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Erosion of the continental lithosphere at the cusps of the Calabrian arc: Evidence from *S* receiver functions analysis

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[1] Mediterranean tectonics has been characterized by an irregular, complex temporal evolution with episodic rollback and retreat of the subducted plate followed by period of slow trench-migration. To provide insight into the geodynamics of the Calabrian arc, we image the characteristics and lithospheric structure of the convergent, Apulian and Hyblean forelands at the cusps of the arc. Specifically we investigate the crustal and lithospheric thicknesses using teleseismic S-to-p converted phases, applied to the Adria-Africa plate margin for the first time. We find that the Moho in the Apulian foreland is nearly flat at ~30 km depth, consistent with previous *P* receiver functions results, and that the Hyblean crustal thickness is more complex, which can be understood in terms of the nature of the individual pieces of carbonate platform and pelagic sediments that make up the Hyblean platform. The lithospheric thicknesses range between 70–120 km beneath Apulia and 70–90 km beneath Sicily. The lithosphere of the forelands at each end of the Calabrian arc are continental in nature, buoyant compared to the subducting oceanic lithosphere and have previously been interpreted as mostly undeformed carbonate platforms. Our receiver function images also show evidence of lithospheric erosion and thinning close to Mt. Etna and Mt. Vulture, two volcanoes which have been associated with asthenospheric upwelling and mantle flow around of the sides the slab. We suggest that as the continental lithosphere resists being subducted it is being thermo-mechanically modified by toroidal flow around the edges of the subducting oceanic lithosphere of the Calabrian arc. **Citation:** Miller, M. S., and N. Piana Agostinetti (2011), Erosion of the continental lithosphere at the cusps of the Calabrian arc: Evidence from *S* receiver functions analysis, *Geophys. Res. Lett.*, *38*, L23301, doi:10.1029/2011GL049455.

1. Introduction

[2] The 200-km wide Calabrian arc (Figure 1) rifted off Sardinia 10–12 Ma during the opening of the Tyrrhenian Sea and its collision with Adria along the northeast and Africa in the southwest produced the Apennines and the Maghrebides-Sicilian orogenic belts, respectively [*Faccenna et al.*, 2001; *Gueguen et al.*, 1998; *Lucente et al.*, 2006; *Malinverno and Ryan*, 1986; *Rosenbaum and Lister*, 2004]. The active Calabrian arc is where the last remnant oceanic lithosphere continues to subduct, as evident by both tomography [*Lucente et al.*, 1999; *Piromallo and Morelli*, 2003; *Wortel and Spakman*, 2000] and deep seismicity [*Chiarabba et al.*, 2005], along a once much wider subduction zone.

[3] Subduction zone evolution is driven by the physical properties and structure of the overriding plate. Plate boundary geometry, subducting plate morphology and convergence velocity are all strongly affected by the structure, thickness and composition of the lithosphere at the convergent boundary. During subduction of the oceanic lithosphere, the downgoing lithosphere is almost homogeneous [*Stern*, 2002], however, structure of continental lithosphere is more complex and heterogeneous. Therefore, delineating the lithospheric structure of downgoing plate (Apulian and Hylbean platforms) at the cusps of the active Calabrian arc can provide important constrains on the behavior of the "subduction factory" and in particular how the present day narrowly defined arc has evolved over the past 10 million years.

2. Data and Method

[4] Receiver functions allow for detection of seismic velocity discontinuities and thus provide an independent proxy for the crust-mantle and lithosphere-asthenosphere boundaries (LAB). The *S*-receiver function (S-RF) method, in particular, has emerged recently as an effective tool for mapping the LAB [*Farra and Vinnik*, 2000; *Abt et al.*, 2010; *Rychert et al.*, 2007; *Yuan et al.*, 2006], especially in tectonically active regions [*Li et al.*, 2007]. Since *S*-receiver functions use converted *P* waves with wavelengths ~5–10 times greater than *P*-receiver functions, S-RFs rarely resolve intracrustal structure, but are suitable for determining Moho depth, and are excellent for detecting relatively broad vertical gradients in velocity, such as might be expected for a thermally controlled LAB [*Eaton et al.*, 2009; *Miller and Eaton*, 2010]. S-RFs are better suited to this application than conventional *P*-receiver functions (P-RFs), because the latter often suffer from strong crustal multiple reflections in the range of ~5–15s (depending upon crustal thickness) following the *P* arrival. The use of S-RFs alleviates concerns about crustal reverberations and allows for interpretation of boundaries in the depth range expected for tectonic plates.

