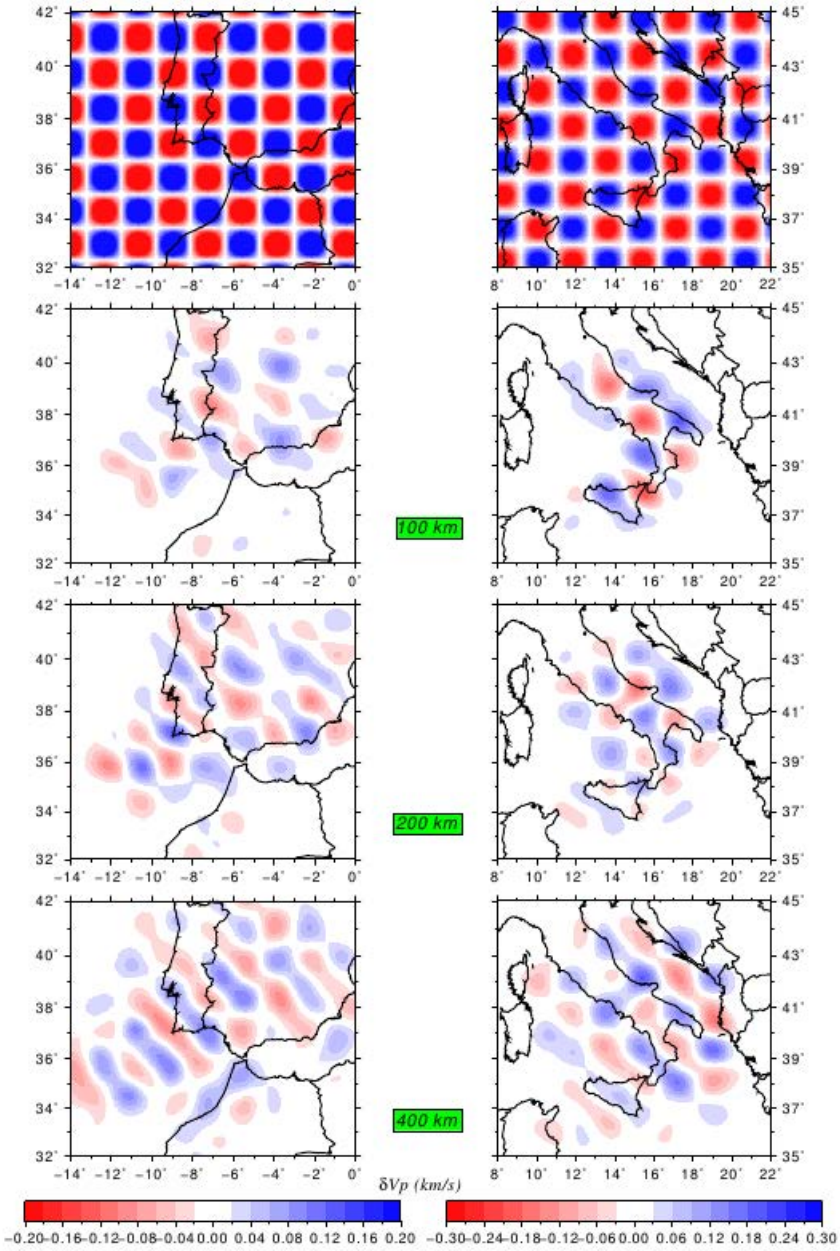


Figure 4

Fig. 4. Map of the seismic stations used in the two tomographic inversions. The OBS array in the Gulf of Cadiz was deployed during the NEAREST project (http://nearest.bo.ismar.cnr.it). The OBS in the Southern Tyrrhenian were deployed during the TYDE (Dahm et al., 2002) and SN1 (Monna et al., 2005) experiments. The temporary land arrays were deployed in Southern Italy during the SAPTEX (red triangles) (Cimini et al., 2006) and SeSCAL (green triangles) (Frepoli et al., 2011) experiments.

Figure 5



1223

1224 **Fig. 5.** Results of the checkerboard resolution test for three depth slices of the two tomographic
1225 models. Left panels are for the GA model, right panels for the CA model. Panels at the top are the
1226 input checkerboard velocity models. These patterns consist of alternating 100x100 km cells of fast
1227 and slow anomalies varing in latitude, longitude, and depth. The recovered patterns show wide
1228 areas of good resolution for both the models. The synthetic data sets, based on the source-receiver
1229 geometries of the GA and CA teleseismic inversions, include gaussian noise with standard
1230 deviations of 0.15s and 0.50s, respectively for picked and bullettin data.

Figure 6

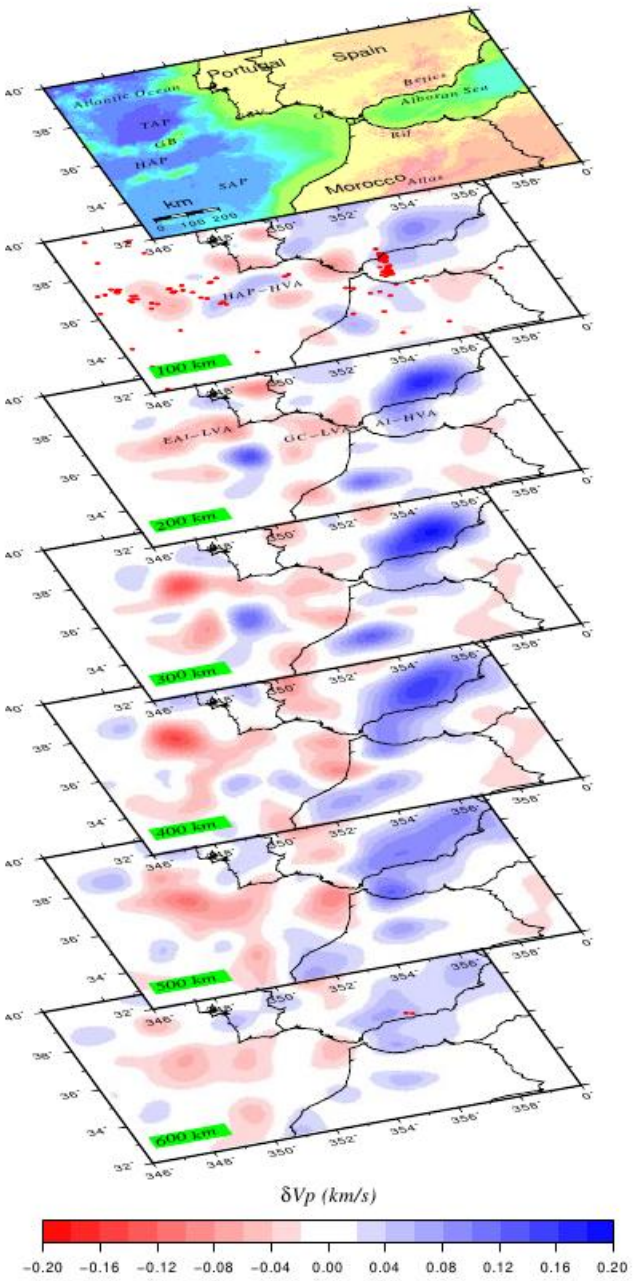
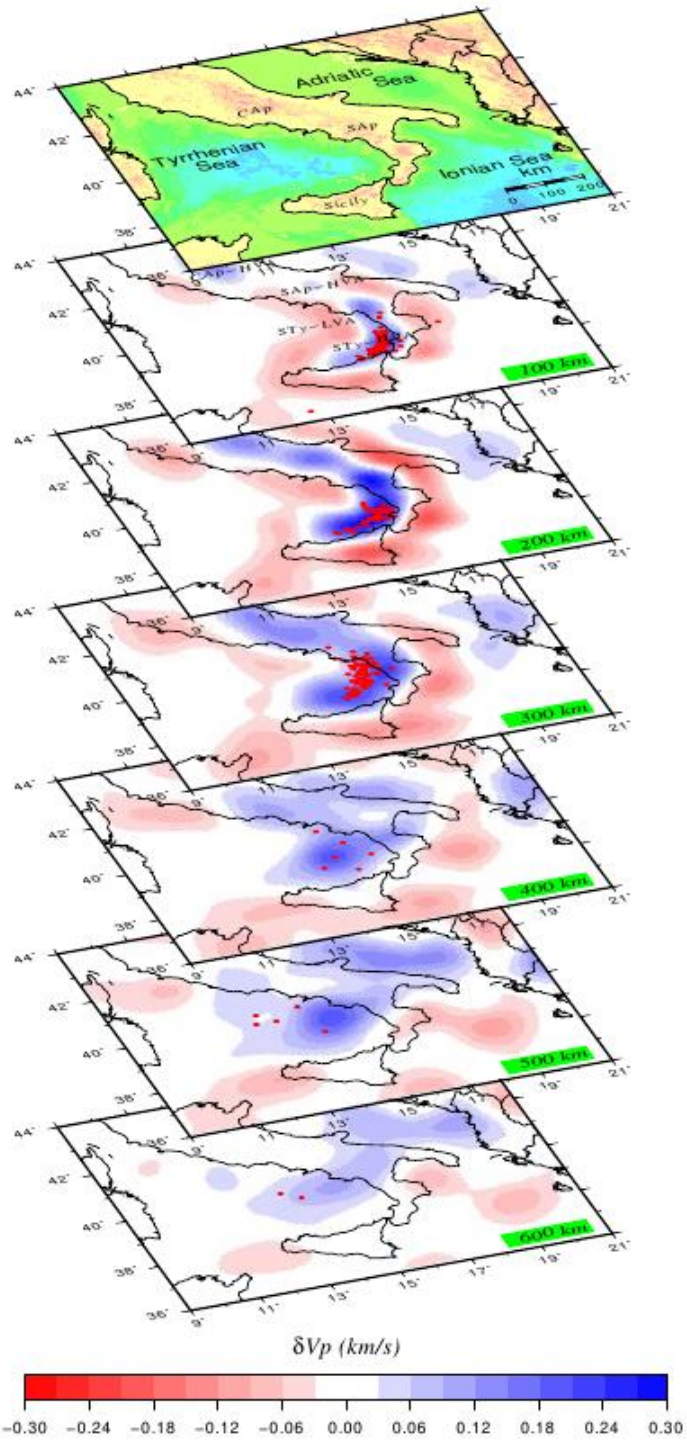


Fig. 6. Perspective view showing a series of horizontal slices extracted from the GA velocity model at depth intervals of 100 km. Blue colored areas indicate high velocity anomalies, present in the Betic-Alboran region (Al-HVA) and in the Atlantic SW Portugal (HAP-HVA). Red colored areas are zones of low velocity anomalies in the Eastern Atlantic (EAt-LVA) and the Gulf of Cadiz (GC-LVA). (After Monna et al., 2015).

Figure 7



1274

1275 **Fig. 7.** Perspective view showing a series of horizontal slices extracted from the CA velocity model
1276 at depth intervals of 100 km. As in Fig. 6, blue colored areas indicate high velocity anomalies,
1277 present in the Southern Tyrrhenian region (STyHVA) and in the Southern Apeninnes (SAp-HVA).
1278 Red colored areas are zones of low velocity anomalies in the Tyrrhenian Sea (STy-LVA) and the
1279 Ionian Sea (Io-LVA).

Figure 8

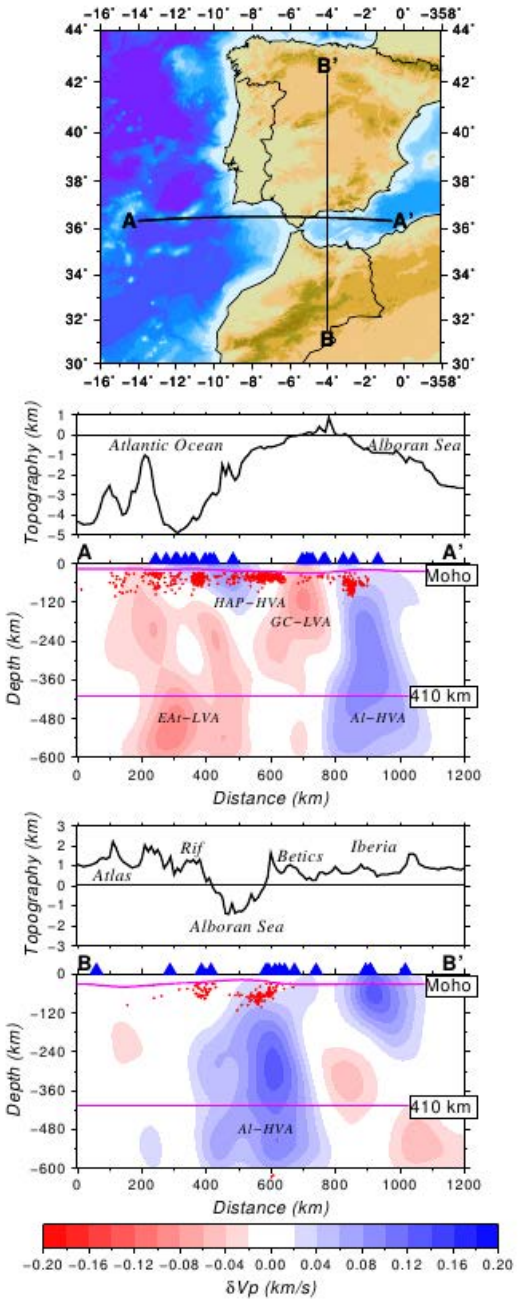


Fig. 8. Vertical slices displaying the velocity anomalies of the GA model along a west to east profile crossing the Gibraltar Arc (AA'), and along a south to north profile crossing the Atlantic the Alboran Sea (BB'). SAP = Seine Abyssal Plain; HAP = Horseshoe Abyssal Plain; TAP = Tagus Abyssal Plain. High velocity anomalies: Al-HVA=Betic-Alboran; HAP-HVA=Horseshoe Abyssal Plane. Low velocity anomalies: GC-LVA=Gulf of Cadiz; EAt-LVA=Eastern Atlantic. Blue triangles indicate the seismic stations and red dots the subcrustal seismicity, located within a 100 km wide zone centered on the profile. In profile BB', hypocenters deeper than 600 km represent the deep events below the Granada region. Moho topography is from the European Moho depth map

(Grad et al., 2009). (After Monna et al., 2013a).

