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Shear-velocity structure of the Tyrrhenian Sea: Tectonics, volcanism and mantle (de)hydration of a back-arc basin

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ABSTRACT

The Tyrrhenian Sea in the Mediterranean formed as the result of roll-back of the Adriatic and Ionian subducting plates. It is mostly underlain by strongly thinned continental lithosphere, but contains two small oceanic basins in the southern Tyrrhenian, the youngest one located just behind the active magmatic arc. Its regional setting with dense station coverage provides a unique opportunity to derive a high-resolution, 3-D shear-velocity model of this back-arc basin and surrounding onshore areas using interstation Rayleigh-wave dispersion measurements. Our tomographic model, extending to a depth of approximately 160 km, displays a pronounced, nearly ring-shaped low shear-velocity zone between 70 and 110 km depth which surrounds the older oceanic Vavilov Basin. The sharp velocity decrease at 70 km depth can be explained by the transition from a relatively dry lithospheric mantle to more hydrous asthenospheric mantle material. The tectonic evolution of the region and the correlation of the low-velocity anomaly with subduction-related volcanism indicate that the low-velocity anomaly reflects hydrous mantle material in (present or former) mantle wedge regions. We suggest that the absence of the low-velocity zone beneath the Vavilov Basin is due to mantle dehydration caused by the creation of MORB crust. Whereas temperature effects may dominate the asthenospheric shear-velocity differences between various back-arc basins, we find that the variations in shear-velocity structure within the Tyrrhenian area are best explained by variations in mantle water content.

1. Introduction

The Tyrrhenian Sea is a back-arc basin in the Mediterranean Sea which formed within the general framework of convergence of Africa and Eurasia. There is general agreement that much of the evolution of the western Mediterranean is governed by several stages of slab roll-back (e.g., Malinverno and Ryan, 1986; Dewey et al., 1989; Gueguen et al., 1998; Wortel and Spakman, 2000; Faccenna et al., 2004; Rosenbaum and Lister, 2004; Faccenna et al., 2007; Jolivet et al., 2009). In the first major stage, from 30 to 15 Ma, Corsica and Sardinia were separated from the European mainland by counterclockwise rotation leading to the opening of the Liguro-Provinçal and Valencia basins. The Tyrrhenian Sea was formed during the second major stage, from 15 Ma to Present. Initially it opened by east–west rifting, driven by the Adriatic slab, along the western margin of Corsica and Sardinia. The northern Tyrrhenian Sea, roughly corresponding to latitudes larger than 41°N, opened at a relatively slow rate (∼1–1.5 cm/yr). The opening of the southern Tyrrhenian Sea is the result of enhanced extension by roll-back of the Adriatic–Ionian slab system towards the southeast. This happened in two steps with the formation of the Vavilov Basin occurring during the first episode (8–4 Ma) (e.g., Argnani and Savelli, 1999; Faccenna et al., 2007). The Marsili Basin, surrounded by the currently active Aeolian island arc, opened during the second episode (2–1 Ma).

Volcanism of the Tyrrhenian Sea and its surroundings shows remarkably large variations in time and space reflecting the complex tectonic evolution of the region. The petrological and geochemical signatures of the subduction-related (ranging from calc-alkaline to shoshonitic and ultra-potassic), intraplate and mid-ocean-ridge-type magmatism point to large differences in mantle source compositions and degrees of melting (e.g., Savelli, 2002; Peccerillo, 2005; Lustrino et al., 2011). The compositional characteristics of volcanism of the last 14 Myr as well as of samples from deep drill holes are depicted in Fig. 1.

The geochemical signatures of the subduction-related magmas require a heterogeneous mantle source, likely including lithospheric- or wedge-mantle material that has been variably metasomatized by fluids derived from continental and oceanic slabs

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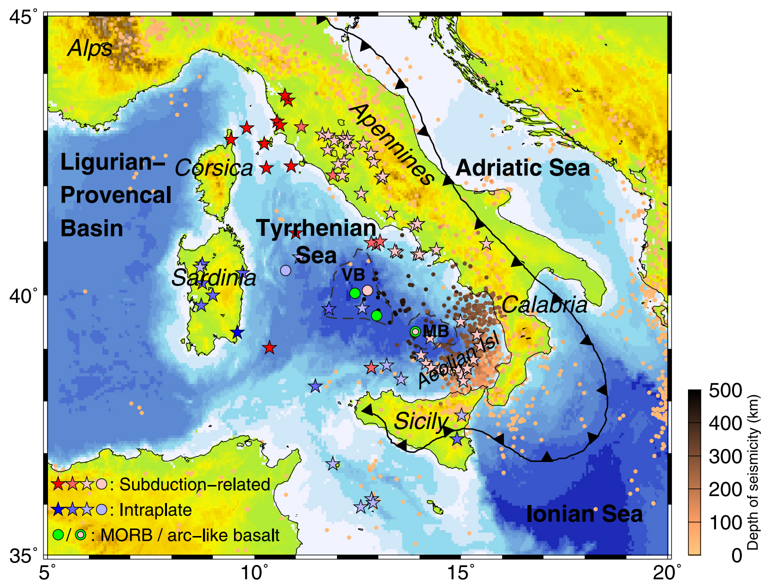

