Mapping the long route of the Tyrrhenian slab through the mantle

F. P. Lucente[1], L. Margheriti[1], C. Piromallo[1] and G. Barruol[2]

[1] Istituto Nazionale di Geofisica e Vulcanologia, Roma @ [2] Observatoire Géodésique de Tahiti, Univ. de la Polynésie Française, Tahiti

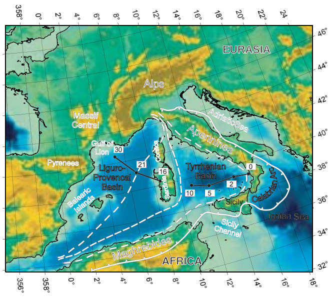
Abstract

In the south-eastern corner of the Tyrrhenian basin, in the central Mediterranean Sea, a tight alignment of earthquakes along a well defined Benioff zone marks one of the narrowest active trenches worldwide, where one of the last fragment of the former Tethys ocean is consumed. Seismic tomography furnishes snapshot images of the present-day position of this slab, and seismic anisotropy allows to reconstruct the past kinematics of the subduction process. Using seismic anisotropy fast directions as a proxy for the present and past mantle flow, we look backward for the seismic traces of the slab motion through the Western-Central Mediterranean mantle, from the starting locus of subduction toward its current day position. The result of combining independent data sets provides a coherent pattern of anisotropy that illustrates an example of slab rollback from its initiation point to its present-day location.

1. Introduction

The Tyrrhenian basin is part of the tectonic boundary between two slowly converging macro-plates, Eurasia and Africa, whose collision led to the existence of a wide belt of crustal deformation that masks the actual plate margins, resulting in a puzzling pattern of extensional basins of newly formed oceanic crust, compressional arcuate mountain belts, and subduction zones of remnant oceanic lithosphere [1]. The opening of the western-central Mediterranean mainly took place in the last 30 Ma, with genesis of irregular basins whose age becomes younger from west to east. These extensional basins were closely related in time and space to the back-arc region of the eastward retreating Apennines-Maghrebides subduction zone [2].

We present a compilation of published and new upper mantle anisotropy measurements along the possible route of the slab through the western-central Mediterranean mantle, from the starting locus of the subduction process to its present day position, together with tomographic images of the upper mantle velocity structure, to demonstrate how the retrograde motion of the sinking slab would have driven a regional flow in the mantle and influenced the evolution of the western-central-Mediterranean.



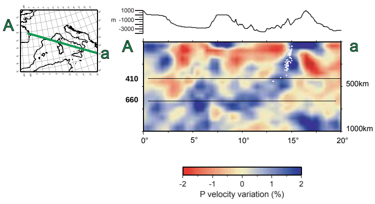


Fig. 1. Topographic map of the western-central Mediterranean region showing a reconstruction of the subduction evolution in the last 30 Myr. Continuous white line with the sawtooth pattern represents the present-day location of the convergent boundary. Dashed white lines approximately indicate past positions of the trench at three stages of its migration [2]. The displacement trajectories related to back-arc extension (redrawn from [10]) are displayed by the black line (numbers are million years).

2. Snapshot image of the present-day Tyrrhenian slab

At present, subduction in the western-central Mediterranean is indicated by the occurrence of deep seismicity beneath the southern Tyrrhenian basin. Seismic tomography [3] images an almost continuous high-velocity body extending from the surface below Calabria, with a NW dip of 70°-80°, and then turning horizontally in the transition zone. According to the various paleogeographic reconstructions and the tomographic images, the Tyrrhenian slab fragment would have rolled back for 800-1000 km, from the present-day south-east coasts of Spain and France toward its current position in the southern Tyrrhenian.

3. Anisotropy and geodynamics in Western-Central Mediterranean

We gather more than 500 seismic anisotropy measurements resulting from analysis of core-phases SKS, SKKS and PKS at 106 stations located in the western-central Mediterranean area from the Pyrenees in the west, to the Calabrian block in the south-east. This compilation of shear wave splitting measurements is mainly derived from previous studies limited to smaller areas and to temporary experiments [4-9], with some new unpublished data. It includes only good quality non-null single events measurements, projected at the 150 km depth piercing point of the incoming rays.

The ensemble of the fast direction bars on the map provides a comprehensive picture of the mantle deformation in the western-central Mediterranean. Moving from West to East we identify three main areas characterized by consistent anisotropy patterns and we interpret these features as related to different sequential phases of the Tertiary tectonic evolution of the region.