Figure 9

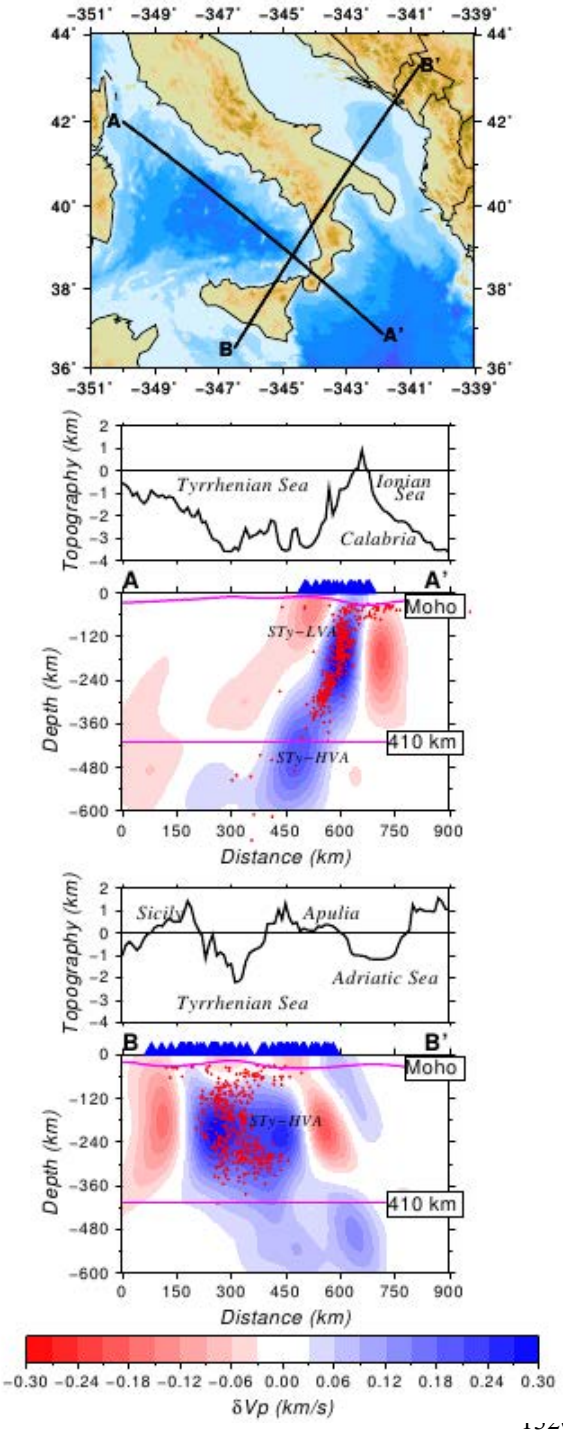


Fig. 9. Vertical slices displaying the velocity anomalies of the CA model along a northwest to southeast profile crossing the Calabrian Arc (AA'), and along a southwest-northeast profile crossing the southern Tyrrhenian basin (BB'). CAp = Central Apennines; SAp = Southern Apennines. High velocity anomalies: STy-HVA=Southern Tyrrhenian. Low velocity anomaly: STy-LVA=Southern Tyrrhenian. Blue triangles and red dots indicate the seismic stations and the subcrustal seismicity located within a 100 km wide zone centered on the profile. Moho topography is from the European

1333 Moho depth map (Grad et al., 2009).

Figure 10

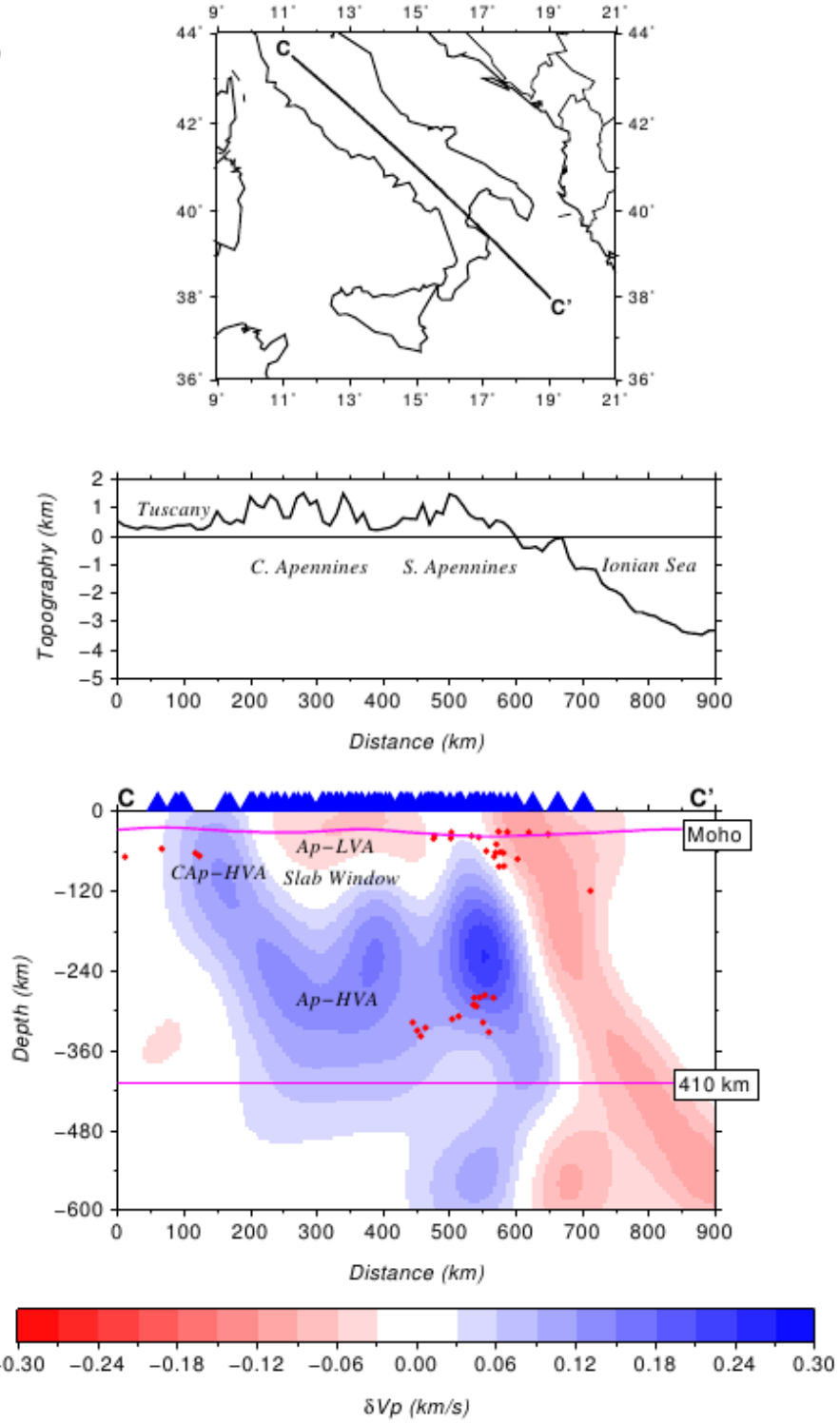


Fig. 10. Vertical slice displaying the velocity anomalies of the CA model along a northwest to southeast profile crossing the Southern Apennines (CC'). The trace and topographic profile are shown in the top and middle panels, respectively. A well defined slab window underneath the Southern Apennines is visible (lower panel). High velocity anomalies: Cap-HVA=Central Apennines; Ap-HVA=Apennines. Low velocity anomaly: Ap-LVA=Apennines-slab window.

Figure 11

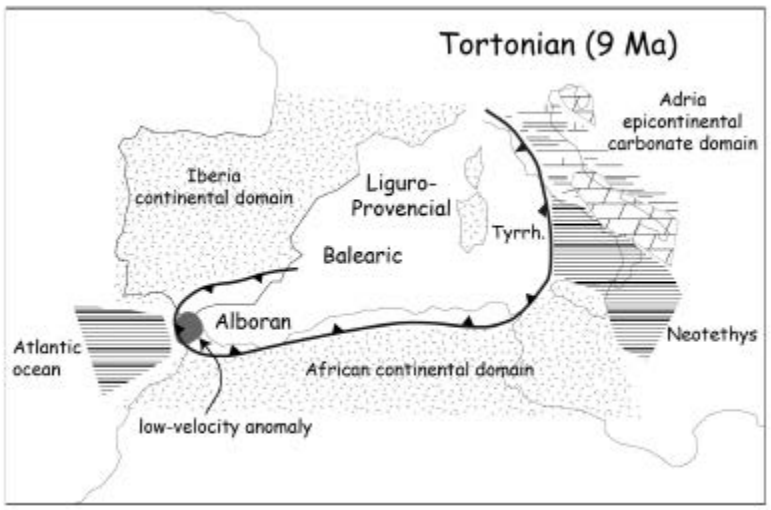


Fig. 11. Simplified tectonic reconstruction of the Mediterrenan in Tortonian time. The African and Italian coasts are positioned with respect to stable Europe. Note that the Gibraltar arc was almost completely formed, whereas the Calabrian arc was still to be defined. During the Pliocene-Pleistocene the subduction and rollback of the narrow Neotethyan branch shaped the final arcuature of the Calabrian arc. The segment of African continental margin imaged just offshore Gibraltar (LVA, low-velocty anomaly) likely prevented any further development of the Gibraltar arc, favouring slab breakoff.

Figure 12

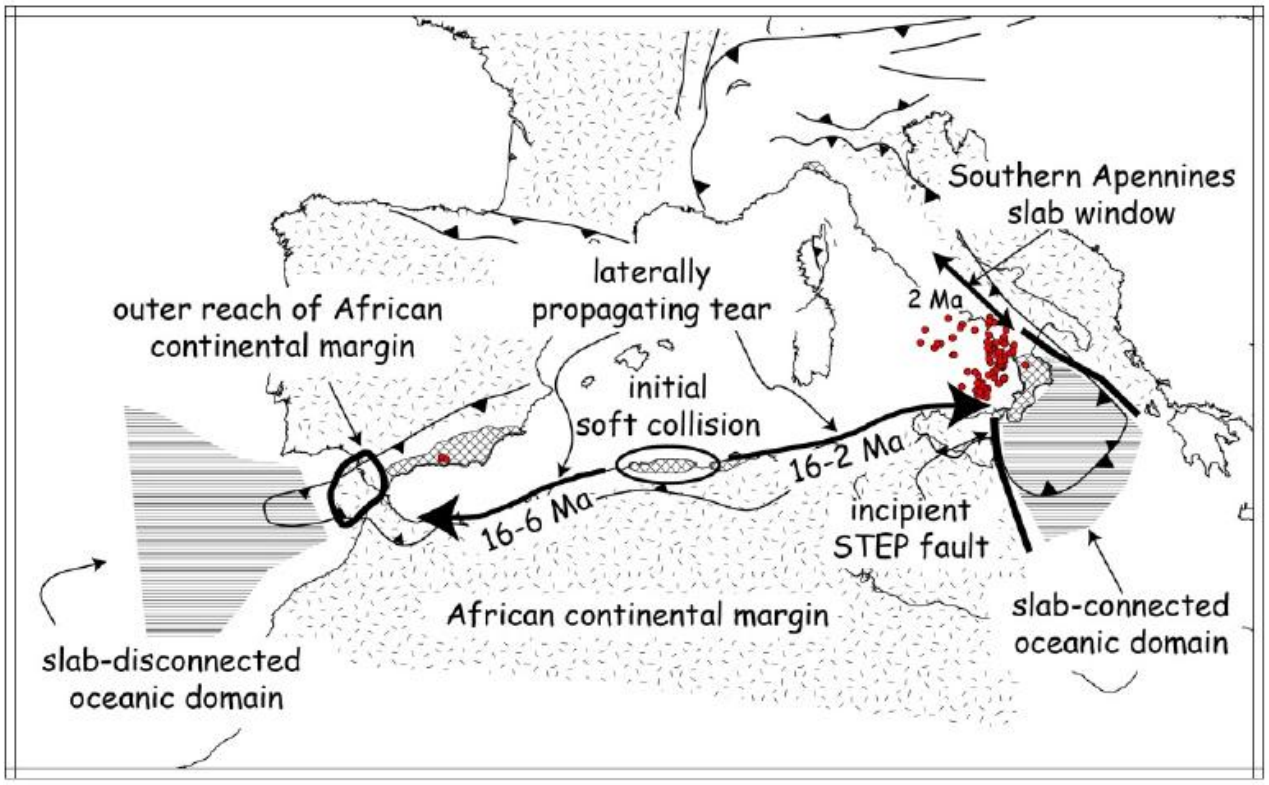


Fig. 12. Interpretation of the evolution of the CWM subduction system highlighting the main features which controlled arc formation. Slab tearing propagated laterally along the north African continental margin, following the initial soft collision in Algeria (ca. 16 Ma). Arc formation proceeded on either side, driven by slab sinking and trench retreat, but slab retreat was impeded in its westward motion by the segment of thinned continental margin imaged by the GA tomography underneath Gibraltar (GC-LVA). The eastward progression of arc formation, on the other hand, continued until very recently, with the opening of the Tyrrhenian basin, driven by the sinking Ionian slab. In its final stage the sinking also promoted the formation of a slab window underneath the Southern Apennines, which is responsible for the magmatism of the Campania Magmatic Province (Serri, 1990). Dots represent deep (depth > 300 km) M>= 3 seismicity.

Title

The role of continental margins in the final stages of arc formation: Constraints from teleseismic tomography of the Gibraltar and Calabrian Arc (Western Mediterranean)

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Abstract

The deep seismicity and lateral distribution of seismic velocity in the Central Western Mediterranean, point to the existence under the Alboran and Tyrrhenian Seas of two lithospheric slabs reaching the mantle transition zone. Gibraltar and Calabrian narrow arcs correspond to the slabs. Similarities in the tectonic and mantle structure of the two areas have been explained by a common subduction and roll-back mechanism, in which the two arcs are symmetrical end members. We present a new 3-D tomographic model at mantle scale for the Calabrian Arc and compare it with a recently published model for the Gibraltar Arc by Monna et al. (2013a). The two models, calculated with inversion of teleseismic phase arrivals, have a scale and parametrization that allow for a direct comparison. The inclusion in both inversions of ocean bottom seismometer broadband data improves the resolution of the areas underlying the seafloor networks. This additional information is used to resolve the deep structure and constrain the reconstruction of the Central Western Mediterranean geodynamic evolution. The Gibraltar tomography model suggests that the slab is separated from the Atlantic oceanic domain by a portion of African continental margin, whereas the Calabrian model displays a continuous oceanic slab that is connected, via a narrow passage (~350 km), to the Ionian basin oceanic domain. Starting from the comparison of the two models we propose the following interpretation: within the Mediterranean geodynamic regime (dominated by slab rollback) the geometry of the African continental margin, located on the lower plate, represents a critical control on the evolution of subduction. As buoyant continental lithosphere entered the subduction zones, slab pull caused tears in the subducted lithosphere. This tectonic response in the final stages of arc evolution, strongly controlled by the paleogeography of the subducted plates, explains the observed differences between the Gibraltar and Calabrian Arcs.

Key words: teleseismic tomography, upper mantle, Gibraltar Arc, Calabrian Arc, subduction zone

1. Introduction

One of the outstanding and controversial features of the Mediterranean region is the presence of large-scale extensional basins within a convergent domain located between the African and European plates. Early studies recognized that the Central Western Mediterranean (CWM) extensional basins (Fig. 1) developed in a backarc setting (Dewey et al., 1973, 1989; Horvath and Berckhemer, 1982; Rehault et al., 1984), and also hypothesized that outward migration of subduction, due to slab sinking and retreat, was the most likely explanation for the observables (Malinverno and Ryan, 1986). Several papers stemmed from these early concepts, with progressive refinement of the timing and kinematics of backarc extensional and outward migration of the fold-and-thrust belt (e.g., Royden, 1993; Lonergan and White, 1997; Seranne, 1999; Argnani and Savelli, 1999).

