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Subduction and volcanism in the Iberia–North Africa collision zone from tomographic images of the upper mantle

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ABSTRACT

New tomographic images of the upper mantle beneath the westernmost Mediterranean suggest that the evolution of the region experienced two subduction-related episodes. First subduction of oceanic and/or extended continental lithosphere, now located mainly beneath the Betics at depths greater than 400 km, took place on a NW–SE oriented subduction zone. This was followed by a slab-tear process that initiated in the east and propagated to the west, leading to westward slab rollback and possibly lower crustal delamination. The current position of the slab tear is located approximately at 4°W, and to the west of this location the subducted lithosphere is still attached to the surface along the Gibraltar Arc. Our new *P*-wave velocity model is able to image the attached subducted lithosphere as a narrow high-velocity body extending to shallow depths, coinciding with the region of maximum curvature of the Gibraltar Arc, the occurrence of intermediate-depth earthquakes, and anomalously thick crust. This thick crust has a large influence in the measured teleseismic travel time residuals and therefore in the obtained P-wave tomographic model. We show that removing the effects of the thick crust significantly improves the shallow images of the slab and therefore the interpretations based on the seismic structure.

1. Introduction

The Gibraltar Arc, located in the western Mediterranean region, is the tightly curved western limit of the Alpine orogenic system (Fig. 1). It is formed by the Betic chain in the southern Iberian Peninsula and the Rif mountains in northern Morocco. The arc, also referred to as the Betic–Rif system, encloses the Alboran Sea, a Neogene extensional basin.

The process or processes responsible for the formation and present-day structure of the Gibraltar Arc continue to be the subject of intense debate, with two major families of models being proposed: subduction-related processes (e.g. active subduction, slab rollback, slab tear, asymmetric delamination) and convective removal of the lithosphere (for a review of the different models see Platt et al., 2013 and references therein). A growing number of geophysical data collected in the last decade have improved our understanding of the region, predominantly favoring the slab rollback process, but still no single model has received a general consensus (see Gutscher et al., 2012; Platt et al., 2013 for recent reviews).

The Gibraltar Arc exhibits features that combined are characteristic (if not exclusive) of a subduction zone: deep seismicity, arc volcanism and an accretionary prism. Deep seismicity in the Betic–Rif is distributed in two zones: a slightly curved, N–S band of intermediate-depth events with foci between 70 and 120 km in the region of maximum curvature of the arc; and a tight cluster of deep-focus earthquakes beneath Granada with depths of about 625 km with two major events in 1954 (Mw 7.8, Chung and Kanamori, 1976) and 2010 (Mw 6.3, USGS). The intermediate-depth earthquakes dip very steeply to the center of the arc suggesting a small Wadati–Benioff zone. Their focal mechanisms are variable but indicate downdip tension (Ruiz-Constán et al., 2011). Volcanic rocks in the Alboran Basin are geochemically similar to volcanic rocks from active subduction zones (e.g. Izu–Bonin and Aeolian island arcs) and consist of low-K (tholeiitic) and medium- to high-K calc-alkaline series (Duggen et al., 2005). Finally, the Gulf of Cadiz, together with the western part of the external Rif and Betics has long been identified as an accretionary prism or wedge (e.g. Gutscher et al., 2009).