Liguro-Provençal area: the splitting measurements evidence a smoothly rotating direction pattern, in clear continuity from the southern Massif Central (ϕ ~ NW-SE) through the Gulf of Lion, in SE France, to the Balearic Islands, where f display a more ENE-WSW direction, to the Corsica-Sardinia block where fast directions ϕ become definitively E-W [9]. We relate this feature to the formation of the Liguro-Provençal basin, which took place since Oligocene (30 Ma) through a rifting episode along the present location of Gulf of Lion induced by the subduction of African oceanic lithosphere under the European margin [10].

Tyrrhenian domain: the anisotropy fast directions display W-E prevalent directions and maintain this constant orientation from the Sardinia-Corsica block to the western coast of the Italian peninsula. This trend can be associated with the new extensional episode which began in the Tortonian (~ 10 Ma), after the termination of the drifting and oceanic spreading in the Liguro-Provençal area marked by the end of the Corsica-Sardinia block rotation. This second lithospheric rifting separated Calabria from the Corsica-Sardinia block causing the opening of the southern Tyrrhenian basin in a roughly W-E direction [11].

Apennines: the fast splitting axes abruptly change direction and become parallel to the mountain belt, following its curvature from NNW-SSE in the north, to N-S and to NE-SW in the farther south Calabria. We relate this complicate mantle flow pattern to the most recent stage of the subduction process, which led to the exposure of the accretionary wedge, and is likely governed by the occurrence of a slab fragmentation processes in response to the heterogeneous nature (continental or oceanic) of the lithosphere entering in the mantle. These processes resulted in the formation of the narrow slab beneath the southern Tyrrhenian [10], where the long route of subduction across the Mediterranean mantle reached its current position.

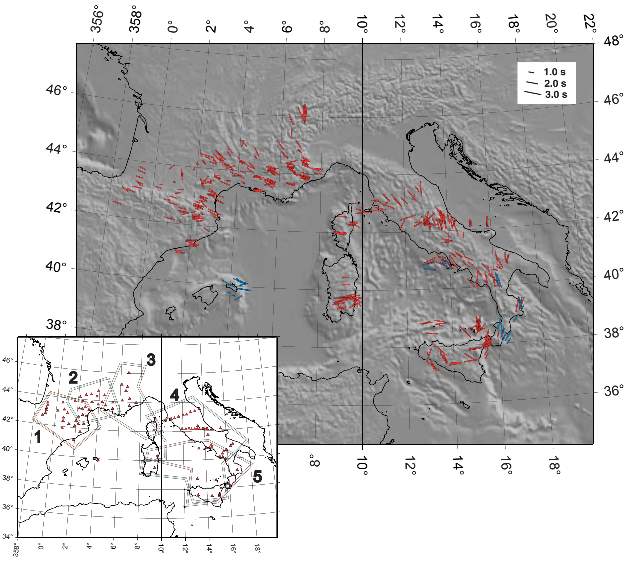
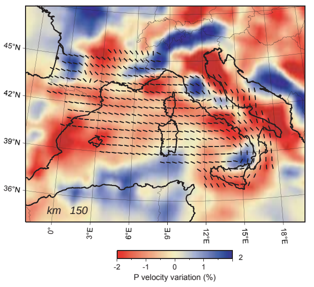


Fig. 3. Compilation of shear wave splitting measurements superimposed on a shaded relief map of the western-central Mediterranean. Measurements are represented by solid red bars (previously published) and solid blue bars (new ones) oriented parallel to the fast polarization directions, with length proportional to the delay time. Each measurement is plotted at the surface projection of the 150 km depth seismic ray piercing point. The inset shows the distribution of seismic stations used in this study and the related references of the previously published anisotropy measurements: 1: [4,5], 2: [6], 3: [7], 4: [8], 5: [9].



4. Anisotropy vs. Tomography: a time-integrated history of the subduction in the western-central Mediterranean

The comparison between complementary data such as P wave velocity anomalies (a snapshot on the present-day mantle structure) and SKS splitting (a time-integrated history of mantle flow), can corroborate the hypothesis that the evolution of the subduction process and the development of the mantle circulation in the western-central Mediterranean are tightly bound.

We interpolate the fast splitting directions with a power distance weight function [12] over a 250 km radius on a grid of 0.5° (lat) x 0.5° (lon) to obtain a simpler flow picture to evaluate and compare with the tomographic image, other than an estimate of the directions also in regions lacking of data point, such as the inner parts of the marine basins. Although such large-scale extrapolation cannot compensate the lack of measurements beneath the ocean basins, it provides a flow model that could be tested in the future for instance by deploying OBS.