A remarkable lateral variability in the character of the fold-and-thrust belts, timing of extension of backarc basins, and so on, is present in the Mediterranean orogen. Two main factors contributed to this result: i) non linear continental margins of the converging plates; and ii) gravitational instability of the subducted lithosphere.

The land-locked condition of the Mediterranean plate boundary, due to the presence of the Adriatic promontory, enhanced the effects of slab rollback (Le Pichon, 1982; Mascle et al., 1988). In fact, the collision of the Adriatic promontory with Eurasia around the Paleocene caused a slowdown in the Africa–Eurasia plate convergence, particularly for the N-ward component (Le Pichon et al., 1988; Dewey et al., 1989). This, in turn, promoted the activation of processes operating within the orogen, such as lithospheric root detachment, lithosphere delamination, lateral escape towards areas of depressed topography and rollback of dense oceanic slab, which are responsible for the origin of the Mediterranean extensional basins (i.e. Le Pichon, 1982; Dewey, 1988; Le Pichon et al., 1988; Otsuki, 1989; Argnani, 2000; Jolivet and Faccenna, 2000).

An additional important aspect is the interaction between lithospheric slabs and asthenosphere which could possibly result into slab breakoff or detachment and delamination of continental lithosphere. Lateral migration of slab breakoff has been proposed as a key factor for lithosphere dynamics in this region in the last 20-30 Ma, especially in the final stage of subduction (Wortel and Spakman, 1992, 2000; Carminati et al., 1998; Faccenna et al., 2004; Rosenbaum et al., 2008; Argnani, 2009). Within this setting, mantle flow possibly played a role in the deformation of the Gibraltar and Calabrian slabs (Gvirtzman and Nur, 1999; Faccenna et al., 2004; Baccheschi et al., 2008). Delamination of continental lithosphere is a process that likely operated within the Mediterranean orogens, following the subductional consumption of oceanic lithosphere (e.

g., Serri et al., 1993; Fillerup et al., 2010; Argnani, 2012; Levander et al, 2014). Although it is

known that continental rocks can experience subduction to depth over 100 km, before returning to shallow depth and becoming exhumed to the surface (e.g., Hacker et al., 2010; Butler et al., 2014), continental subduction is likely to be limited, both in extent and rate of subduction, as suggested by the overall stability of continents (Cloos, 1993). The tectonic evolution of the Mediterranean type orogen suggests that when a continental margin enters a retreating subduction zone (soft collision), the processes of subduction and slab retreat get to the end (e.g., Burchfiel and Royden 1991; Wortel and Spakman, 2000; Argnani, 2009).

The present structure and origin of the Gibraltar Arc-Alboran Basin system (GA) (Fig. 1) does not fit well in this unifying picture based on slab subduction and rollback, and alternative evolution scenarios have been proposed. Several authors do suggest that subduction of oceanic lithosphere (active or extinct) caused extension within the Alboran Basin in the Miocene by slab rollback (Royden, 1993; Lonergan and White 1997; Bijward and Spakman, 2000; Gutscher et al., 2002) or by slab detachment (Zeck, 1996). Alternatively, another group of authors presents an evolution for the Alboran basin initiating with lithospheric thickening during the Paleogene caused by the collision of Europe and Africa. The thickened continental lithosphere was later (ca. 25 Ma) detached by convective removal (Platt and Vissers, 1989) or by delamination (Calvert et al., 2000), leading to recycling of continental material (Levander et al., 2014). The collapse of this lithosphere caused extension of the Alboran and Algerian basins and uplift around the margin, edge delamination under the Betics and Rif margins and mixed continental-oceanic subduction (Booth-Rea et al., 2007; Duggen et al., 2005; Medaouri et al., 2014).

On the other hand, there is a general consensus that the Calabrian Arc-Tyrrhenian Basin system (CA) (Fig. 1) does fit well in the unifying picture: subduction with slab rollback has been the main factor in the opening of the Tyrrhenian Sea (Malinverno and Ryan, 1986), a well defined Wadati-Benioff zone is contained in a high seismic velocity body (Cimini and Marchetti, 2006, and references therein), and subduction-related magmatism is active under the CA (Barberi et al., 1974; De Astis et al., 2003).

Several tomography studies have concentrated on the Mediterranean mantle at different scales. They range from the global (e.g., Bijwaard and Spakman, 2000), to the European (e.g., Koulakov et al., 2009), to the Mediterranean scale (e.g., Piromallo and Morelli, 2003), down to a more regional scale (e.g., Cimini and Marchetti, 2006; Montuori et al., 2007; Bezada et al., 2013).

In this paper we focus on two tomographic P-wave velocity models of the upper mantle beneath the GA and CA regions, which give , with respect to previous models, a more resolved 3-D picture of the two subduction zones and surrounding asthenospheric mantle. Both tomographies take advantage of improved teleseismic-phase arrivals datasets obtained by integrating recordings from permanent national networks with recordings from recent dense deployments of temporary land and

marine (Ocean Bottom Seismometers - OBS) broad band arrays (Dahm et al., 2002; Monna et al., 2005; NEAREST project, http://nearest.bo.ismar.cnr.it). The teleseismic inversions were performed using a modern iterative technique (Rawlinson et al., 2006), by employing the same grid parametrization and depth extension (600 km) of the target volume, which allows for a direct comparison of the images. The GA tomography has been recently published (Monna et al., 2013a, 2015), while for the CA we present a new tomography model. Regarding the deep structure of GA the model shows features that were previously undetected or poorly resolved, in particular the lithosphere-upper mantle structure of the Gibraltar Strait-Atlantic sector, whereas for the CA the slab geometry and the surrounding asthenosphere are more accurately defined with respect to a previous models based on OBS data (Montuori et al., 2007). The inversion results are the starting point for a discussion and comparison of the two subduction systems within the geodynamic and tectonic framework of the Western Mediterranean region.

2 Geodynamic and tectonic evolution of the Central Western Mediterranean

Africa moved several 100's km towards Europe from the Cenomanian to the Chattian, and 200-300 km of convergence occurred in the Eocene-Oligocene time interval. Average N-S convergence between Africa and Europe slowed down since the Chattian, following the Alpine collision, and, as a result, rollback of subducted lithosphere initiated the opening of the backarc basins and the concomitant outward migration of the fold-and-thrust belts, that characterize the Western Mediterranean (Fig. 2) (Le Pichon, 1982; Dewey, 1988; Le Pichon et al., 1988; Argnani, 2000; Jolivet and Faccenna, 2000). The concomitant presence of calk-akaline volcanism along the European margin (Sardinia, offshore western Corsica, Provence) is an evidence that subduction of oceanic lithosphere occurred during the formation of these backarc basins (Argnani and Savelli, 1999).

The Balearic backarc basin was the first to open (Fig. 1) from late Oligocene to early-middle Miocene (Rehault et al., 1984; Chamot-Rooke et al., 1997; Faccenna et al., 1997) and extend to the western end of the Mediterranean, up to the Alboran basin (Watts et al., 1993; Booth-Rea et al., 2007). In the Algerian sector, the opening of the basin continued until late Miocene, possibly with oceanic crust emplacement in late Miocene (Mauffret et al., 2004; Booth-Rea et al., 2007; Medaouri et al., 2014). The Tyrrhenian backarc basin opened from Late Miocene to Pleistocene above the NW-dipping subduction of the Ionian lithosphere (Malinverno and Ryan, 1986; Kastens et al., 1988; Argnani and Savelli, 1999). Evidence from regional geophysics, arguments from plate kinematics and palaeo-reconstructions, suggest that the oceanic lithosphere, that subducted during the Tyrrhenian opening, belonged to a Triassic seaway (Argnani, 2005; Speranza et al., 2012).

The most striking feature in this process of backarc basin opening is the formation of the two tightly

arcuate features: the Gibraltar and Calabrian arcs (Fig. 1) (Horvath and Berckhemer, 1982; Faccenna et al., 2004; Rosenbaum and Lister 2004). The foreland of the Calabrian Arc fold-and-thrust belt faces the African plate (s.l.), although the nature of the lithosphere varies from oceanic in the apex of the arc to continental on either side. The foreland of the Gibraltar Arc fold-and-thrust belt, instead, covers both the African and Iberian plates; this plate boundary location contributes to additional tectonic complexity.

The large-scale models, that explain the Gibraltar and Calabrian arc subduction as coming from a single slab SE-ward retreat of the western Mediterranean (Faccenna et al., 2004; Carminati et al., 2012), may be too oversimplified to account for the geological complexity of the Alboran region. Other evolutionary models start with a shorter subduction zone, that is initially limited to the Balearic region (e.g., Lonergan and White, 1997; Rosenbaum et al., 2002; van Hinsbergen et al., 2014); this class of models seem to explain more satisfactorily the geological evolution of the Alboran region (Platt et al., 2013; Chertova et al., 2014).

2.1 Gibraltar Arc-Alboran Basin

The Atlantic sea-floor magnetic anomalies (Srivastava et al., 1990) indicate that the Iberia plate experienced a complex kinematics within the Africa-Eurasia convergence. Iberia was part of Africa from Late Cretaceous to Early Oligocene, whereas from Late Oligocene to present it became part of Europe, following the Pyrenean collision. As an alternative, recent reviews of the magnetic anomalies (Vissers and Meijer, 2012) allow for some 50-70 km convergence between Africa and Iberia for the Late Cretaceous-Middle Eocene time span. The west-ward arc propagation of the Betic-Rif fold-and-thrust belt is larger than the 200-250 km N-S convergence between Africa and Iberia, as suggested by the length of the east-dipping subducted slab imaged by high-resolution seismic tomography (e.g., Bezada et al., 2013; Palomeras et al., 2014). This propagation has been modelled with a substantial westward slab rollback (e.g., Royden, 1993; Lonergan and White, 1997; Gutscher et al., 2002; Rosenbaum et al., 2002). The internal Betics and Rif units (Fig. 2a) have a continental substrate of Palaeozoic age with a Mesozoic-Cenzozoic sedimentary cover, and have been affected by Palaeogene HP/LT metamorphism (Platt et al., 2013). These internal units have been also recovered in the Alboran Sea, defining the so-called Alboran Domain. The external Betics and Rif units are characterized by successions derived from the Iberian and African passive continental margins that were emplaced during the opening of the Alboran basin (e.g., Blankenship, 1992; Wildi, 1983). The sediments of the Flysch basin were thrusted by the Alboran Domain units that were moving west-southwest-ward during the Oligocene-Early Miocene (Fig. 2a; Wildi, 1983). The basement of the Flysch basin domain was likely oceanic and could correspond to the oceanic slab imaged by tomography under the Alboran basin. Most of the vertical-axis rotation and arc

formation in the Rif and western Betics was accomplished by the early Pliocene, as indicated by paleomagnetic data (e.g., Platt et al., 1995; Platzman et al., 1993; Krijgsman and Garces, 2004; Cifelli et al., 2008; Fig. 2a).

The Alboran Sea basin, which was formed in the Neogene as a result of extensional tectonics, is currently floored by thinned continental crust, 13-20 km thick (Watts et al., 1993), and by magmatically accreted arc-type crust in its eastern sector (Booth-Rea et al., 2007).

Recent tectonic models try to account for the details of the geological evolution of the Alboran region. Platt et al. (2013), following their previous work, propose a NW-ward Paleogene subduction that originated the Alboran Domain, followed (during the Early Miocene) by orogenic collapse and a new subduction on the Iberian side of the Alboran Domain. As an alternative explanation, Vergés and Fernandez (2012) propose a continuous southward subduction of the Iberian plate, with slab rollback and slab break-off, that would account for both the Paleogene and Miocene subduction events. This reconstruction which describes the evolution of the Betics, requires the occurrence of a major transform boundary that separates the Betics (northward polarity) from the eastern Maghrebides (southward polarity) subduction segments, and implies some difference in the tectonic evolution of the Maghrebian belt of north Africa, for which there is not much evidence in the field. Finally, a recent reconstruction (Van Hinsbergen et al., 2014) assumes that the Alboran terranes mostly formed along an oblique subduction zone located south of the Balearic islands, partly building on the reconstruction of Rosenbaum and Lister (2004). Here, the early Miocene heating and exhumation affecting the peridotite mantle and overlaying Alboran terranes occurred within a forearc setting, with the Alboran terranes subsequently dispersed across the western Mediterranean during backarc opening.

A number of tomographic studies have been performed in the last decade to image the deep seismic velocity structure of the GA. These studies agree on the presence of a high-velocity body under the Alboran Sea, down to mantle depths (Blanco and Spakman, 1993; Bijwaard and Spakman, 2000; Calvert et al., 2000). Very recent high-resolution tomography studies (Bezada et al., 2013; Palomeras et al., 2014; Thurner et al., 2014; Bonnin et al., 2014; Villaseñor et al., 2015) confirm the presence of a slab-shaped high velocity body, seen from the surface down to the bottom of the transition zone. The GA slab has a small curvature radius, similarly to the CA, but it does not show a Wadati-Benioff plane. In fact, sub-crustal seismicity (Figs. 3 and 8) is mostly located near the Strait of Gibraltar within 120 km depth and distributed in a very narrow north-south oriented vertical band (Seber et al., 1996), with a mixture of focal mechanisms showing both compression and extension (Buforn et al., 2004). Deep earthquakes (depth > 300km) are rare and occur at the bottom of the transition zone (~630 km depth) under southern Spain in the Granada area, and show dip-slip motion with a vertical north–south plane and a nearly horizontal plane with the pressure

axis dipping 45° to the east (Buforn et al., 2004, 2011).

The large amount of geophysical and geological data for this area confirms a complex geodynamic evolution, and in fact the high velocity anomaly below the Alboran has been interpreted as a continuous subducting slab (Gutscher et al., 2002; Piromallo and Morelli, 2003), as a broken-off slab (Blanco and Spakman, 1993), and as lithosphere which has undergone delamination (Calvert et al., 2000), or convective removal of the root (Platt and Vissers, 1989).

One of the open problems for the GA has been the interaction between the Atlantic and Alboran domains, west and east of the Gibraltar Strait. Although global scale tomography studies cover both regions, they do not have the capability to resolve the finer details. On the other hand, in spite of the increase in available data, the great majority of the higher resolution (regional scale) tomography models do not image the mantle below the Atlantic region west of the Gibraltar Strait due to a lack of station coverage at sea. A recent regional scale tomography model (WMGC-OBS) based on OBS data which includes both domains, has been proposed by Monna et al. (2013a). A relevant aspect of model WMGC-OBS is that there is a separation of the two lithospheres of the two domains, thus excluding the existence of a single continuous slab coming from the Atlantic side and subducting eastward below the Alboran.