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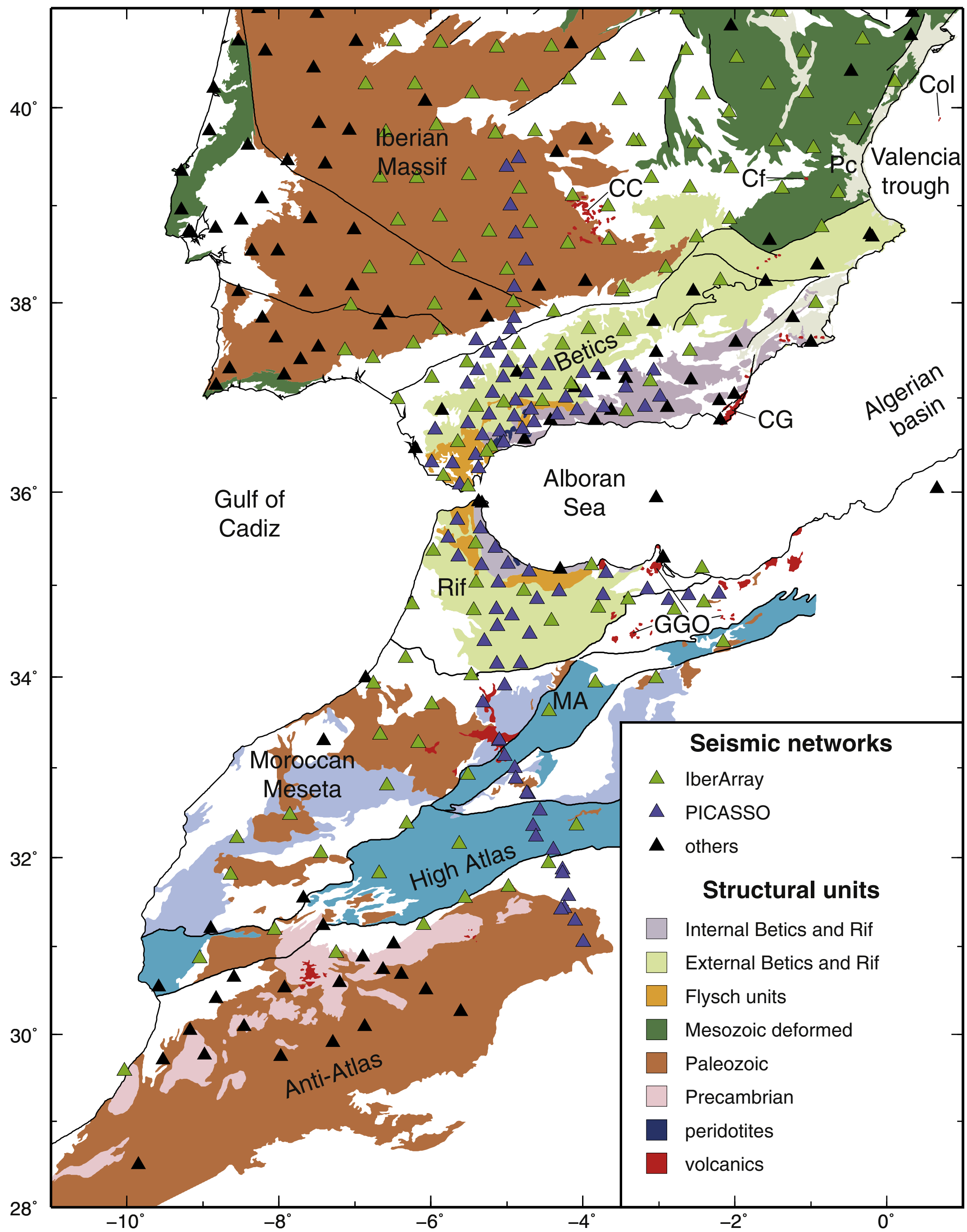

Fig. 1. Location map of the study region showing the different structural units. The broadband stations used are shown as triangles and color coded according to the network. CC: Campo de Calatrava volcanics, Cf: Cofrentes, CG: Cabo de Gata volcanics, Col: Columbretes Islands, GGO: Guelliz, Gourougou and Oujda volcanics, MA: Middle Atlas, Pc: Picassent.

Another characteristic feature of most subduction zones is the existence of a positive *P*-wave velocity anomaly in the mantle that, in the case of the Alboran region, extends continuously from shallow depths to the base of the transition zone (660 km seismic discontinuity). This feature has been identified by many authors (Blanco and Spakman, 1993; Calvert et al., 2000; Piromallo and Morelli, 2003; Spakman and Wortel, 2004) and has also been the subject of recent studies, some using a similar dataset to this one (Bezada et al., 2013, 2014; Bonnin et al., 2014; Monna et al., 2013). Although most studies agree in the general shape of the anomaly, they differ in aspects that have important geodynamic implications. Is the high-velocity body attached to the surface and where? Do intermediate-depth earthquakes occur in regions of high or low *P*-wave velocity? Does the high velocity anomaly continue to the east along the coast of North Africa? Is the high velocity anomaly continuous or broken into different blocks?

In order to answer these questions, and to better understand the past and present-day evolution of the region, a number of projects have been carried out recently using different methodologies and approaches. As part of the TOPO-IBERIA project (2007–2013) the IberArray network, consisting of seismic, geodetic, and magnetotelluric instruments was deployed in Spain and Morocco (Díaz et al., 2009). In coordination with the seismic component of IberArray, which included approximately 200 sites equipped with broadband seismic instruments, other temporary broadband networks were deployed in Morocco,