Overall, the mantle flow configuration in the western-central Mediterranean basin follows the displacement trajectories related to back-arc extension (see Fig. 1) [10], suggesting that the opening of the basins and the mantle flow detected by anisotropy can be regarded as the manifestations of an unique phenomenon: the sinking and the rollback of the subducting Tyrrhenian slab. In particular, the smoothed map enhances the return flow trajectories around the western edge of the present-day Tyrrhenian slab, mirroring the results of laboratory experiments in the case of trench migration and rollback sinking of oceanic plates [13] and the trench-parallel pattern along the Apennines, which can be explained by the presence of strained material in the sublithospheric mantle as a consequence of a pressure induced by its retrograde motion (Fig. 4) [i.e. 14]. Clearly, alternative mechanisms in generating seismic anisotropy such as in high stress or high water content environment or the existence of pre-existing frozen anisotropies cannot be completely ruled out.

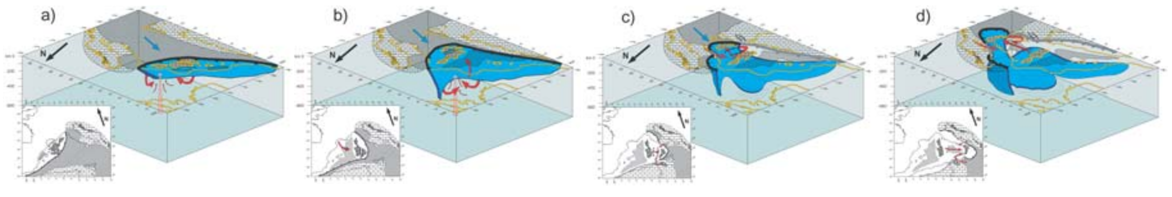


Fig. 5. Red arrows represent the 3D mantle flow induced by the slab rollback process. Light red arrows symbolize the hot mantle plume upwelling beneath the Massif Central (France) during Miocene time. Blue arrow indicates the direction of subduction. Dashed areas are old (thicker hatching) and new formed (lighter hatching) oceanic basins. Bricks-like fillings stand for continental lithosphere. The Corsica-Sardinia and Calabria blocks are small squares filled. Line with the sawtooth pattern indicate trench line which is black where the subducting slab is considered to be continuous up to the surface, while it is grey where slab is assumed to be detached.

5. Toward a 3D interpretative model of mantle flow in the western-central Mediterranean

The map of the anisotropy parameters in western-central Mediterranean shows an overall coherent pattern which is hardly compatible with an asthenospheric flow primarily related to the protracted (from late Cretaceous) motion of Africa toward the Eurasian plate, likely resulting in a general N-S trend of fast directions ϕ. Instead, the geometry of mantle flow retrieved by seismic anisotropy suggests a straightforward relationship between anisotropy and subduction in this area: the dynamics of the Tyrrhenian slab seem to have governed the regional mantle circulation, leaving clear traces of its motion all along its retreating route.

-At the initiation time of the first rifting-drifting episode (Fig. 5a), which led to the opening of the Liguro-Provençal basin (30 Ma), the western Mediterranean subduction zone was probably continuous and extended for about 1500 km from the Gibraltar region to the western Alps [i.e. 10]. During these early stages of subduction, material from the ocean side of the plate can move under the plate's tip [13].

-The end of this first extensional phase (16-15 Ma) coincides with, and is possibly caused by, the slab arrival at the 660 km discontinuity (Fig. 5b) [11]. In this early stage of subduction the plume upwelling beneath the Massif Central [6] could have enhanced the transfer of material from below the slab and amplified the shearing effect exerted by the rollback suction on the upper mantle.

-Around 12-10 Ma, the locus of extension jumps southward to the Tyrrhenian basin, and the second rifting-drifting episode begins (Fig. 5c). From this moment onward, the transfer of mantle material from beneath is prevented by the slab lying flat on the upper-lower mantle discontinuity (cfr. Fig. 2), and the unique wedge feeding mechanism becomes the flow of material from around the edges of the plate [13].

-The eastward retreat of the slab to its current position beneath the Calabrian arc (Fig. 5d) is achieved when the plate is deformed enough (creating an arc and opening a slab window) to permit the lateral escape of sub-slab material [15]. Slab windows opened along the Sicily channel and below the southern Apennines, respectively to the south [10] and north [16] of the current southern Tyrrhenian slab. This created two natural pathways for the mantle material to go from behind the slab, around the edges of the plate and toward the inner Tyrrhenian basin (Fig. 5c,d).