2.2 Calabrian Arc-Tyrrhenian Basin

The Calabrian Arc connects the Sicilian Maghrebides and Southern Apennines and is characterized by a stack of basement units, coming from different levels of a Hercinian continental crust (Fig. 2b) (Bonardi et al., 2001). A thick forearc sedimentary succession crops out in the Ionian side of Calabria, supporting the accretion of the Calabrian Arc terranes within a subduction system (Bonardi et al., 2001). The wide accretionary complex of the External Calabrian Arc extends into the Ionian Sea and is confined to the NE and SW by the Apulian and Malta Escarpments, respectively (e.g., Biju Duval et al., 1982; Argnani and Bonazzi, 2005; Argnani, 2006).

The evolution of the Calabrian Arc is strictly related to the opening of the Tyrrhenian backarc basin (Malinverno and Ryan, 1986; Patacca et al., 1993) and is marked by a progressive narrowing of the subducted slab. Palaeomagnetic data support the saloon-door opening of the Tyrrhenian basin (Cifelli et al., 2007), as the structural units of the Southern Apennines experienced a counter-clockwise rotation of 60° during Middle-Late Miocene (Gattacceca and Speranza, 2002), whereas the structural units of the Sicilian Maghrebides show a large clockwise rotation of ca. 70° between Langhian and Late Tortonian (Channell et al., 1990; Speranza et al., 1999).

The Tyrrhenian Basin is located on the wake of the Apennines and Sicilian Maghrebides. The amount of extension is greater in the southern basin which, in fact, is characterized by a thin crust (less than 10 km) and high heat flow (Kastens et al., 1988), with possibly wide stretches of

exhumed mantle (Prada et al., 2014). A girdle of volcanic islands, the Aeolian Islands, located north of Sicily represents the volcanic arc of the Tyrrhenian subduction, with calc-alkaline activity that spans from 1 Ma to the Present (Fig. 2b) (Barberi et al., 1974; De Astis et al., 2003). The rocks of the Campania Magmatic Province (Fig. 2b), that includes the Campi Flegrei high potassium calcalkaline (2.0 - 1.6 Ma), the Campi Flegrei, Ischia and Procida shoshonites (100 ka - Present), and the Vesuvio leucitite and leucitite basanite (1 Ma - Present), also show affinity with island arc magmatism. Magmatic rocks from Campania and the Aeolian volcanic arc have comparable geochemical features, suggesting a similar Oceanic Island Basalt mantle source, enriched by components derived from subducted oceanic lithosphere (Serri, 1990).

The onshore Calabrian Arc has been affected by major uplift in the last 0.8 Ma, with rates up to 2.0 mm/yr (Westaway, 1993; Bordoni and Valensise, 1998), and presents extensional grabens filled by Late Pliocene-Quaternary sediments, trending both parallel and perpendicular to the arc (Tortorici et al., 1995). This active tectonic regime is supported by extensional focal mechanisms (e.g., Vannucci et al., 2004). To the west of the central Aeolian Islands, earthquake focal mechanisms indicate that active compressional deformation occurs offshore northern Sicily (Pondrelli et al., 2004; Argnani et al., 2007; Serpelloni et al., 2007), although the seismogenic structures have not been properly identified. This compressional boundary has been considered as part of a kinematic rearrangement that occurred about 2 Myr ago (Jenny et al., 2006).

For the CA there is a wide consensus that subduction of oceanic lithosphere below the southern Tyrrhenian is taking place. In the tomographic images the subduction is represented as a narrow arc-shaped high velocity body which flattens in the transition zone at the 660 km discontinuity between upper and lower mantle (Cimini, 1999; Piromallo and Morelli, 2003; Spakman and Wortel, 2004; Montuori et al., 2007). The existence of subduction and overlying mantle wedge for the CA is confirmed by other geophysical and geochemical observations, such as, for example, the presence of a volcanic arc (Barberi et al., 1974; De Astis et al., 2003). Furthermore, the spatial distribution of the deep events (Figs. 3 and 9) (Frepoli et al., 1996) shows a Wadati-Benioff zone dipping ~70° NW beneath the southern Tyrrhenian, down to about 600 km depth (Cimini and Marchetti, 2006, and references therein). The focal mechanism P-axes show steep down-dip compression at intermediate depths (between 160 and 370 km). The deepest events (below 370 km) have P-axes with shallower dip (Frepoli et al., 1996).

The tomographic models have been interpreted as representing the final result of a subduction with rollback process which has caused the opening of the Tyrrhenian Sea in the last ~13 Ma (Wortel and Spakman, 2000; Piromallo and Morelli, 2003).

The tomographic images show that there is not a continuous slab under the Italian peninsula, as it is interrupted by a low-average velocity volume below the central-southern Apennines at lithospheric

depths. Other distinct high velocity bodies are found below the Northern Apennines and the Alps (Spakman and Wortel, 2004; Piromallo and Morelli, 2003; Giacomuzzi et al., 2012). This distribution in space of the high velocity bodies, prompted several authors to hypothesize the existence of an original single slab which had undergone one or more slab tears and/or detachment (e.g., Wortel and Spakman, 1992; 2000; Amato et al., 1993; Spakman and Wortel, 2004).

In recent years, thanks to the improvement of the Italian National Seismic Network, regional tomography studies could resolve finer details of the CA lithosphere-asthenosphere structure (e.g., Chiarabba et al., 2008). Furthermore, inversion of the 3-D attenuation structure (Chiarabba et al., 2008; Monna and Dahm, 2009) has added independent constraints, which are especially helpful in distinguishing the role of chemical composition and temperature as causes for seismic velocity anomalies.

3. Teleseismic tomography models of GA and CA based on OBS data

In this section we describe 3-D P-wave velocity models computed for the upper mantle of GA and CA. The CA images are derived from the new tomographic model presented in this work The GA images are derived from model WMGC-OBS presented in two recent papers (Monna et al., 2013a, 2015). To calculate both models we used accurate time picks of teleseismic waveforms recorded by the integrated arrays shown in Fig. 4 at epicentral distances between 25° and 95° (P phases) from worldwide Mw ≥ 5.5 earthquakes. The time picks were corrected for station elevation/bathymetry, Earth's ellipticity, local crustal structure (see sections 3.1 and 3.2), and then reduced to relative arrival time residuals using the ak135 global velocity model (Kennett et al., 1995). We applied the iterative nonlinear tomography method developed by Rawlinson et al. (2006) to map these residuals into 3-D P wave velocity anomalies. We note that inversion of relative traveltime residuals produces only 3-D velocity perturbations with respect to an average (usually 1-D) Earth model modified for the appropriate crustal structure. In the inversion scheme, the calculation of teleseismic wavefronts and the traveltimes from the base of the model volume to the array of receivers on the surface is performed with the fast marching method (FMM) (Sethian and Popovici, 1999). For both study regions, the bottom of the 3-D model was set at 600 km depth and the grid spacing used for the parametrization of mantle structure was 60 km. Outside the model volume the Earth is assumed to be spherically symmetric, which allows the use of a 1-D global reference model to rapidly compute the traveltimes from the distant sources to all grid nodes at the bottom. For a detailed description of the technique and the inversion equation we refer the reader to Rawlinson et al. (2006). In both cases, the nonlinear inversion was performed by testing different values of the maximum iteration number, to check the overall stability and performance in modeling the residual data. The tomographic images displayed in the following subsections describe the velocity field

computed at the third iteration, as only minor improvements in the data fit (<1%) and small structural changes in the velocity patterns were observed, for both cases, with successive inversion steps. Since the parametrization for the two models is the same, their direct comparison is possible. In general, the images for the CA show stronger anomalies, which explains the different scale of the color palettes in Figs. 6-10, +/- 0.2 km/s for the GA and +/- 0.3 km/s for the CA, in spite of the stronger regularization applied in the CA inversion. The difference in the amplitude of the anomalies could be explained by differences in accuracy of the two datasets and in the RMS reduction, but also by a greater heterogeneity of the CA upper mantle with respect to GA. With respect to previous tomographic studies at the same scale (e.g., Montuori et al., 2007; Giacomuzzi et al., 2011) the CA inversion we present has greater resolution and coverage of the oceanic areas. A comparison between the resolution of the GA and CA models is performed using the "checkerboard tests" displayed in Fig. 5. In this test the input velocity model is formed by alternating regions of fast and slow anomalies (with added gaussian noise to account for errors in the data; Monna et al., 2013a). The recovered pattern provides information on the well resolved areas of the models. We note that the CA model could be parametrized with a smaller grid (~80 km), but we have chosen the same parametrization as for GA (100 km) to better compare them. In any case, in both cases the parts that we intepret are in volumes of the models that are reliably reconstructed in the synthetic tests. We have clarified this aspect in the text.

3.1 Gibraltar Arc (GA) model

The information on the GA model that we present in the following is an updated summary of the results presented in Monna et al. (2013a, 2015). The teleseismic data set for the GA model is composed by 152 events recorded in the period 2007-2009 by the permanent networks of Spain, Portugal, and Morocco, and by the NEAREST OBS array (Carrara et al., 2008) deployed in the Gulf of Cadiz from August 2007 to August 2008 (in total 111 seismic stations; Fig. 4; left). This data set provided 6238 residuals for the tomography. The OBS array (25 seafloor broad band stations) recorded waveforms from 67 events. Other waveforms were collected from two land stations operating in SW Portugal installed during the experiment, and from the European Integrated Data Archive (EIDA; http://eida.rm.ingv.it). To improve ray coverage, arrival times extracted from the ISC bulletin (http://www.isc.ac.uk) were also added. The average time pick error was estimated in 0.43s. A crustal correction was applied based on four models which take into account up-to-date information available from published studies. These four models represent the Atlantic Ocean Domain, the Iberian Peninsula, Betics and Rif, and Atlas (see Table 1 in Monna et al., 2013a).

The GA-Alboran Basin model lateral extension (Fig. 3; left) spans 12.0° in latitude (from 31.0°N to

43.0°N), and 16.0° in longitude (from 15.0°W to 1.0°E). The 3-D velocity grid comprises 5544 nodes at 60 km spacing in all three dimensions (depth, latitude, longitude). The tomographic inversion was carried out with damping and smoothing parameters of 5.0 and 2.5, respectively. The three-step inversion reduced the data variance by 26% from 0.53 to 0.39 s^2 (Monna et al., 2013a).

We now briefly describe the main features found in the GA model as represented in Figs. 6 (maps) and 8 (cross-sections). Further details on the velocity pattern imaged in the Atlantic portion of the GA model can be found in Monna et al. (2015). The tomographic images show:

1) A high velocity body with arcuate geometry under the Betics-Alboran Sea area (Al-HVA). This fast structure depicts an L-shaped slab steeply dipping from the uppermost mantle to the transition zone where it becomes less curved.

2) A high-velocity body under the Horseshoe Abyssal Plain in the Atlantic region (HAP-HVA).

3) A diffuse low velocity anomaly (EAt-LVA) present in the Eastern Atlantic region south of the Gloria fault, down to the mantle transition zone.

4) A prominent low velocity anomaly below the Gulf of Cadiz (GC-LVA) which separates the two high-velocity bodies found under the Alboran (Al-HVA) and Atlantic regions (HAP-HVA).

Al-HVA extends from the surface to the base of our model (Figs. 6 and 8), and its maximum width is ~300 km in the EW direction below the Granada region (AA'). The AA' profile, which crosses the southern tip of the Iberian peninsula, shows the transition from the Atlantic to the Alboran domain, and the width of the slab (100–200 km). Section BB' crosses the Alboran Sea and shows the north-south extension of Al-HVA (approximately 300 km). Subcrustal seismicity is distributed along an arc-shaped belt with the deeper events contained in the uppermost part of the Al-HVA. These intermediate-depth earthquakes have a distribution which is not typical of subduction zones, in contrast with the clear Benioff zone of the Calabrian Arc (Fig. 9). Nevertheless, they provide information on the subducted oceanic slab beneath the Alboran basin, as their occurrence is usually linked to dehydration reactions in subducting oceanic lithosphere (e. g. Hacker et al., 2003).

GC-LVA extends from the top of the model down to ~250 km depth in (AA'). Below the NEAREST OBS array, roughly under the Horseshoe Abyssal Plain, the model shows HAP-HVA down to a depth of ~240km (Fig. 6). From profile AA' we obtain an east-west extension for HAP-HVA of ~250 km. This feature has been interpreted as a developed subduction process in the Gorringe Bank region (Monna et al., 2015).

3.2 Calabrian Arc (CA) model

The teleseismic events were collected from the Italian National Network (managed by INGV) and from temporary experiments performed both at sea (TYDE (Dahm et al., 2002) and NEMO-SN1 (Favali et al., 2013) and on-land (SAPTEX (Cimini et al., 2006) and SeSCAL (Frepoli et al., 2011))

during the last decade. The integrated network used in this study includes 209 stations (Fig. 4; right). The dataset spans the years 2000-2008 and consists of 276 events for a total of 8635 residuals. Crustal corrections of traveltime residuals were performed on the basis of two models (Monna et al., 2013b), one for the continental part (Sicily and Apennines) and one for the oceanic part (southern Tyrrhenian and Ionian Seas). Differently from the GA data set, the CA data set comes all from very accurate handpicked arrival times with an estimated average error of 0.16s which is almost 1/3 of the GA time pick error. The high quality of the CA data led to a solution model which is associated to a significant reduction of the residual variance.

The CA-Tyrrhenian Basin model lateral extension (Fig. 3; right) spans 8.0° in latitude (from 36.0°N to 44.0°N), and 12.0° in longitude (from 9.0°E to 21.0°E). The 3-D velocity grid comprises 3344 nodes spaced apart, 60 km in all the three directions, as for the GA model.For the CA model we obtained a variance improvement of over 51%, from 0.41 to 0.20 s^2.

The main features found in the CA model, represented in Figs. 7 (maps) and 9 (cross-sections), are:

1) A high velocity body with slab-like shape under the Tyrrhenian Sea area (STy-HVA).

2) A high-velocity body under the Apennines (Ap-HVA).

3) A high velocity anomaly visible below the Adratic Sea (Adr-HVA) adjacent to the Ap-HVA visible below 300 km depth.

4) A diffuse low velocity anomaly (STy-LVA) adjacent to Sty-HVA and Ap-HVA, found down to ~350 km depth. In the depth interval ~100-300 km, STy-LVA and the prominent low velocity zone imaged in the Ionian side (Io-LVA) join in a continuous belt surrounding the main fast structures.

5) A low velocity anomaly (Ap-LVA) at lithospheric depths below the central and southern Apennines, down to 120 km depth. Ap-LVA interrupts the lateral continuity of Ap-HVA, suggesting that the Apenninic slab has been subjected to tearing and slab window formation processes. Its geometry is clearly defined by the NW-SE profile shown in Fig. 10 (cross-section CC').