[5] For the study of the Calabrian arc we used 36 teleseismic events with magnitude (Mw) greater than 6.0 at a distance of 55 to 85 degrees away from Italy (Figure 2, inset). These events were recorded between 2005–2009 by 12 broadband stations, which are made up of eight stations in the Apulian foreland and four in the Hyblean foreland (Figure 1). The instruments are a combination of stations from the Italian National Seismic and MedNET networks, using Trillium-40s, Trillum-120s, and Strekeisen STS-2 sensors. In this study, *S* receiver functions for 12 seismic stations deployed along the peri-Calabrian region, were

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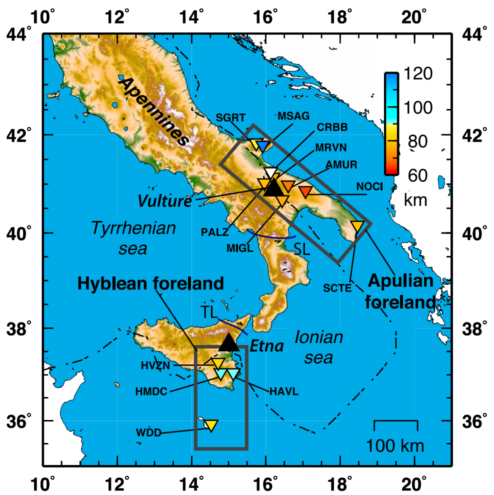

Figure 1. Simplified map of southern Italy and the Tyrrhenian Sea. The lines with triangles indicate the plate boundaries of the central Mediterranean subduction zone, the inverted triangles are the 12 broadband seismic stations used in the study color-coded with LAB depth in km and one white triangle is station CRBB from *Steckler et al.* [2008]. Black triangles represent the locations of Mt. Etna on Sicily and Mt. Vulture in the Italian peninsula. SL indicates the Sangineto line and TL indicates the Taormina line which mark the position of lithospheric tear faults at either side of the active Calabrian arc.

computed in order to characterize the lithospheric structure of the Adria-Africa continental margin at the cusps of the Calabrian arc (Figure 1). For each station Sp converted phases were migrated in the depth-domain as proxy of the Moho and LAB depths.

[6] Preparing the broadband teleseismic data involved a series of quality checks and multiple processing steps. Initially each *S* waveform is visually inspected for clear *S*-wave arrivals in the appropriate time window. Then the records were transformed from Z, N, and E to P, SV, and SH components. The *S* receiver functions were produced by deconvolving the SV component from the P component in the frequency domain [*Langston*, 1977] and then the amplitudes were then reversed so that positive amplitudes indicate an impedance increase, such as the Moho, allowing for easier visualization and comparison to *P* receiver functions. After deconvolution, the receiver functions were re-inspected for another quality check, where anomalous traces were deleted, such as those that arise due to noise or interference with other phases or events from the same time period, especially those with no apparent Moho signal. The receiver functions were converted to depth using a 1D model, *iaspi91* [*Kennett and Engdahl*, 1991], which is considered a close approximation for the Italian continental lithosphere recent from p-wave tomography studies [*Giacomuzzi et al.*, 2011], corrected using a cross-correlation method for residual statics (if/when bulk shift is necessary) introduced by near-surface irregularities by picking a "pilot" or representative trace, and then stacked at each station. Example of results for station SCTE in Apulia are shown in Figure 2a, where the individual receiver functions are sorted by azimuth and the stacked receiver function is shown with an estimate of gradient for the Moho and LAB signal respectively. The Moho is clearly evident as a positive-amplitude phase for each event. As discussed below, negative-amplitude phase at greater depths (>60km) is interpreted as the lithosphere-asthenosphere boundary (LAB), which are arrivals expected for a *S* velocity drop of 0.3 km/s from 4.8 km/s to 4.5 km/s. Synthetic tests of this magnitude change in velocity at a range of depths and thickness (0–50 km thick transition) were computed by *Miller and Eaton* [2010] and were again found to be representative of the negative signals found in the *S* receiver functions for these Italian data. The gradient of the Moho (LAB) pulse is computed as the sum of the square of the amplitude variation (every1-km steps), in a −/+10 km-depth interval centered on the maximum (minimum) of the pulse itself. Such measure can used to give a relative indication of the variation of shape of the pulse between stations.

