Crustal structure in the Southern Apennines from teleseismic receiver functions

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ABSTRACT

While the upper crustal structure of the Southern Apennines is known, lack of control on the deep structure allows competing thin-skinned and thick-skinned models of the orogen. In thin-skinned models, the detachment decouples a stack of rootless nappes from the basement. In thick-skinned models, basement is involved in the most recent phase of thrusting. To examine the crustal structure, we use teleseismic data from the Calabria-Apennine-Tyrrhenian/Subduction-Accretion-Collision Network (CAT/SCAN) array in southern Italy. We use receiver functions (RF) processed into a common conversion point stack to generate images of the crust. Interpretation and correlation to geological structure are done using inversions of individual station RFs. We focus on a shallow discontinuity where P-to-S conversions occur. In the foreland, it corresponds to velocity jumps between carbonate and clastic strata with basement. A similar interpretation for the Apennines provides the most parsimonious explanation and supports a thick-skinned interpretation. In a thick-skinned reconstruction, the amount of shortening is much smaller than for a thin-skinned model. This implies considerably less Pliocene–Pleistocene shortening across the Apennines and suggests an east-southeast motion of the Calabrian arc subparallel to the southern Apennines rather than a radial expansion of the arc.

Keywords: thrust tectonics, Apennines, continental collision, seismology, receiver functions, structural geology.

INTRODUCTION

The Southern Apennines result from the impact of the continental Apulian platform with the Calabrian arc. Abundant outcrop, seismic, and well data (e.g., Cello and Mazzoli, 1998) constrain the shallow part of the orogen. Here, large carbonate banks are involved in both the allochthonous (Apenninic) and autochthonous (Apulian) parts of the Southern Apennines. The Apenninic units comprise large nappes that overthrust the Apulian platform, similar to many fold-and-thrust belts with detached strata imbricated above basement. Beneath these nappes, the Apulian platform becomes involved in the thrusting. However, seismic data, including recently published CROP (a deep crustal seismic profiling of the Mediterranean and Italy) lines (Sroccca et al., 2005; Finetti et al., 2005), do not resolve whether basement is involved in the deeper thrusts. Thin-skinned reconstructions with imbricated Apulian platform units above a detachment (e.g., Mazzotti et al., 2000) and thick-skinned reconstructions with thrusts rooted in basement beneath the Apulian platform (Menardi Noguera and Rea, 2000) are both viable. The geometries permitted imply large differences in shortening. Thick-skinned models require <30 km shortening of Apulia, while thin-skinned models imply >120 km shortening. This has significant implications for opening of the Tyrrhenian Sea. Did the Calabrian arc expand radially or primarily roll back toward the east or southeast? What is the amount of obliquity in the Southern Apennines?

In 2003, we deployed a broadband seismic array, the Calabria-Apennine-Tyrrhenian/Subduction-Collision-Accretion Network (CAT/SCAN), to image the Southern Apennines, Calabrian arc, and the transition between them (Fig. 1). We image the crust of the Southern Apennines using receiver functions (Burdick and Langston, 1977). Velocity boundaries within the crust produce partial conversions of incoming P waves to S waves. We use CAT/SCAN data to map velocity discontinuities and use this data for interpreting the structure of the Southern Apennines.

GEOLOGIC SETTING

During the Neogene, rollback renewed the oceanic lithosphere of the western Mediterranean (Malinverno and Ryan, 1986; Gueguen et al., 1998; Rosenbaum et al., 2002). First, the Corsica-Sardinia block rifted off Europe and opened the Balearic Sea, but stalled at 17–18 Ma, possibly due to collision with outer blocks of Apulia (Rosenbaum et al., 2002; Catalano et al., 2004). Resumed rollback led to rifting of Calabria off Sardinia at 10–12 Ma and the opening of the Tyrrhenian Sea (Malinverno and Ryan, 1986; Gueguen et al., 1998). During rollback of the Calabrian arc, the northern part of the arc progressively collided with Adria to create the Apennines and the southern part obliquely collided with Africa to form the Maghrebides. Calabria and northeastern Sicily are the only remaining part of the subduction zone still consuming oceanic crust (Fig. 1).

The Southern Apennines is a stack of north-verging thrust sheets with four major units. The uppermost is the Ligurian Complex, a Jurassic–early Miocene set of heterogeneous units that are the accretionary complex of the former subduction zone (Catalano et al., 2004).

Structurally below is the Apennine platform. It is primarily Triassic–Miocene shallow-water carbonates and associated deposits (Cello and Mazzoli, 1998; Menardi Noguera and Rea, 2000; Finetti et al., 2005). The Apennine platform may have started as a Bahamas-like set of carbonate banks (Cello and Mazzoli, 1998;
As a result, two contrasting end-member models of the Southern Apennines complicate the structure. Basins, including the 7070 m Puglia-1 well (Fig. 1), indicate high velocities for the Apulian platform, over a lower velocity for the basal clastics (Improta et al., 2000; GSA Data Repository Fig. DR4).