The deep seismicity delineates a well defined Wadati-Benioff plane, which is included in the volumes with the highest velocity perturbations, and is mostly concentrated in the 100-350 km depth range (Figs. 7 and 9). The high velocity slab shows a remarkable horseshoe shape in the 100-300 km interval. STy-HVA extends from crustal depths down to the bottom of the model (the lower part of the transition zone), and its lateral extension is about 350 km (Fig. 9, BB'). Ap-HVA appears from uppermost mantle depths down to ~120 km depth, as two distinct anomalies, one under the central (CAp-HVA) and the other below the southern Apennines (SAp-HVA). Ap-HVA seems to merge with Sty-HVA from 180 km depth down to the bottom of the model (Fig. 7).

The pattern of low P-wave velocity perturbations visible around Sty-HVA (Fig. 7), is recognizable also in the PM0.5 model by Piromallo and Morelli (2003) at 150 and 200 km depth.

4. Discussion

The aim of this discussion is not to tackle the reconstruction of the long-term evolution of the Western Mediterranean region, which has been described in several papers, but rather to focus on the final stages of arc formation in the Western Mediterranean and, in particular, on the interaction of the subduction system with the portions of continental margin that are approaching the subduction zone. Some key features of the Gibraltar and Calabrian subduction systems are compared and contrasted on the basis of the two presented tomographic models and other geophysical and geological data. We first describe and compare the lithosphere-asthenosphere structure of the two arcs, then their seismicity and active tectonics, and finally we focus on the slabs evolution.

Lithosphere-asthenosphere structure

There are two main high velocity anomalies (HVA) evident in the horizontal layers (Figs. 6 and 7), that underlie the Alboran (Al-HVA) and the Tyrrhenian (STy-HVA) basins. Both HVAs reach the mantle transition zone down to at least 600 km depth, the bottom of our models. While the STy-HVA presents a more evident arcuate shape, the Al-HVA is thicker, and the stronger part of the anomaly is blob-like, especially in the top 300 km. Moreover, the STy-HVA mostly underlies the Tyrrhenian basin, whereas the Al-HVA is mostly located below the Betics and the Granada area, where the scarce deep seismicity is found.

In both areas there are strong LVAs that surround the slab.

In the Calabrian Arc the LVA underlies the Tyrrhenian basin (STy-LVA) and the oceanic crust of the Ionian Sea (Fig. 9) . The lithosphere-asthenosphere structure under the Ionian side is only partially resolved due to the lack of long term broadband OBS deployments in the Western Ionian Sea. Continuity of the slab is inferred only from indirect evidence (e.g., slab geometry and seismicity). On the contrary, the lithosphere-asthenosphere structure below the Gulf of Cadiz (GC-LVA, Fig. 8) is well resolved and represents the key feature separating the two high velocity anomalies underlying the Atlantic and the Alboran, respectively (Monna et al., 2013a). We are confident that GC-LVA is not an effect of low velocity uppermost crustal layers smeared down the upermost mantle, given the strong crustal correction we applied that includes a thick low-velocity sedimentary layer (see Table 1 in Monna et al., 2013a).

Seismicity and active tectonics

Comparison of vertical profiles in Figs. 8 and 9 also clearly shows a very different spatial

distribution of sub-crustal seismicity, with a typical Wadati-Benioff zone for the CA and a belt of intermediate-depth seismicity (<120km) for the GA. While for the CA seismicity is included in the volume with the largest positive velocity anomalies, for the GA seismicity is concentrated on top of the HVA. Profiles BB' give a measure of the width of the two slabs, which is about 300 km for Al-HVA and 350 km for STy-HVA.

The different patterns of sub-crustal seismicity in the Gibraltar and Calabrian Arcs, suggests that a different tectonic regime is active in the two arcs (Fig. 3). It is noteworthy that only limited seismicity occurs offshore in the CA accretionary prism, but remarkable seismicity with large earthquakes, mostly hystorical but also instrumental, characterizes the onshore, uplifted region of the arc, continuing into the southern Apennines. Focal mechanisms of crustal earthquakes indicate orogen-perpendicular extension (Vannucci et al., 2004; Frepoli et al., 2011). In the GA almost no seismicity occurs in the outer accretionary prism; instead, seismicity (found also down to ~60 km) is present in the Gorringe Bank-Horseshoe Abyssal Plain (e.g., Geissler et al., 2010), where it is associated to a high velocity subducting lithosphere (Monna et al., 2015). No relevant seismicity is present at the apex of the GA, whereas some seismicity is related to the right-lateral strike-slip regime found in the eastern Betics, and a remarkable crustal seismicity is present in the Alboran basin (Serpelloni et al., 2007; Stich et al., 2006; 2010), along the Trans-Alboran shear zone (Alvarez-Marron, 1999). The distribution of crustal seismicity appears to reflect the occurrence of a diffuse plate boundary deformation that shifts from the Gloria Fault-Gorringe-SW Iberia system to the Maghrebides of north Africa; this southward shift occurs just across the Alboran basin (Fig. 3) (Serpelloni et al., 2007).

Evolution of the two subduction systems

The evolution of the Mediterrenean subduction is strongly controlled by the paleogeography of the African margin (lower plate), and in particular by the location and extent of its oceanic domains. A tectonic reconstruction at Tortonian time (Fig. 11) shows the different stages in the formation of the Gibraltar and Calabrian arcs. This time is crucial since the Tyrrhenian basin was in its initial stage, and the Calabrian Arc formed subsequently, driven by the subduction and rollback of the Neotethyan ocean located between Africa and Adria. On the contrary, the Gibraltar Arc was almost completely defined.

We propose an interpretation that is summarized in Fig. 12.

During the evolution of the retreating Mediterranean subduction, the soft collision of the outward-migrating orogen with the African margin first occurred in the Magrebides (e.g., Lonergan and White, 1997; Rosenbaum and Lister, 2004). The soft collision was followed by a slab breakoff,

marked by a change from orogenic to anorogenic magmatism (Maury et al., 2000; Abbassene et al., 2016), that disrupted the originally continuous subducted slab, and propagated laterally both eastward and westward (Fig. 12), to originate the Calabrian and Gibraltar Arcs, respectively (Wortel and Spakman, 2004). Slab tearing focussed trench retreat, favouring the formation of tightly arcuate subduction zones (e.g., Schellart et al., 2007). The narrow CA subducted slab (Fig. 9; BB') is discontinuous on either side, underneath Sicily and southern Apennines. The lack of high velocity bodies underneath western Sicily is likely a result of progressive lithospheric tearing. Tearing propagated eastward along the north African continental margin, removing the slab, during the Tyrrhenian opening from 10 to 2 Ma (Carminati et al., 1999; Faccenna et al., 2004; Goes et al., 2004; Argnani, 2009). An interruption of the slab or slab window underneath the Southern Apennines (Fig. 12) is visible in the tomography models as a low velocity anomaly at lithospheric depths (Fig. 10). The presence of a slab window is consistent with abundant volcanic products younger than 2 Ma in the Campania Magmatic Province, which supports the tapping of deep mantle reservoirs (Serri, 1990).

The low mantle velocity underneath Calabria (e.g., Mele, 1998) suggests a decoupling of the slab from the overlying lithosphere, that can be partly responsible for the recent uplift of Calabria (Gvirtzman and Nur, 1999; Argnani, 2000). A role of toroidal mantle flow dynamically sustaining the Calabrian topography has also been inferred (Faccenna et al., 2011), although the contribution of dynamic topography is likely a minor one (Molnar et al., 2015). The existence of lithospheric tears located on either side of the Calabrian Arc is supported also by

local earthquake and seismic velocity distribution. Some authors have inferred the occurrence of north-west-trending tears, that are supposed to favor the south-eastward drift of Calabria (e.g., Neri et al., 2012). The seismicity gaps and reduced seismic velocities presented by Neri et al. (2012), however, seem to outline discontinuities that propagated parallel to the trench, which are difficult to reconcile to north-west-trending lithospheric tears that would allow displacement perpendicular to the trench. In this last case, in fact, the tomographic model should suggest slab segments that are laterally shifted in the north-west-direction with respect to each other, a feature that is not observed (Fig. 7). In fact, the only discontinuity perpendicular to the trench is an incipient, ca. north-south-trending, lithospheric tear (STEP fault) (Govers and Wortel, 2005) which is located offshore eastern Sicily (Figs. 2b and 11) (Argnani, 2009).

As described in the following, we infer that the portion of continental lithosphere defined by our tomography (Fig. 6) may have played a role in preventing a further evolution of the Gibraltar Arc. In the Gibraltar system the narrow (ca. 300 km wide) high velocity body is not a typical subducting slab, given its seismicity and its blob-like shape underneath the Betics (Fig. 6). Recent studies show

561 that underneath most of the Betics the subducted slab is partly torn off its adjacent continental
562 margin, whereas underneath the Rif it is still attached to the crust (e.g., Levander et al., 2014). In
563 particular, observations from seismic tomography (Bezada et al., 2013; Palomeras et al., 2014) and
564 receiver function analysis (Mancilla et al., 2015; Thurner et al., 2014) are consistent with the
565 presence of continental crust that was removed from the continental margins and is now part of the
566 slab.
567 Both slabs below the Alboran and Tyrrhenian basins are thought to belong to narrow oceanic
568 basins. The original oceanic domain belonged to the Alpine Tethys and Neotethys for the Calabrian
569 subduction (e.g., Stampfli and Borel, 2002; Argnani, 2005), and to the Alpine Tethys and Central
570 Atlantic for the Gibraltar subduction (e.g., Gutscher et al., 2012). However, the physical connection
571 between Alpine Tethys and the Central Atlantic proposed by several authors (see Section 2.1) can
572 be questioned. In fact the occurrence of an arcuate structure underneath the Gibraltar Arc, with a
573 seismic velocity pertaining to continental lithosphere, suggests the presence of a possible
574 continental domain located just west of Gibraltar in the GA model (Figs. 6 and 8; Monna et al.
575 (2013a, 2015)). Recent tomography models (Bonnin et al., 2014; Villaseñor et al., 2015) show a
576 low velocity anomaly at lithospheric depths just west of the Gibraltar Strait, which agrees very well
577 with our GC-LVA.
578 The existence of possibly Jurassic oceanic crust in the Gulf of Cadiz has been documented by
579 refraction data (Sallares et al., 2011), but the refraction profile is located further to the west of the
580 low-velocity anomaly that we attribute to continental lithosphere (Fig. 2a), and recent refraction
581 data across the Gibraltar Strait show a continental crustal structure (Gil et al., 2014). The boundary
582 between continental and oceanic mantle domain is placed just east of Gibraltar Arc (Morais et al,
583 2015) through receiver function analysis, and the continuity of the thickened crust along the
584 Gibraltar Arc (Mancilla et al., 2015) seems to support the occurrence of a substrate of continental
585 nature. Although Mancilla et al (2015) propose an oceanic connection between the Atlantic and the
586 subducted slab, their receiver functions data are also compatible with our hypothesis, as their data
587 do not constrain the nature of the crust in the western offshore of Gibraltar.
588 The presence of a portion of continental lithosphere that has limited the Alpine Tethys to the west,
589 and that is now choking the subduction underneath the Alboran basin, fits well with other recent
590 high resolution tomography models (Bonnin et al., 2014; Palomeras et al., 2014; Villaseñor, 2015).
591 These tomography images can be explained by a process of ongoing delamination, with a sinking
592 oceanic slab pulling and thinning the lithosphere of the Betics and Rif.
593 In our interpretation, continental lithosphere is entering subduction in the Gibraltar Arc from the
594 west, and due to its positive buoyancy it contrasts the slab pull effect, favoring slab break-off,
595 delamination, and limiting asthenosphere wedging west of the Gibraltar Arc, and thus limiting

uplift and extension. Active extensional tectonics and recent uplift, in fact, have not been observed at the apex of the Gibraltar Arc; recent uplift occurs mostly in the Sierra Nevada (Perez-Pena et al., 2010; Braga et al., 2003). On the contrary, in the CA, subduction of oceanic lithosphere is well documented, with the slab connected to the oceanic Ionian lithosphere (Fig. 11) (Argnani, 2005; Speranza et al., 2012). The slab pull, which is still active, favored the wedging of asthenospheric mantle and ensuing uplift (Gvirtzman and Nur, 1999). The uplift, in turn, promotes gravitational collapse towards the topographically low Ionian Sea and possibly triggers the extension which is ongoing in Calabria (Argnani, 2000; D'Agostino et al., 2011).

5. Summary and Conclusions

The Western Mediterranean subduction system was active mostly during the Neogene, creating the arcuate mountain belts and deep basins that characterize the Mediterranean orogen. Slab sinking and trench retreat contributed to the opening of the Balearic and Tyrrhenian basins. Although the main driving force is likely given by trench retreat of oceanic subduction within a low plate-convergence setting, additional complexities came into play throughout the evolution of the Western Mediterranean, the major factor being the interaction between the European subduction in the Alps and the African subduction in the Apennines (e.g., Argnani, 2012). In this paper we focus on the origin of the two tight loops of the Gibraltar and Calabrian Arcs using two teleseismic tomography models. These two arcuate features have been often described together and considered as typical of the Western Mediterranean evolution (Horvath and Berckhemer, 1982; Rosenbaum and Lister, 2004; Faccenna et al., 2004). The fact that trench retreat has overtaken convergence throughout the Neogene evolution of the Mediterranean implies that the nature of the lower plate lithosphere may strongly affect the geodynamic balance of the system. In fact, the arcuate orogenic belts were mostly formed in the final stages of the Western Mediterranean evolution and, apart from trench rollback, they were affected in an important way by the geometry of the continental margins. In the Gibraltar Arc both slab rollback and gravitational potential of a thickened orogen have been driving forces for the emplacement of the Alboran units in the early Miocene.

The continuity of oceanic subduction represents the major difference between the Calabrian and Gibraltar arcs. In the Gibraltar Arc the continental margin domain is entering subduction. The GA tomography model suggests that the Gibraltar Arc was docking into a portion of thinned continental crust, located just west of Gibraltar (Fig. 12). This buoyant lithosphere was likely responsible for the end of trench retreat, and its related extension in the Alboran basin. As the subduction of the oceanic lithosphere was progressively completed, the continental margin lithosphere of Africa and Iberia entered into the subduction zone and was pulled down by the sinking oceanic slab, leading to ongoing continental delamination underneath the western Rif and the Betics and slab breakoff

(Bezada et al., 2013; Levander et al., 2014; Thurner et al., 2014; Mancilla et al., 2013, 2015). Active deformation in the region is reflected in the location of the roughly east-west-trending Africa-Iberia plate boundary. This boundary shifts from the southwest Iberian margin to north Africa just across the Alboran Sea, mostly ignoring the arcuate structures of the Gibraltar Arc, and confirming that subduction is not the main operating mechanism at the moment (Zitellini et al., 2009).