We have then obtained a picture of the western-central Mediterranean as a plate convergent environment where the gravity-controlled sinking of a cold, denser oceanic slab into the subduction zone and its rollback has to be considered as the major force acting in the system in the last 30 Myr, responsible for the stretching of the overriding plate and the formation of new oceanic lithospheres. The sinking of the slab and its progressive migration toward its current position may have induced a NW-SE pressure gradient within the asthenosphere responsible for the observed mantle flow beneath the whole western-central Mediterranean area. Such a flow has likely been preserved in the upper mantle and may dominate the present-day observed anisotropy, given that no other relevant tectonic and/or thermal episode - at the same strength and spatial scale - occurred in the subsequent time.

By reconciling the anisotropy observations with the tomographic geometry of the Tyrrhenian slab, we gain insights into the mantle circulation in the area, which seems to have developed in a regional convective cell driven by a rollback process and evolved in a regime of restricted mantle circulation. Therefore, we identify in the feedback mechanism between subduction and triggered mantle flow the principal cause of the fast tectonic evolution in the western-central Mediterranean system.

References

[1] B. Durand, A. Mascle, L. Jolivet, F. Horvàth, M. Séranne (Eds.), The Mediterranean basins: Tertiary extension within the Alpine Orogen, Geol. Soc. London, Spec. Publ. 156 (1999).
[2] C. Faccenna, T.W. Becker, F.P. Lucente, L. Jolivet, F. Rossetti, History of subduction and back-arc extension in the Central Mediterranean, Geophys. J. Int. 145 (2001) 809-820.
[3] C. Piromallo, A. Morelli, P wave tomography of the mantle under the Alpine-Mediterranean area, J. Geophys. Res. 108 (2003). DOI:10.1029/2002JB001757.
[4] G. Barruol, A. Souriau, Anisotropy beneath the Pyrenees range from teleseismic shear wave splitting, Geophys. Res. Lett. 22 (1995) 493-496.
[5] G. Barruol, A. Souriau, A. Vauchez, J. Diaz, J. Gallart, J. Tubia, J. Cuevas, Lithospheric anisotropy beneath the Pyrenees from shear wave splitting, J. Geophys. Res. 103 (1998) 30039-30054.
[6] G. Barruol, M. Granet, A Tertiary asthenospheric flow beneath the southern French Massif Central indicated by upper mantle seismic anisotropy and related to the west Mediterranean extension, Earth Planet. Sci. Lett. 202 (2002) 31-47.
[7] L. Margheriti, F.P. Lucente, S. Pondrelli, SKS splitting measurements in the Apenninic-Tyrrhenian domain (Italy) and their relation with lithospheric subduction and mantle convection, J. Geophys. Res. 108 (2003). DOI:10.1029/2002JB001793.
[8] S. Civello, L. Margheriti, Toroidal mantle flow around the Calabrian slab (Italy) from SKS splitting, Geophys. Res. Lett. 31 (2004). DOI:10.1029/2004GL019607.
[9] G. Barruol, A. Deschamps, O. Coutant, Mapping upper mantle anisotropy beneath SE France by SKS splitting indicates a Neogene asthenospheric flow induced by the Apenninic slab rollback and deflected by the deep Alpine roots, Tectonophysics 394 (2004) 125-138.
[10] C. Faccenna, C. Piromallo, A. Crespo-Blanc, L. Jolivet, F. Rossetti, Lateral slab deformation and the origin of the western Mediterranean arcs, Tectonics 23 (2004). DOI:10.1029/2002TC001488.
[11] C. Faccenna, F. Funiciello, D. Giardini, F.P. Lucente, Episodic back-arc extension during restricted mantle convection in the Central Mediterranean, Earth Planet. Sci. Lett. 187 (2001) 105-116.
[12] B. Müller, V. Wehrle, S. Hettel, B. Sperner, K. Fuchs, A new method for smoothing orientated data and its application to stress data, in: M.S. Ameen (Ed.), Fracture and In-Situ Stress Characterization of Hydrocarbon Reservoirs, Geol. Soc. London, Spec. Publ. 209, (2003) 107-126.
[13] C. Kincaid, R.W. Griffiths, Laboratory models of the thermal evolution of the mantle during rollback subduction, Nature 425 (2003) 58–62.
[14] R.M. Russo, P.G. Silver, Trench-parallel flow beneath the Nazca plate from seismic anisotropy, Science 263 (1994) 1105-1111.
[15] F. Funiciello, C. Faccenna, D. Giardini, K. Regenauer-Lieb, Dynamics of retreating slabs: 2. Insights from three-dimensional laboratory experiments, J. Geophys. Res. 108 (2003). DOI:10.1029/2001JB00896.
[16] F.P. Lucente, F. Speranza, Belt bending driven by deep processes: geophysical evidences from the northern Apennines (Italy), Tectonophysics 337 (2001) 51-62.