The Apennine-Lagonegro terranes were emplaced by Miocene thin-skinned thrusting. The shearing off the Apulian platform from its basement may have enabled Calabrian arc rollback to resume. Following subduction of the Lagonegro oceanic(?!) basin, the northern Calabrian arc collided with the Apulian platform. The Apulian platform is first cut by normal faults related to flexural bending, but then as it underthrusts the Apennines, becomes offset by thrusts.

Well and seismic data constrain the structure of the Apennine-Lagonegro terranes. The top of the Apulian platform is widely recognized but its base is only seen locally. Recent normal faults and extensional basins on the Tyrrhenian side of the Southern Apennines complicate the structure. As a result, two contrasting end-member models (Fig. 2) satisfy existing data: a thick-skinned model where thrusts involved Apulian basement since the late Triassic–Early Triassic clastics. Well logs, including the 7070 m Puglia-1 well (Fig. 1), indicate high velocities for the Apulian platform, over a lower velocity for the basal clastics (Improta et al., 2000; GSA Data Repository Fig. DR4).

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tinuous throughout the illuminated parts of the Southern Apennines. We focus on the shallowest converter located at 8–11 km depth; it is located at the bottom of the well-constrained structure of the Southern Apennines (see Scrocca et al., 2005), and is the most relevant to the structural style of the Apennines. This conversion is continuous in parts of the CCP volume and separated into two distinct surfaces elsewhere.

Calabria (Fig. 3, lower left) exhibits a very different character without the strong conversions seen in the Southern Apennines. This fits the contrasting structure of Calabria, which is still subducting oceanic crust and has not (yet) collided with Apulia. The transition between the Southern Apennines and Calabria has few coherent features. This is also the case for SKS splitting (Baccheschi et al., 2007), and likely reflects a complex structure at the transition.

Figure 4 compares the CCP image and RF inversions to the geologic cross sections. To obtain the best resolution, we sampled the CCP volume along the transect of seismic stations nearest the geologic sections (see Fig. 3). The strong positive conversion at 7–10 km is composed of two separate features, beneath the foreland and under the Apennines. Elsewhere, off the profile, they blend into a single surface.

The best constraints on the origin of this conversion come from seismic station CRBB in the Apulian platform (Fig. 4; Fig. DR3). The Puglia-1 well provides geology and velocity constraints (±7 km). The CRBB RF shows little azimuthal dependence, consistent with the flat-lying Apulian platform, and can be modeled using a 1D S-velocity profile. The inversion yields velocity layering similar to that of the top. We find that a low velocity corresponding to the clastic layer in the Apulian platform is required, and that Apulian platform layering is composed of two main units, the deeper (dolomites) being faster than the shallower (carbonates). With this structure the RF (Fig. DR3) shows a strong positive pulse (red shallow conversion in CCP) corresponding to the top of basement; the conversion from the base of the clastics overwhelms negative conversion from its top. The Moho is clear at 30 km, consistent with earlier estimates.

This correlation is reinforced by the inversion of seismic station VENO, which exhibits almost the same structure beneath low-velocity foreland strata. The low-velocity zone (LVZ) is not absolutely required, but is a prominent feature of most models. RF inversions and the CCP clearly identify the structure of the Apulian platform as it enters the orogen from the foreland.

Farther west in the Apennines, PICE shows a low-velocity cover overlying layering similar to that of the Apulian platform at the other stations (Fig. 4; Fig. DR3). PICE in situated in Lagonegro strata; the Apennine platform only extends that far farther north. Below the Lagonegro, the inversion yields layering almost identical to that at VENO and CRBB. The thin LVZ is not fully resolved, but appears in most inversions, including the mean model (Fig. 4; Fig. DR3). The LVZ is coincident with the decollement between Apulia carbonates in the upper plate and the descending lower plate.

The inversion for seismic station POLA yields two LVZs. We identify the top one with the Lagonegro clastics between the Apennine and Apulian carbonates (Fig. 4). The deeper LVZ correlates with the red CCP converter. In the thin-skinned model, this corresponds to the basal clastics and top of Apulian basement. In the thick-skinned model, the signal arises from within the imbricated Apulian carbonates. The Apulian platform layers are nearly identical to those of the other stations.

The stations further west are off section. The base of the Apennine platform in the thick-

**Figure 3.** Perspective image of common conversion point (CCP) volume. Cutaway shows strong continuous features across Southern Apennines and change in character at Southern Apennines–Calabrian arc transition. Dots are Calabria–Apennine–Tyrrenian/Subduction-Collision-Accretion Network (CAT/SCAN) stations and dashed line is Apennine thrust front. Stations used for receiver function (RF) inversions are labeled. Map shows piercing points for rays used in CCP image, geologic sections, and CCP section.