In the case of the Calabrian Arc, the slab is connected to the Ionian basin that is likely floored by oceanic lithosphere (Argnani, 2005; Speranza et al., 2012). The opening of the southern Tyrrhenian basin caused a soft collision of the outward migrating fold-and-thrust belt into the continental margins of Adria (southern Apennines) and Africa (Sicilian Maghrebides). This soft collsion was followed by a trench-parallel slab break-off in both the southern Apennines and Sicilian Maghrebides (Fig. 12). This process produced the slab window visible, in our CA tomographic model (Figs. 7 and 10). The window underneath Sicily is much wider because the slab was progressively torn off at the African margin during the Tyrrhenian backarc opening (Argnani, 2009), whereas the slab window under the Southern Apennines formed in the last 2 Ma and extends for about 300 km along the chain (Fig. 12). A choked subduction, at much reduced rates, of a narrow oceanic slab continued underneath Calabria. The pull exerted by the sinking oceanic lithosphere, narrowed after slab breakoff on either side of the arc, promoted the initiation of lateral tears (or STEP fault) (Govers and Wortel, 2005), particularly on the western Ionian side and along the north-south branch of the Aeolian Islands (Argnani and Bonazzi, 2005; Argnani et al., 2007; Argnani, 2009). The sinking Ionian slab decoupled from the overlying Calabrian orogen and released the upper plate from compressional stresses, favouring the wedging of asthenosphere, as indicated by reduced upper mantle Pn velocities (Mele et al., 1998) and confirmed by seismic attenuation measurements (Chiarabba et al., 2008; Monna and Dahm, 2009); this last process, in turn, promoted uplift and extension in the Calabrian Arc.

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Data from SAPTEX and SeSCAL experiment are available upon request from giovannibattista.cimini@ingv.it. The figures were produced with GMT (Wessel and Smith, 1991).

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Figure 1

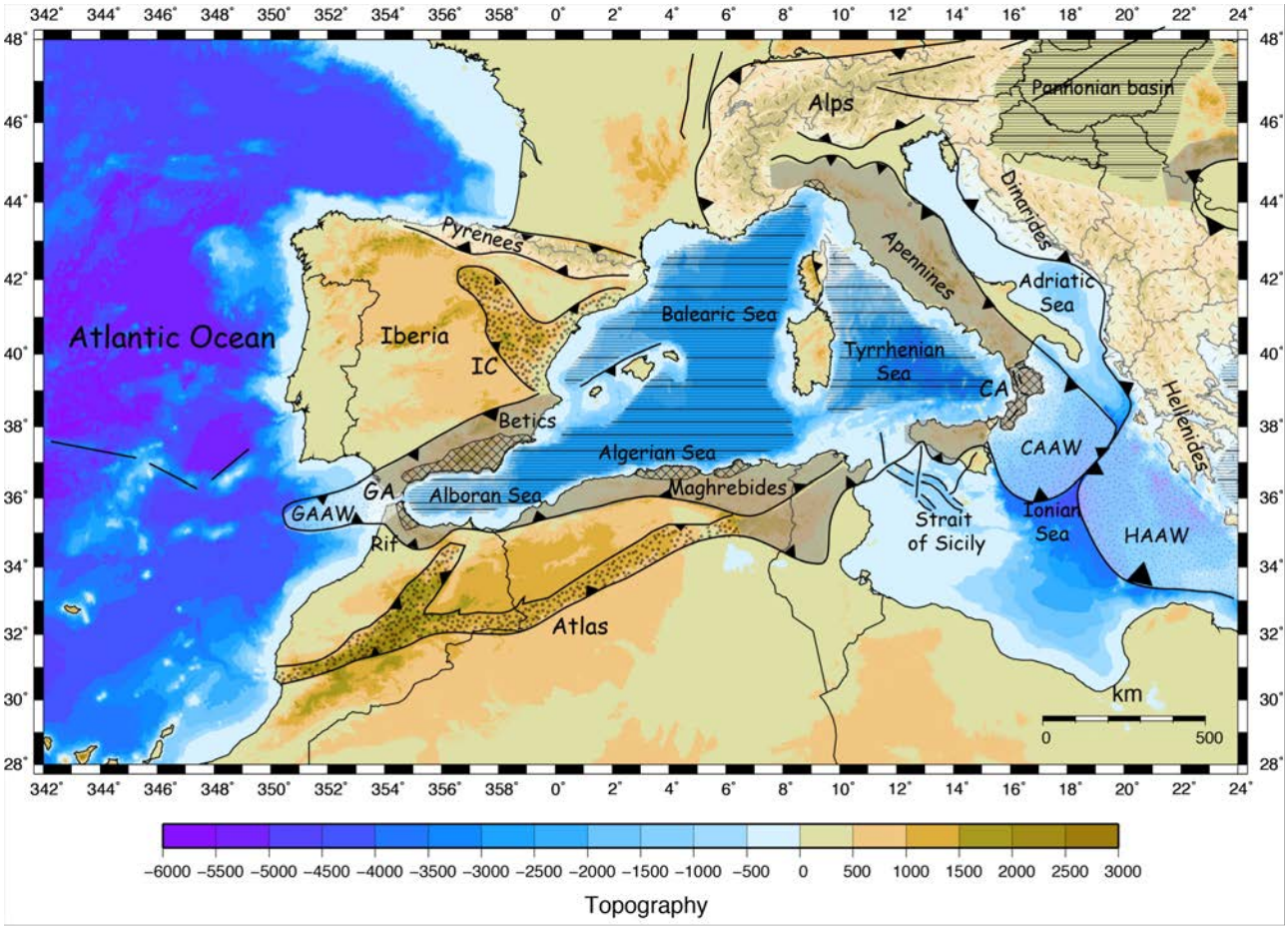

Fig. 1. Simplified geological map of the CWM region. The system of fold-and-thrust belts, indicated in gray, formed from Late Oligocene to Pliocene, during the opening of the backarc basins (horizontal rules; also including the volcanic arcs). The accretionary wedges related to oceanic subduction are indicated with fine dots (GAAW: Gibraltar Arc Accretionary Wedge; CAAW: Calabrian Arc Accretionary Wedge; HAAW: Hellenic Arc Accretionary Wedge). The units belonging to the internal domain are shown with cross hatching. The collisional belts are indicated with random dashes, whereas the Atlas and Iberian Chain (IC) intracontinental belts are indicated with coarse dots. BF: Bradanic foredeep basin; GCF: Gela-Catania foredeep basin.

Figure (with caption below and on the same page)

Figure 2a

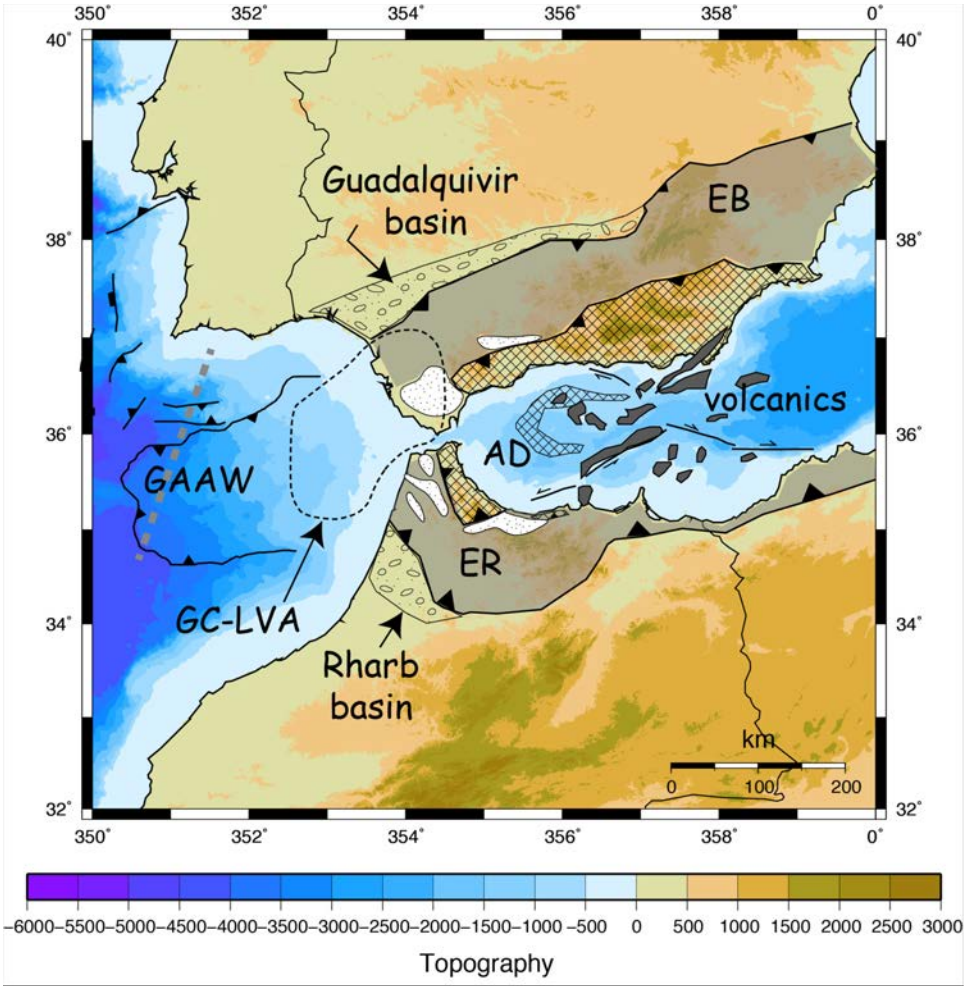

Figure 2b

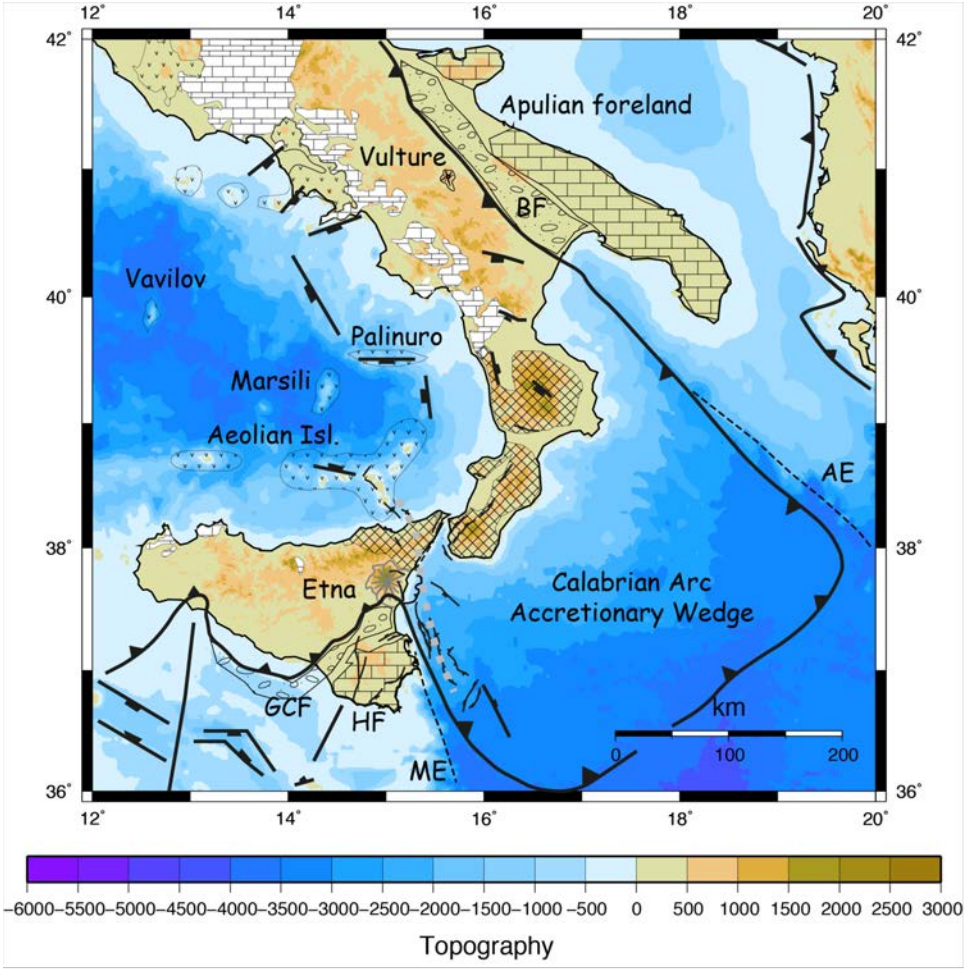

Fig. 2 Simplified geological maps of the two study regions. **a)** Gibraltar-Alboran region (after Alvarez-Marron, 1999; Platt et al., 2013; Gutscher et al., 2012; Duarte et al., 2013). The Alboran Domain (AD), that includes the Internal Betics and Internal Rif, is indicated by cross hatched pattern. The External Betics (EB in gray pattern) includes the Subbetic and Prebetic, and the External Rif (ER in gray pattern) includes the Intrarif and Mesorif. The white field with dotted pattern represents the Flysch belt, and the volcanics are indicated in dark gray. GAAW: Gibraltar Arc Accretionary Wedge; GC-LVA: approximate location of the low-velocity anomaly (from 100 to 200 km depth). Trace of seismic refraction profile (Sallares et al., 2011) indicated by thick gray dashed line. (After Monna et al., 2015).

Calabrian Arc-Southern Tyrrhenian region (after Bigi et al., 1990; Argnani, 2005). The outcrops of Apulian and Hyblean (HF) foreland are indicated with large brick pattern, whereas the carbonate

units encased within basinal units of the Southern Apennines-Maghrebides are indicated as white fields with brick pattern. The conglomerate pattern indicates the Bradanic (BF) and Gela-Catania (GCF) foreland basins. The mostly crystalline units of the Calabrian Arc are shown with cross hatching. The V pattern indicates Pliocene-Quaternary volcanics, including the Campania Magmatic Province. The Malta and Apulia Escarpments (ME and AE, respectively) are also indicated with a dashed line. The thick, gray dashed line offshore eastern Sicily marks the approximate location of the incipient lithospheric tear (after Argnani, 2009).

Figure (with caption below and on the same page)

Figure 3

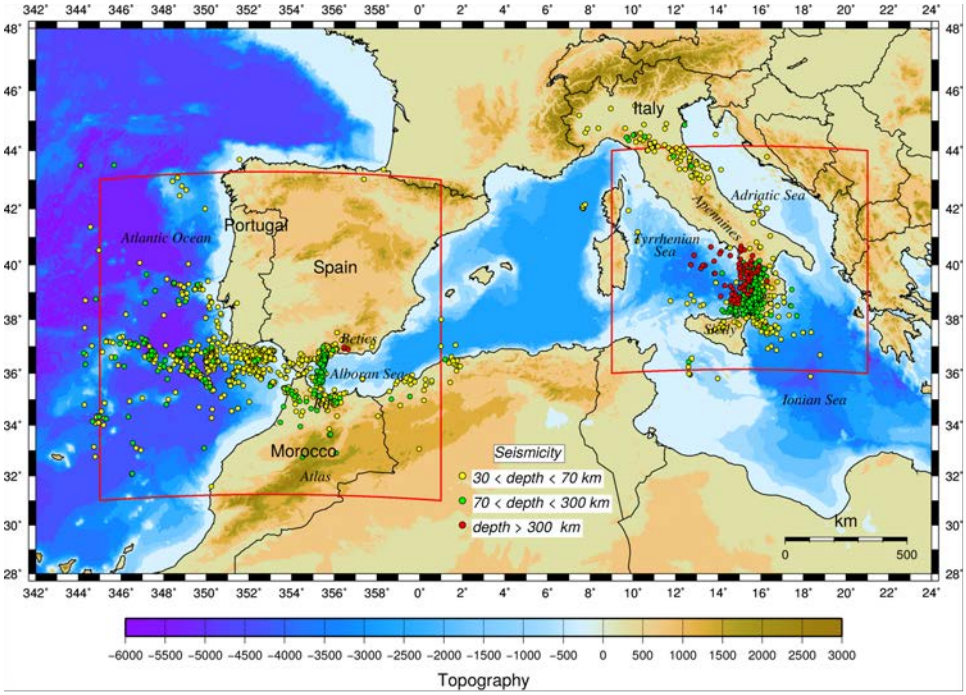

Fig. 3. Map of the CWM region with the two study areas. Colored circles show the sub-crustal seismicity (M>= 3) which occurred in the years 1990-2013. Hypocentral parameters from IGN catalogue and INGV bulletins. Topography/bathymetric profiles are from the Global-Integrated-Topo/Bathymetry Grid (GINA) (Lindquist et al., 2004).