3. Results

[7] The stacked *S* receiver functions provide lithospheric scale images of the structure of the continental material of the Apulian and Hyblean forelands surrounding the active Calabrian arc. The single station results are shown along two profiles, one for each region. For the Hyblean foreland, the profile is almost normal to the strike of the trench and for the Apulian platform the profile is almost parallel to the trench. For each of the stacked S-RFs the picks for the Moho and LAB interfaces (blue and red dashes, respectively) and a color-shaded (red-to-blue) filled circle beneath the Moho and LAB symbols indicate the sharpness of the relative pulse in the stacked S-RF. Grey diamonds show previous estimates (if they exist) of the Moho depth picked from *P* receiver functions [*Piana Agostinetti and Amato*, 2009]. In general, the S-RF for different stations display good coherence in the two regions, both for the positive (Moho) pulses and the negative (LAB) pulses, but there are some regional differences. Overall the lithospheric thickness range, between 70–120 km, with station MSAG having the thickest (120km), and stations AMUR and NOCI the thinnest (Figures 1 and 2b).

[8] Across the Apulian foreland the Moho signal is very clearly defined at ~30 km depth (Figure 2b) for all the stations, which is consistent with previous results from P-RF studies [*Piana Agostinetti and Amato*, 2009]. The Moho Sp pulse is sharp for all the seismic stations, indicating an abrupt velocity contrast at the crust-mantle boundary. Unlike the Moho signal, the negative pulse we interpret as originating from the lithosphere-asthenosphere boundary is less consistent. The lithospheric thickness is thinnest at stations in the middle of the profile, which are closest to Mt. Vulture, and displays a sharper gradient with respect to the other stations along the profile. Along the northern portion of the Apulian profile, farthest from the Calabrian arc, the LAB is deeper, and the associated Sp pulse is broader than in the southern part of the foreland, ranging from 80–120 km depth in the north, to 70–80 km depth in the south.

[9] In contrast, the Hyblean foreland is characterized by broader Moho pulses, with respect to those beneath Apulia. Moho depth ranges from the shallowest in the southeast (25 km) to the deepest in the northwest (~35 km). The Moho depth estimates are in agreement with P-RF results except for station HAVL, where the P-RF result is poorly constrained (σ = 11 km) [see *Piana Agostinetti and Amato*, 2009]. However, the P-RF results for the region display the