Fig. 1. Tectonic map of the larger Tyrrhenian Sea area. The plate boundary along the Adriatic and Ionian arc is shown as thick black line with triangles indicating the sense of subduction. The Vavilov Basin (VB) and Marsili Basin (MB) are outlined by dashed lines. Volcanic centres are indicated by stars and samples from deep drill holes by outlined circles. Different rock types are represented by different colours: Subduction-related in red (14–4 Ma), dark pink (4–2 Ma) and light pink (2–0 Ma); Intraplate in blue (14 Ma), lighter blue (4–2 Ma) and light blue (2–0 Ma). Samples from deep drill holes with MORB (4–3 Ma) and arc-like basalt (2–0 Ma) are depicted in green and combined green/pink, respectively. Brown circles indicate seismicity. Sources for volcanism are Savelli (2002), Peccerillo (2005) and Lustrino et al. (2011). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(for an overview see Peccerillo, 2005). The subduction-related volcanism in the northern Tyrrhenian Sea shows an eastward age decrease which can be related to roll-back of the Adriatic plate in an eastward direction. The geochemical signature of recent potassium-rich volcanism in central Italy is associated with past subduction of the continental Adriatic slab. In large parts of peninsular Italy, volcanic activity postdates the timing of subduction or metasomatism, and may have been initiated by later changes in mantle conditions, possibly caused by slab detachment and the subsequent opening of a slab window (Bianchini et al., 2008; Rosenbaum et al., 2008; Nikogosian and Van Bergen, 2010). On the other hand, the current, mostly calc-alkaline, volcanism of the Aeolian arc is associated with active subduction of the oceanic Ionian plate.

In the southern Tyrrhenian Sea, intraplate volcanism as well as mid-ocean ridge basalts (MORBs) recovered from two deep ocean drill holes in the oceanic Vavilov Basin are not directly associated with subduction. Instead, they are likely generated by extension in a back-arc setting, producing upwelling and decompression melting of mantle material.

In spite of the fact that the Tyrrhenian Sea is an extensively studied area, much of the upper mantle seismic structure beneath the Tyrrhenian Sea is still poorly resolved. The station distribution on land inhibits proper illumination of the shallow Tyrrhenian mantle by tomographic studies that use teleseismic P- and S-wave arrival times (e.g., Lucente et al., 1999; Piromallo and Morelli, 2003; Spakman and Wortel, 2004; Di Stefano et al., 2009; Giacomuzzi et al., 2011, 2012). Studies using surface waves (Panza et al., 2007; Schivardi and Morelli, 2011) or waveform modelling (Schmid et al., 2008; Zhu et al., 2012), on the other hand, suffer from large source–receiver distances with additional sensitivity outside the area of interest. In this study we therefore used the two-station method to reduce the surface wave propagation effects from the event to the most nearby station.

We measured interstation Rayleigh-wave phase velocities, which were inverted to model the upper-mantle ($<$ 200 km) shear-velocity structure. Linking the seismic model to the volcanics and tectonic evolution of the region, we infer that subduction-induced mantle hydration, as well as mantle dehydration caused by extension and the formation of new oceanic crust, have been instrumental for the present state and composition of the Tyrrhenian upper mantle.

2. Data and interstation phase-velocity measurements

We used the two-station method as developed by Meier et al. (2004) to determine the upper-mantle shear-velocity structure beneath the Tyrrhenian Sea. The two-station method is a technique to determine the surface-wave phase velocity between two stations by cross-correlation. In case of an event located along a great circle connecting two recording stations, it assumes that the phase difference between the stations is mainly caused by the structure along the interstation path (De Vos et al., 2013). Compared to the more commonly used source–receiver geometries, surface wave interstation measurements often have the advantage of a closer spacing, providing a higher lateral resolution.

The two-station method relies on event–station constellations which provide a good path coverage of the study region and good azimuthal coverage to decrease finite frequency effects. Thus, we examined data from teleseismic and regional earthquakes recorded at 386 stations over a period of more than a decade (07/1995–06/2009). The chosen stations are part of temporary (CATSCAN, MIDSEA, RETREAT) and permanent (MEDNET, Italian National Seismic Network, French BB, GEOFON, IMS) networks in Italy, southern France, Corsica and Tunisia. All seismographs are corrected for instrument response and downsampled to 1 s before phase velocities are measured.

We measured interstation phase velocities of fundamental-mode Rayleigh waves from the phase of the cross-correlation function of two vertical component seismograms for events taken within 7° of the interstation azimuth. The cross-correlation function is filtered with a set of frequency-dependent Gaussian band-pass filters and windowed in the time domain to suppress effects from other signals. To avoid multiple-cycle ambiguities each curve is individually picked by comparing to a reference phase-velocity curve. Only smooth segments of the phase-velocity curves are selected, to avoid irregularities which could be artifacts from finite-frequency effects. For each interstation path, the measured dispersion curves were averaged to obtain the final path-averaged