Figure (with caption below and on the same page)

Figure 4

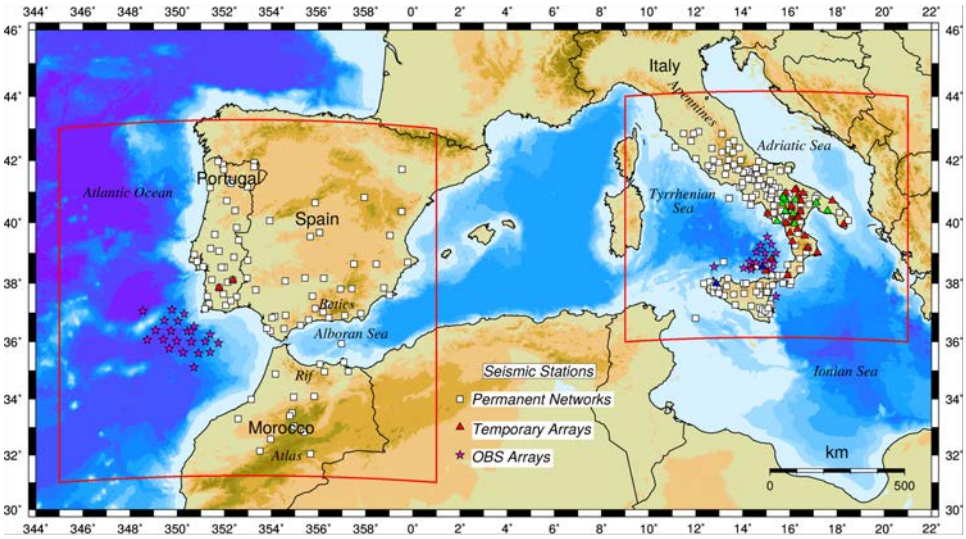

Fig. 4. Map of the seismic stations used in the two tomographic inversions. The OBS array in the Gulf of Cadiz was deployed during the NEAREST project (http://nearest.bo.ismar.cnr.it). The OBS in the Southern Tyrrhenian were deployed during the TYDE (Dahm et al., 2002) and SN1 (Monna et al., 2005) experiments. The temporary land arrays were deployed in Southern Italy during the SAPTEX (red triangles) (Cimini et al., 2006) and SeSCAL (green triangles) (Frepoli et al., 2011) experiments.

Figure (with caption below and on the same page)

Figure 5

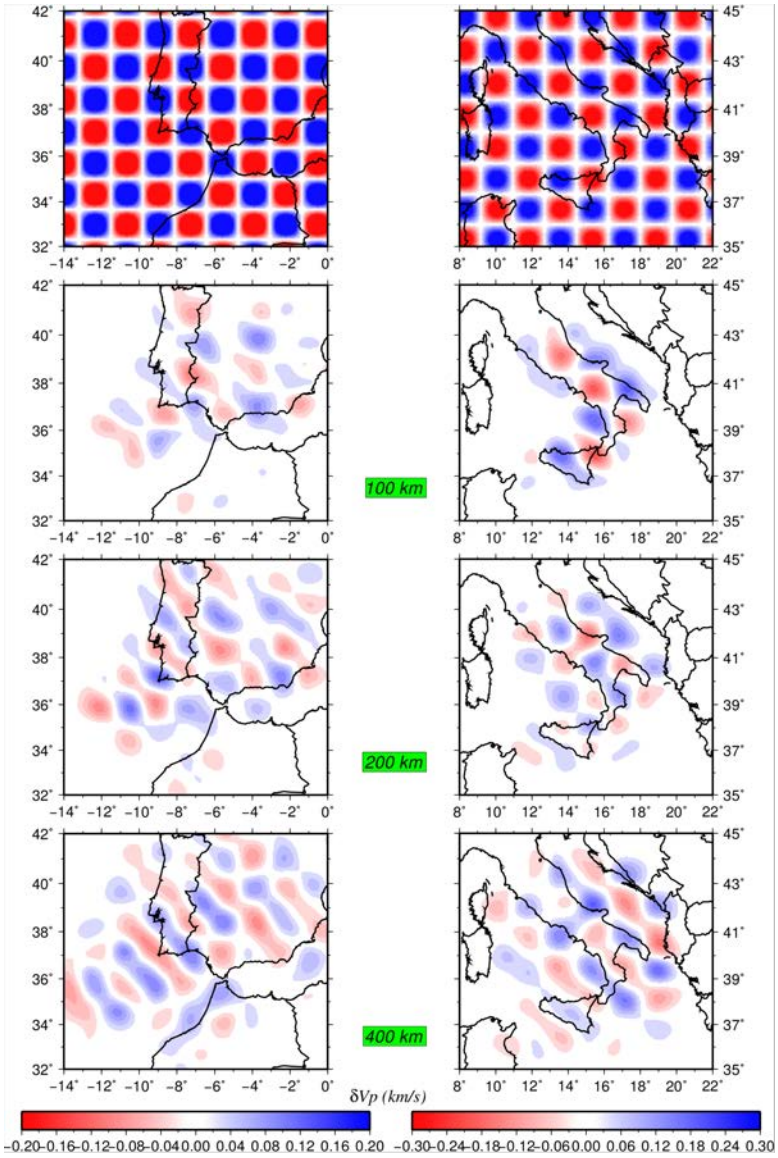

Fig. 5. Results of the checkerboard resolution test for three depth slices of the two tomographic models. Left panels are for the GA model, right panels for the CA model. Panels at the top are the input checkerboard velocity models. These patterns consist of alternating 100x100 km cells of fast and slow anomalies varing in latitude, longitude, and depth. The recovered patterns show wide areas of good resolution for both the models. The synthetic data sets, based on the source-receiver geometries of the GA and CA teleseismic inversions, include gaussian noise with standard deviations of 0.15s and 0.50s, respectively for picked and bullettin data.

Figure (with caption below and on the same page)

Figure 6.

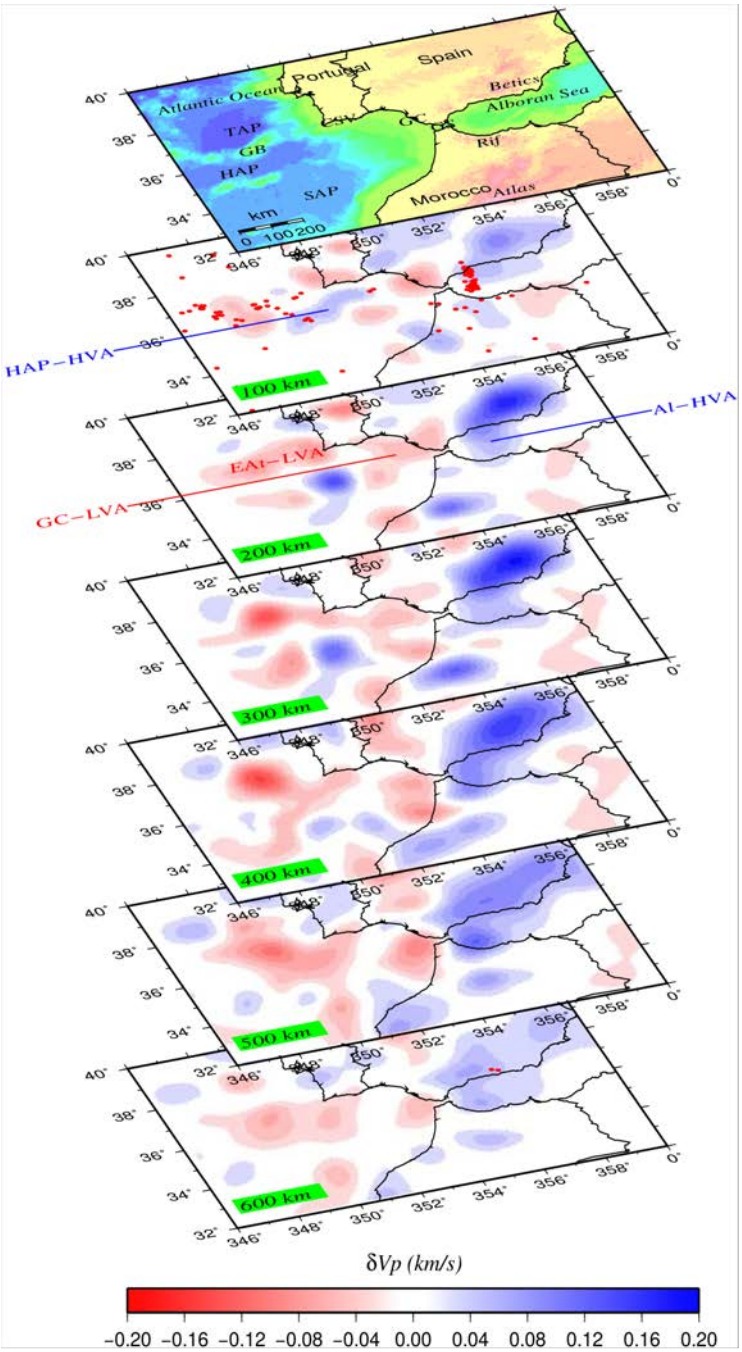

Fig. 6. Perspective view showing a series of horizontal slices extracted from the GA velocity model at depth intervals of 100 km. Blue colored areas indicate high velocity anomalies, present in the Betic-Alboran region (Al-HVA) and in the Atlantic SW Portugal (HAP-HVA). Red colored areas are zones of low velocity anomalies in the Eastern Atlantic (EAt-LVA) and the Gulf of Cadiz (GC-LVA). (After Monna et al., 2015).

Figure (with caption below and on the same page)

Figure7

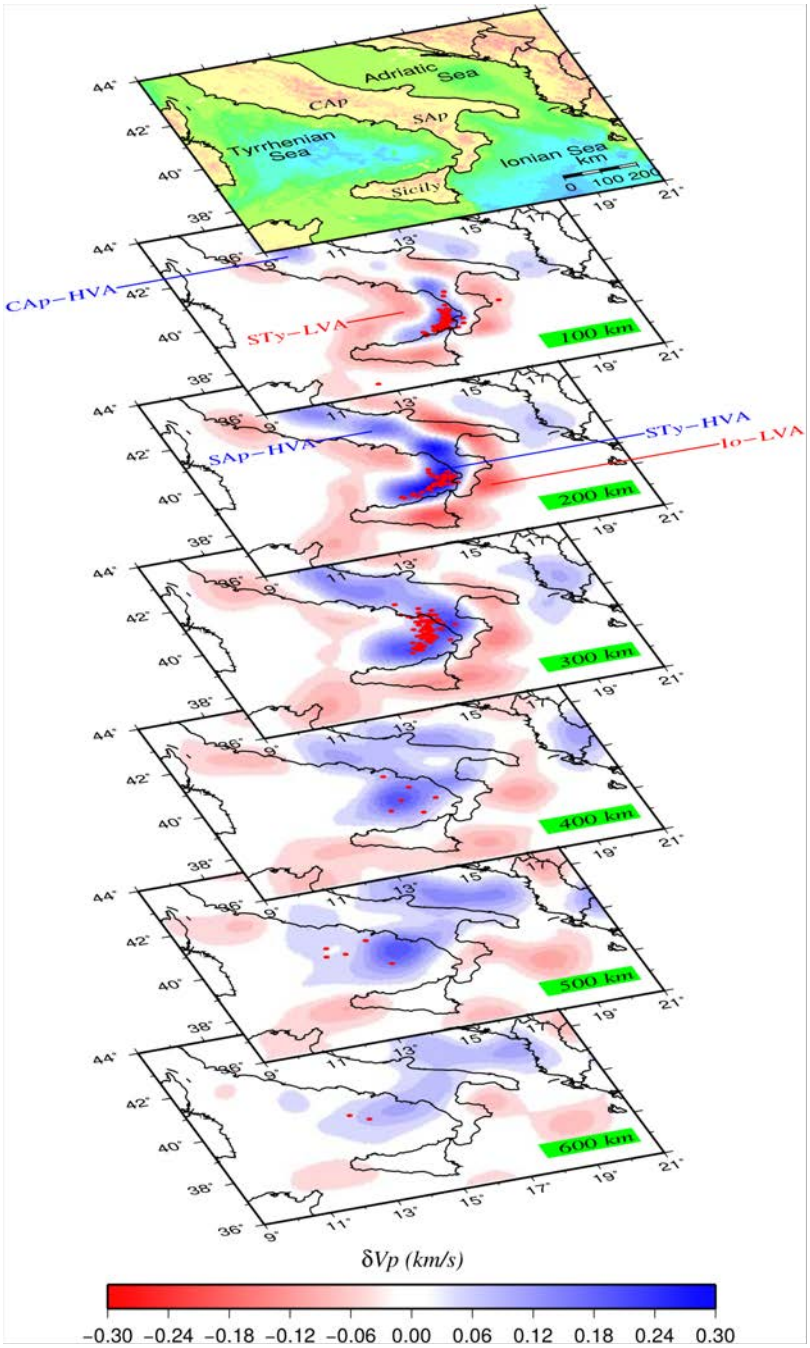

Fig. 7. Perspective view showing a series of horizontal slices extracted from the CA velocity model at depth intervals of 100 km. As in Fig. 6, blue colored areas indicate high velocity anomalies, present in the Southern Tyrrhenian region (STyHVA) and in the Southern Apeninnes (SAp-HVA). Red colored areas are zones of low velocity anomalies in the Tyrrhenian Sea (STy-LVA) and the Ionian Sea (Io-LVA).