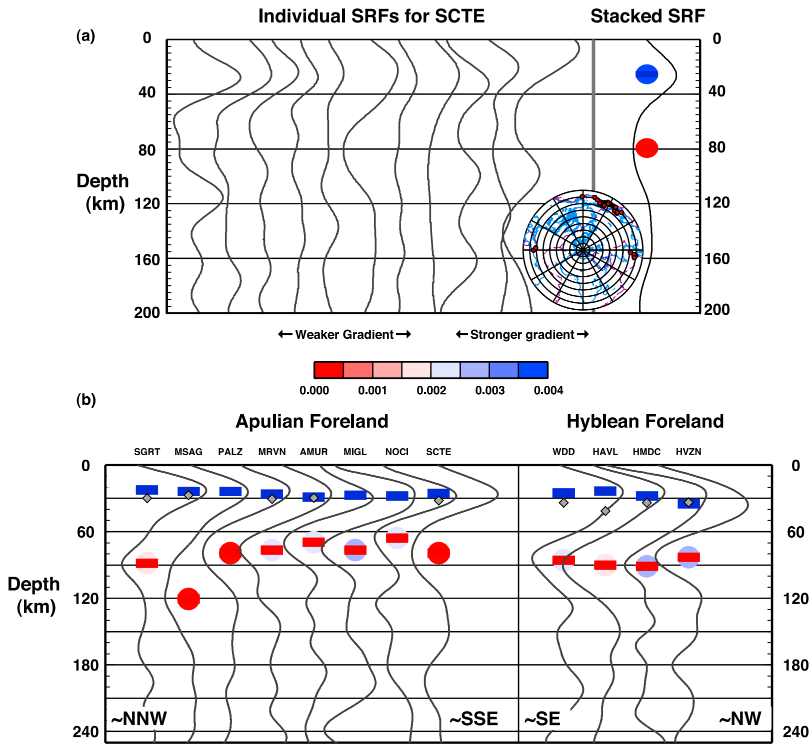

Figure 2. (a) Individual receiver functions for station SCTE in southeastern Apulia, as shown in Figure 1, sorted by azimuth and then stacked. The Moho is clearly evident as a positive-amplitude phase for each event and marked with a red line. Negative-amplitude phase at greater depths (>60 km) are interpreted as the lithosphere-asthenosphere boundary (LAB) and marked with a blue line. An estimate of the gradient is represented by a color-coded circle for the Moho and LAB picks. The inset is an event map for the 36 earthquakes during 2004–2009 with magnitude greater than 6.0 used in the study. (b) S-RF stack for the stations shown in Figure 1. Blue and red lines indicate Sp from the Moho and Sp from the LAB. Colored circles indicate the gradient of the negative pulses. Grey diamonds represent Moho depth estimates from P-RF analysis [*Piana Agostinetti and Amato*, 2009].

opposite trend, representative of thinning of the crust toward the northwest. The Hyblean lithosphere is generally thicker than the Apulian lithosphere, but has a smaller range of only 80–90 km thick (Figure 2). The LAB is thinnest in the northwest at HVZN, closest to Mt. Etna, which also corresponds to the sharpest LAB Sp pulses. Due to the limited distance between the stations in the Hyblean foreland, the thinning of the lithosphere cannot be well-defined, but it appears to be thinner than in the Apulian foreland.

4. Discussion and Conclusion

4.1. Crustal Thickness

[10] The S-RF results allow for constraining the Moho depth between 25 km and 45 km depth which are in agreement with previous results obtained using P-RFs [*Piana Agostinetti and Amato*, 2009; *Steckler et al.*, 2008], despite the low-frequency content of *S*-waves. For example in the Apulian foreland, where the shallowest Moho is 25 km at station SGRT, and the deepest Moho is observed at station AMUR, both of which are consistent with previous P-RF estimates for this region (Figure 2) and are in general agreement with other studies of Aegean and African plate crustal thickness from the Hellenic subduction zone [*Sodoudi et al.*, 2006; *Li et al.*, 2003]. *P* receiver functions for the CAT-SCAN temporary station, CRBB, [*Steckler et al.*, 2008] in the Apulian foreland, shows little azimuth dependence which is representative of the undeformed platform and has a Moho depth of 30 km which is in agreement with our results. From the presence of a 6-km thick carbonates series (drilled in the Puglia-1 well [*Improta et al.*, 2000] it can be inferred that the original thinned continental crust would be about 25-km thick. Such a value of the crustal thickness over a wide portion of the margin would mean that the Apulian foreland represents a "Type I" rifted margin (following *Huismans and Beaumount* [2011]). "Type I" rifted margin is characterized by: evaporite deposits (found in the Puglia-1 well log [see *Improta et al.*, 2000]), a wide area of thinned crust (i.e. smooth change in crustal thickness toward the ocean-continent boundary) and the removal of the original continental lithospheric mantle. However higher frequency investigations, such as a detailed seismic velocity profile, are needed to better define the small-scale characteristics of the Adria crust.