**Figure 4.** A: Results of the receiver function (RF) inversions along profile (Fig. 3). Red lines show correlations (top and base Apulia—solid; base Apennine—dashed). B: Thin-skinned geological model with common conversion point (CCP) image and RF inversions. C: Thick-skinned geological model with CCP image and RF inversions. In RF profiles, Apulian carbonates are filled and heavy line is Moho. Detachment is shown by black-white line. P velocities of Puglia-1 well are also shown. See text for discussion. PPD—posteriori probability distribution.
skinned model fits the LVZ in seismic station SGIO because the profile and station are close and does not indicate that this model is preferred. Rather, it is evidence of the good fit of the RFs to the local geology. The most significant result in seismic stations SGIO and CA VE is shallow Moho at 23 and 21 km depth. This is shallower than either of the geologic models, but is consistent with other data indicating a shallow Moho on the Tyrrhenian side of the Southern Apennines (Piana Agostinetti et al., 2002). The Apulian layers are not seen in the inversion, but would compose almost the entire crust if present intact.

Consistency between the geology, RF inversions, and CCP image on the Apulian platform foreland is strong (Fig. 4; Fig. DR4). The LVZ required by the RF inversion gives rise to the red horizon on the CCP image. This can be traced into the beginning of the fold belt where the Apulia Platform begins to plunge downward.

The shallow parts of the Southern Apennines also show a consistency between the geology and the RF inversions (Fig. 4). Low near-surface velocities correspond to the foreland basin sediments and Lagonegro strata. Higher velocities correspond to the Apennine platform. LVZs at their base are seen at SGIO and POLA.

At greater depth, the interpretations beneath the Southern Apennines differ. For the thick-skinned model (Fig. 4C), the LVZ corresponds to the base of Apulian platform carbonates and top of basement. The red converter in the CCP is too shallow, perhaps due to the generic velocities used to convert the CCP to depth. For the thin-skinned model (Fig. 4B), the LVZ and red converter are in the midst of imbricated Apulian platform strata. It is possible that there is a preserved low-velocity clastic horizon, but it would have to be thick and coherent enough to generate the conversions seen in the RF and CCP.

Alternatively, the thrusts could be thin-skinned, but without the imbrication, so that the converter corresponds to the base of the thrust sheet.

The stations on the Tyrrhenian side also have a well-defined Moho shallower than in either model. In the thin-skinned model, the Apulian carbonates would extend down to the Moho. In the thick-skinned model, the Tyrrhenian stations are beyond the western edge of the Apulian platform. An initially thin or tectonically thinned basement would underlie the Apennine nappes. Scrocca et al. (2005) proposed the formation of a shallower “New” Tyrrhenian Moho related to the Tyrrhenian extension.

CONCLUSIONS

Both thin- and thick-skinned models contain elements that fit and do not fit CAT/SCAN seismic data. We find that the thin-skinned model is most consistent with the seismic data, requiring a uniform explanation for the velocity boundaries producing the P-S conversions observed in the RF. The consistent structure of the Apulian platform across the orogen is compelling. For the thin-skinned model to fit, the extent of imbrication of the Apulian platform must be drastically reduced, greatly lowering the shortening estimates for the orogen. The low amount of shortening implied by the thin-skinned model suggests that the Calabrian arc primarily migrated to the east-southeast and implies some obliquity to the orogen (e.g., Rosenbaum and Lister, 2004).

However, left-lateral deformation is known primarily from late extension that postdates thrusting (Catalano et al., 2004). The greater shortening of the thin-skinned model implies a more radial expansion of the Calabarian arc, which may reflect the shape of the circular Marsili basin in the eastern Tyrrhenian Sea. However, both models must better account for the larger-scale descent of the Apulian plate into the mantle (Scrocca et al., 2005). Neither is consistent with a shallow Moho near the Tyrrhenian Sea. Thus both models need to be fully integrated with the three-dimensional geometry of the subduction system.

ACKNOWLEDGMENTS

This work was funded by National Science Foundation grant EAR-99-10554 and by the Istituto Nazionale di Geofisica e Vulcanologia. We thank all the participants in the Calabrian-Tethys-Tyrrhenian Subduction-Accretion-Collision Network (CAT/SCAN) field work, and L. Margheriti for a constructive review. Data collection and archival were facilitated by Incorporated Research Institutions for Seismology (IRIS). Lamont-Doherty Earth Observatory publication 7086.

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Manuscript received 18 May 2007
Revised manuscript received 2 October 2007
Manuscript accepted 7 October 2007

Printed in USA