Figure (with caption below and on the same page)

Figure 8

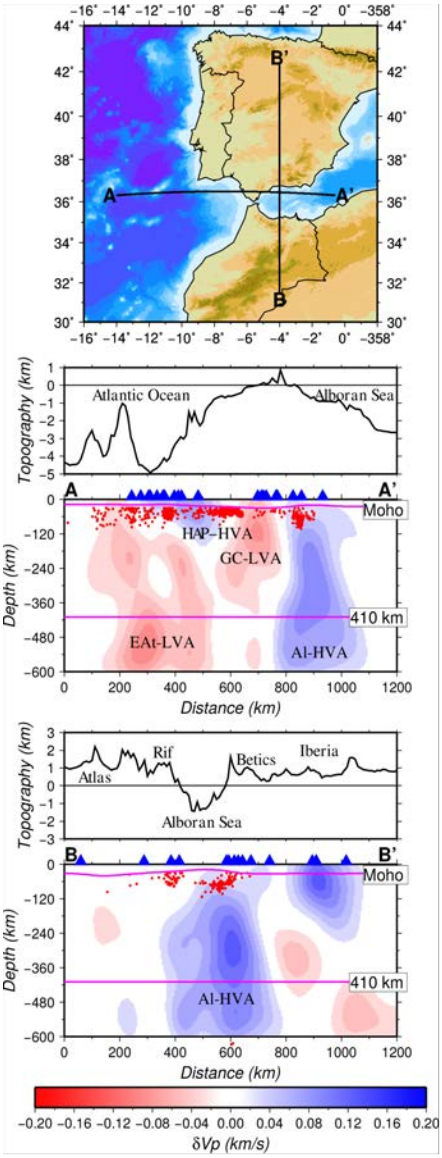

Fig. 8. Vertical slices displaying the velocity anomalies of the GA model along a west to east profile crossing the Gibraltar Arc (AA'), and along a south to north profile crossing the Alboran Sea (BB'). SAP = Seine Abyssal Plain; HAP = Horseshoe Abyssal Plain; TAP = Tagus Abyssal Plain. High velocity anomalies: Al-HVA=Betic-Alboran; HAP-HVA=Horseshoe Abyssal Plane. Low velocity anomalies: GC-LVA=Gulf of Cadiz; EAt-LVA=Eastern Atlantic. Blue triangles indicate the seismic stations and red dots the subcrustal seismicity, located within a 100 km wide zone centered on the profile. In profile BB', hypocenters deeper than 600 km represent the deep events below the Granada region. Moho topography is from the European Moho depth map (Grad et al., 2009). (After Monna et al., 2013a).

Figure (with caption below and on the same page)

Figure9

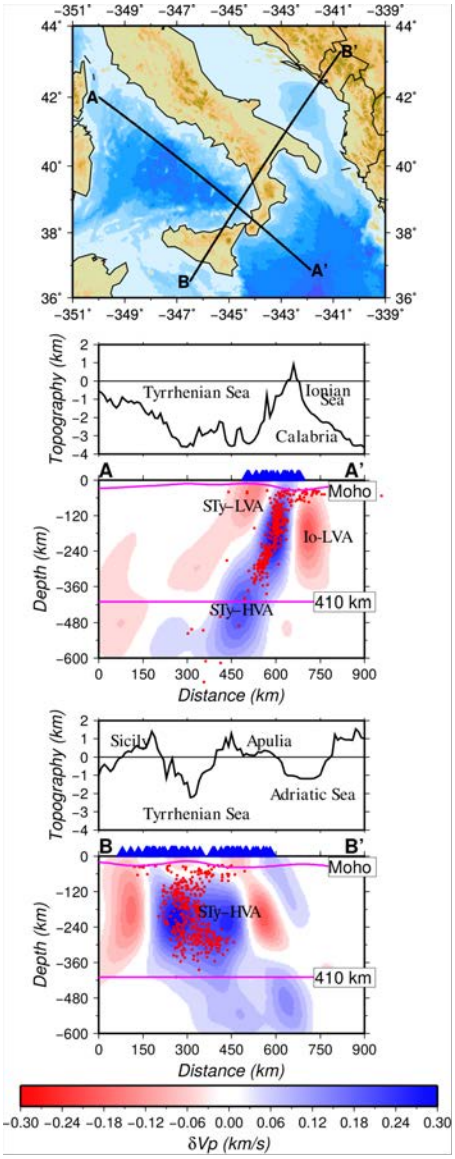

Fig. 9. Vertical slices displaying the velocity anomalies of the CA model along a northwest to southeast profile crossing the Calabrian Arc (AA'), and along a southwest-northeast profile crossing the southern Tyrrhenian basin (BB'). CAp = Central Apennines; SAp = Southern Apennines. High velocity anomalies: STy-HVA=Southern Tyrrhenian. Low velocity anomaly: STy-LVA=Southern Tyrrhenian. Blue triangles and red dots indicate the seismic stations and the subcrustal seismicity located within a 100 km wide zone centered on the profile. Moho topography is from the European Moho depth map (Grad et al., 2009).

Figure (with caption below and on the same page)

Figure10

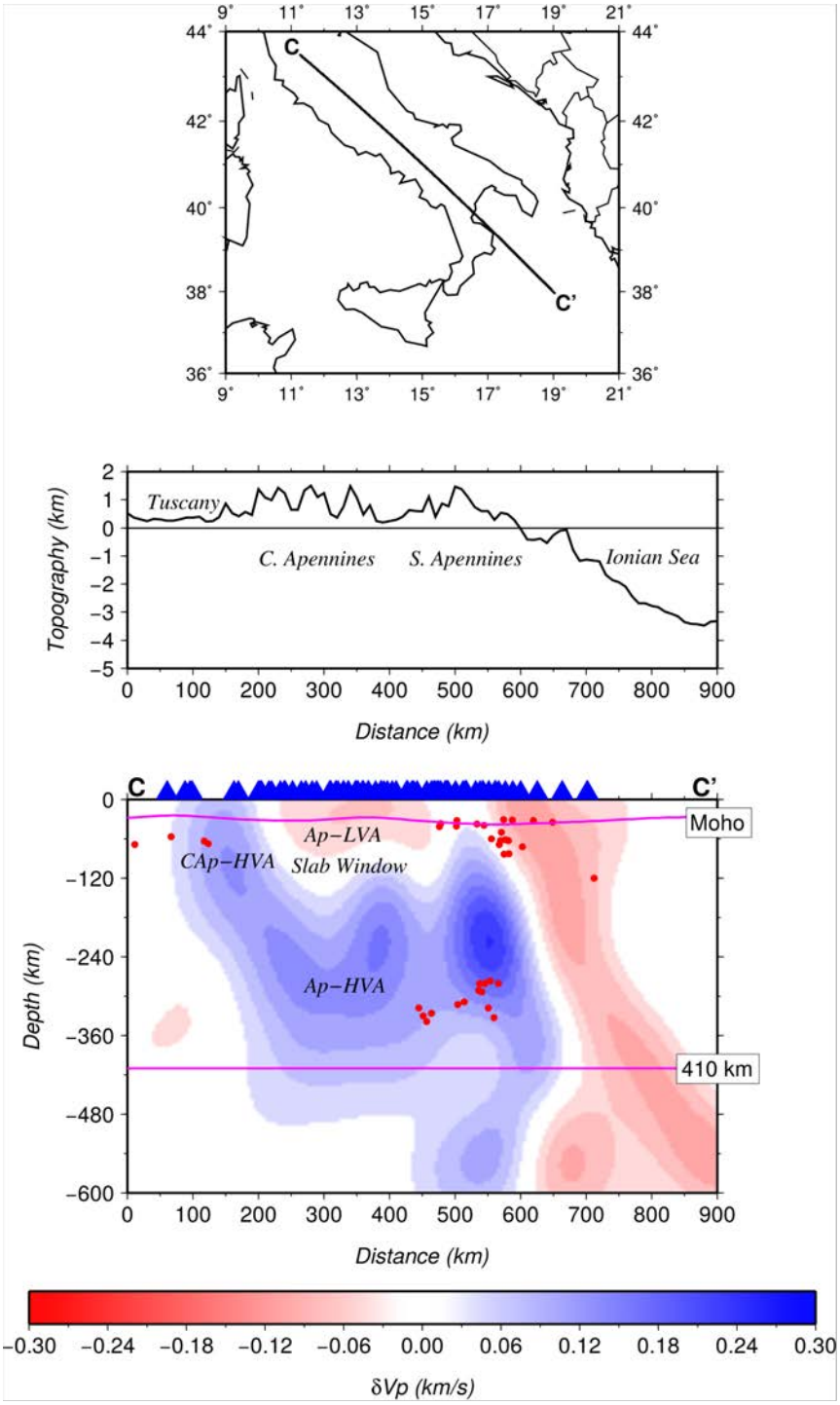

Fig. 10. Vertical slice displaying the velocity anomalies of the CA model along a northwest to southeast profile crossing the Southern Apennines (CC'). The trace and topographic profile are shown in the top and middle panels, respectively. A well defined slab window underneath the Southern Apennines is visible (lower panel). High velocity anomalies: Cap-HVA=Central Apennines; Ap-HVA=Apennines. Low velocity anomaly: Ap-LVA=Apennines-slab window.

Figure (with caption below and on the same page)

Figure11

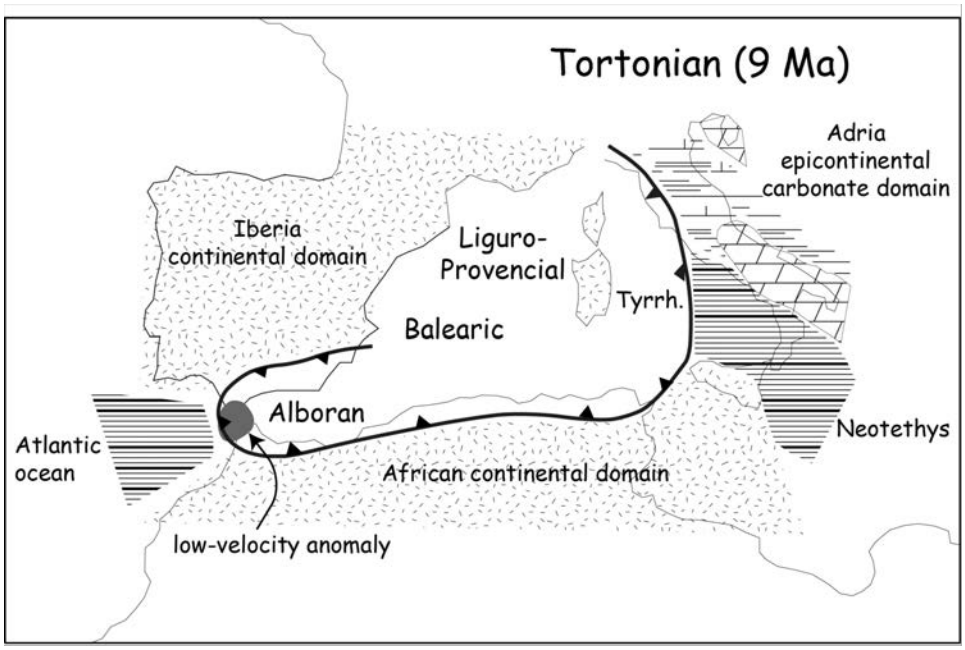

Fig. 11. Simplified tectonic reconstruction of the Mediterrenan in Tortonian time. The African and Italian coasts are positioned with respect to stable Europe. Note that the Gibraltar arc was almost completely formed, whereas the Calabrian arc was still to be defined. During the Pliocene-Pleistocene the subduction and rollback of the narrow Neotethyan branch shaped the final arcuature of the Calabrian arc. The segment of African continental margin imaged just offshore Gibraltar (LVA, low-velocty anomaly) likely prevented any further development of the Gibraltar arc, favouring slab breakoff.

Figure (with caption below and on the same page)

Figure12

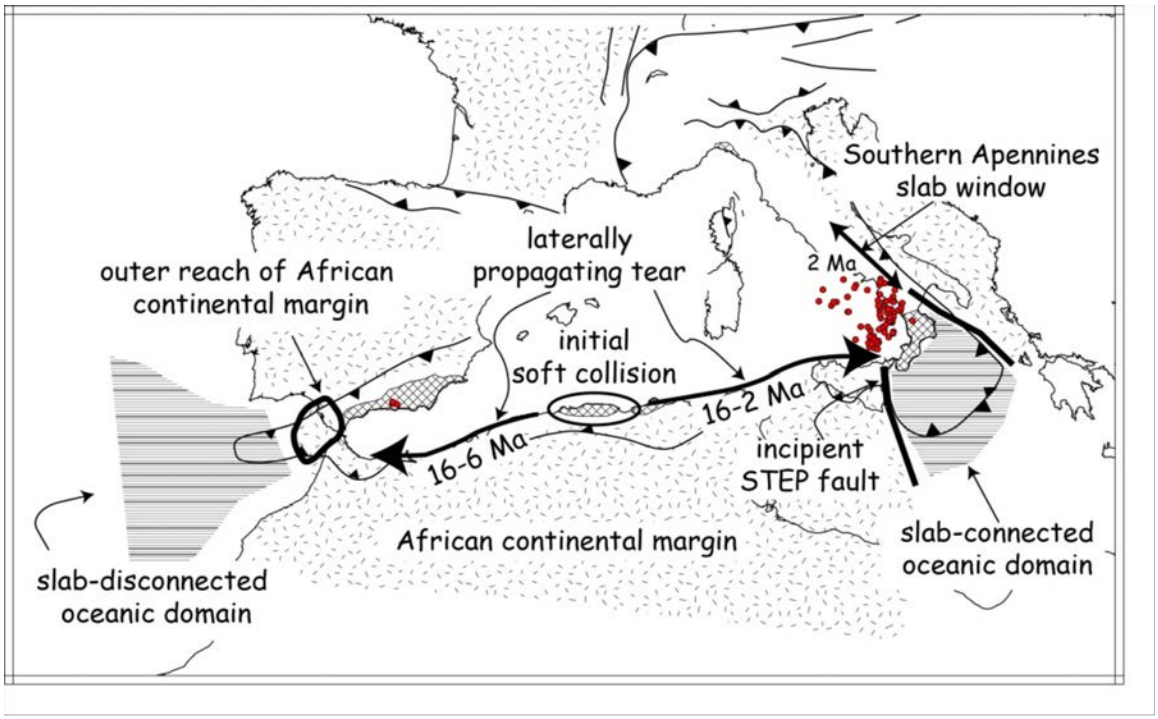

Fig. 12. Interpretation of the evolution of the CWM subduction system highlighting the main features which controlled arc formation. Slab tearing propagated laterally along the north African continental margin, following the initial soft collision in Algeria (ca. 16 Ma). Arc formation proceeded on either side, driven by slab sinking and trench retreat, but slab retreat was impeded in its westward motion by the segment of thinned continental margin imaged by the GA tomography underneath Gibraltar (GC-LVA). The eastward progression of arc formation, on the other hand, continued until very recently, with the opening of the Tyrrhenian basin, driven by the sinking Ionian slab. In its final stage the sinking also promoted the formation of a slab window underneath the Southern Apennines, which is responsible for the magmatism of the Campania Magmatic Province (Serri, 1990). Dots represent deep (depth > 300 km) M>= 3 seismicity.