[11] In the Hyblean Foreland, the *S* receiver functions show a thicker crust toward the trench, which is in disagreement with the P-RFs results [*Piana Agostinetti and Amato*, 2009] for station HAVL, that shows the largest discrepancy in interpretation of the Moho depth (~15 km). Such difference can be the result of various factors. Both methods use *iasp91* as a 1D reference model [*Kennett and Engdahl*, 1991], but P-RF results are obtained from a grid search that allows for varying the *S*-velocity, which is fixed in the S-RF migration. Moreover, we observe that the Sp phases

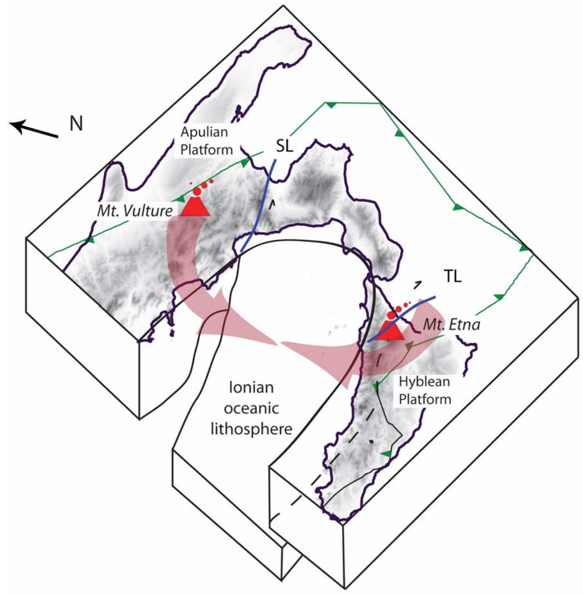

Figure 3. Schematic interpretation of the Calabrian arc lithospheric structure (not to scale). The red arrows indicate toroidal flow around the edges of the subducting Ionian oceanic lithosphere of the Calabrian arc due to rollback. Thinned continental lithosphere, interpreted from S-RFs, beneath both Apulia and Sicily near Mt. Vulture and Mt. Etna, respectively, is suggestive of thermo-mechanical erosion of the continental lithosphere by mantle flow. Blue lines show the Sangineto (SL) and Taormina lines (TL) marking the positions of lithospheric tear faults at either end of the active Calabrian arc.

generated at the Moho are rather broad in this tectonic region, which implies a broad "transition" zone at the bottom of the crust where the *S*-velocity slowly increases, or large lateral heterogeneity in the crustal structure. In both cases, the different frequency-sensitivity of the two methods can lead to different results. Finally, the fact that the S-RF piercing points for the Moho are significantly different from P-RFs due to the oblique angle of the incoming *S* wave, implies that the two methods "sample" the crust in different areas. The above mentioned features can explain the discrepancy in the two receiver function results for station HAVL. If we consider the *P* receiver function result for station HAVL, it can be interpreted that the Hyblean foreland displays a deeper Moho with respect to Apulia.

4.2. Lithospheric Thickness

[12] The continental lithospheric thickness estimates from the S-RFs range between 70 and 120 km, with a mean value of 85 +/−15 km. The thinnest part the lithosphere in the foreland is about 70 km beneath AMUR and NOCI stations, which are located in the southern part of the Apulian foreland. Our results are in general agreement with the values found by *Sodoudi et al*. [2006], where they observe the African continental margin subducted beneath Crete. There, the thickness of the lithosphere of the African margin is 100 km at the trench, and 65-km beneath the Aegean volcanic arc, suggesting that the African lithosphere is thinned as it is being subducted and recycled in the upper mantle. It worthwhile to note that, in Apulia, both for a "Type I" rifted margin, where continental lithospheric mantle is removed, and "Type II" rifted margin (due to the proximity of the ocean-continent boundary), the mean value of the thickness of the lithosphere should be similar to the lithospheric thickness of the adjoined oceanic plate [*Crosby et al*, 2011]. Such an interpretation does not agree with the classical thermal model for the thickening of the oceanic lithosphere where the lithosphere of a 200 My old oceanic plate would be more than 100 km thick, supporting the idea of a different process for the evolution of the LAB in this region.

[13] It is possible that the thinning of the Adria lithosphere during the last few million years may be a result of lithospheric erosion due to a strong asthenospheric mantle flow triggered by the evolution of a slab tear at the northeastern edge of the Calabrian arc. It has been suggested that the subducted lithosphere beneath Italy has been segmented and torn into distinct pieces due to rollback of Calabria over the past ~10 My [e.g., *Rosenbaum and Lister*, 2004; *Rosenbaum et al.*, 2008; *Faccenna et al.*, 2004, 2005]. Calabria has rolled back into its current location and evolved into a narrow 200 km wide arc, which is controlled by the surrounding geology and availability of oceanic lithosphere to subduct and the relationship to lithospheric scale tear faults. On the NE side of the Calabrian arc, near Apulia, the left lateral Sangineto line (SL) bounds the arc and on the SW side the Taormina line (TL) bounds the active arc and has been identified as the edge of the thin-skinned Calabrian nappes [*Lentini et al.*, 1994; *Panza et al.*, 2007]. These slab tear faults (Figure 1) along the margin active arc extend to depths of 100–340 km [*Rosenbaum et al.*, 2008], and are characterized in the near surface by NE-SW faults in the southern Apennines, and NW-SE faults in Sicily [*Billi et al.*, 2006; *Goes et al.*, 2004].

[14] The location of the edge of the subducted oceanic lithosphere and proposed slab tears can also be identified with upper mantle anisotropy as an indicator of mantle flow, as modeled by toroidal flow in laboratory experiments [e.g. *Kincaid and Griffiths*, 2003; *Funiciello et al.*, 2003, 2006; *Faccenna et al.*, 2007], and numerical solutions [e.g., *Piromallo et al.*, 2006; *Stegman et al.*, 2006; *Di Giuseppe et al.*, 2008], and seismically [e.g., *Russo and Silver*, 1994]. Flow around the edge of the slab have been proposed at the western end beneath Sicily and at the edge of the southern Apennines and the Apulian platform from both SKS splitting [*Margheriti et al.*, 2003; *Civello and Margheriti*, 2004] and other multi-disciplinary studies [*Faccenna et al.*, 2005, 2011]. The position of Mt. Etna and Mt. Vulture are situated on the margin of the forelands and have been suggested to each be the result of asthenospheric upwelling along slab tear faults [e.g. *Gvirtzman and Nur*, 1999; *Doglioni et al.*, 2001; *Trua and Marani*, 2003; *Faccenna et al.*, 2005, 2011]. The thinnest lithosphere beneath both Apulia and the Sicily imaged with our S-RFs are positioned on the foreland side of these proposed tear faults and closest to these two volcanoes (Figures 1 and 3). We interpret the thinned continental lithosphere near these volcanoes it is being thermo-mechanically modified by toroidal flow around the edges of the subducting oceanic lithosphere of the Calabrian arc due to rollback, which is shown schematically in Figure 3.

[15] Evidence of mantle material flowing around the slab can be traced in magma compositions, where if enough

mantle material flow through the slab tears the signature of the arc volcanoes can change from predominately calc-alkaline to alkaline [*De Astis et al.*, 2006]. *Beccaluva et al.* [2002] found that Mt. Vulture, which lies on continental lithosphere, has intermediate isotopic and geochemical characteristics between Na-alkaline and K-alkaline, which can be indicative of both subduction-related metasomatism and enrichment of alkaline components. This also supports the idea of a slab tear on the NE side of the Calabrian arc and influx of mantle material from behind the slab. On the SE side, Mt. Etna is also situated on continental lithosphere, does not have volcanic arc geochemical characteristics which has been attributed to decompression melting that may be generated from the vertical flow component of toroidal flow around the corner of the slab [*Gvirtzman and Nur*, 1999; *Faccenna et al.*, 2011]. The chemical differences between these two magma compositions at volcanoes on either side of the actively subducting slab, can be also related to the maturity of the slab tears, where the toroidal flow beneath the southern Apennines and Apulia is recently developed and the flow beneath Sicily is much more established [*Faccenna et al.*, 2005, 2010, 2011].

[16] Finally, the gradient of the Sp pulse generated at the LAB could indicate the presence of partial melts at the top of the asthenosphere [e.g., *Fischer et al.*, 2010]. This study provides an initial relative measure of the sharpness of the Sp pulse between stations. The trend identified in both the forelands may be suggestive of an increase of melt concentration in the uppermost asthenosphere nearest Mt. Etna and Mt. Vulture. These results for the Sp gradient could be biased by the limited frequency band analyzed in this study, and requires further modeling, however is an independent calculation for melt in the asthenosphere and support of our hypothesis of thermo-mechanical erosion of the continental lithosphere beneath the forelands at each cusp of the Calabrian arc due to toroidal flow.

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