Crustal Structure in the Southern Apennines from Teleseismic Receiver Functions

Michael S. Steckler[1], Nicola Piana Agostinetti[2], Charles K. Wilson[1], Pamela Roselli[3], Leonardo Seeber[1] A. Amato[2] and A. Lerner-Lam[1]

[1]*Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA*
[2]*Istituto Nazionale di Geofisica e Vulcanologica, Centro Nazionale Terremoti, Roma, Italia*
[3]*Istituto Nazionale di Geofisica e Vulcanologica, Osservatorio Sismologico Arezzo, Arezzo, Italia*

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

Abstract

While the upper crustal structure of the Southern Apennines is known, lack of control on the deep structure allows competing thin-skin and thick-skin models of the orogen. In thin-skin models the detachment decouples a stack of rootless nappes from the basement. In thick-skin models, basement is involved in the most recent phase of thrusting. To examine crustal structure, we use teleseismic data from the CAT/SCAN array in southern Italy. We use receiver functions (RF) processed into a Common Conversion Point (CCP) stack to generate images of the crust. Interpretation and correlation to geological structure is 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-skin interpretation. In a thick-skin reconstruction, the amount of shortening is much smaller than for a thin-skin model. This implies considerably less Plio-Pleistocene shortening across the Apennines and suggests an E-SE motion of the Calabrian Arc subparallel to the southern Apennines rather than a radial expansion of the Arc.

Introduction

The Southern Apennines (SA) results from impact of the continental Apulian Platform (AP) with the Calabrian Arc (CA). 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 SA. The Apenninic units comprise large nappes that overthrust the AP, similar to many fold-and-thrust belts with detached strata imbricated above basement. Beneath these nappes, the AP becomes involved in the thrusting. However, seismic data, including recently published CROP lines (Scrocca et al., 2005; Finetti et al., 2005) do not resolve whether basement is involved in the deeper thrusts. Thin-skin reconstructions with imbricated AP units above a detachment (e.g., Mazzotti et al., 2000) and thick-skin reconstructions with thrusts rooted in basement beneath the AP (Menardi Noguera and Rea, 2000) are both viable. These geometries permitted imply large differences in shortening. Thick-skin models require <30 km shortening of Apulia, while thin-skin models imply >120 km shortening. This has significant implications for opening of the Tyrrhenian Sea. Did the CA expand radially or primarily rollback towards the E or SE? What is the amount of obliquity in the SA?

In 2003, we deployed a broadband seismic array, the Calabria-Apennine-

Tyrrhenian/Subduction-Collision-Accretion Network (CAT/SCAN) to image the SA, CA and the transition between them (Fig. 1). We image the crust of the SA 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 SA.

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 CA, 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 NE Sicily are the only remaining part of the subduction zone still consuming oceanic crust (Fig. 1).

The SA is a stack of NE-verging thrust sheets with 4 major units. The uppermost is the Ligurian Complex, a Jurassic-E. 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 (ApP). It is primarily Triassic to Miocene shallow-water carbonates and associated deposits (Cello and Mazzoli, 1998; Menardi Noguera and Rea, 2000; Finetti et al., 2005). The ApP may have started as a Bahama-like set of carbonate banks (Cello and Mazzoli, 1998; Ciarapica and Passeri, 2005) that formed the outer blocks of Apulia. The ApP was eventually sheared off its basement as a set of rootless nappes.

Next is the Lagonegro Sequence, the cover of the deep-water basin separating the Apennine Platform from Apulia. The lower Lagonegro sequence grades from Permian-E. Triassic rift basin facies to deep-water facies (Mostardini and Merlini, 1986). The distinct upper sequence grades from a L. Cretaceous deep-water facies to a Miocene terrigenious flysch and mélange.

Lowermost is the AP, the autochthonous basement in the foreland. The AP is composed of 5-7 km of Triassic-Miocene shallow-water carbonates and dolomites overlying >1 km of Permian-L. Triassic clastics. Well logs, including the 7070m Puglia-1 well (Fig. 1), indicate high velocities for the AP, over a lower velocity for the basal clastics (Improta et al., 2000; DR4).

The Apennine-Lagonegro terranes were emplaced by Miocene thin-skin thrusting. The shearing off of the AP from its basement may have enabled CA rollback to resume. Following subduction of the Lagonegro oceanic(?) basin, the northern CA collided with the AP. The AP 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 AP is widely recognized but its base is only seen locally. Recent normal faults and extensional basins on the Tyrrhenian side of the SA complicate the structure. As a result, two contrasting end-member models (Fig. 2) both satisfy existing data: A thick-skin model where thrusts involved Apulian basement since the late Pliocene-early Pleistocene (Menardi Noguera and Rea, 2000; Finetti et al., 2005) and a thin-skin model where thrusts imbricate the AP, but do not penetrate its basement (Mazzotti et al., 2000).

Butler et al. (2004) and Scrocca et al. (2005) discuss the merits of the two models but reach

opposite conclusions. For the thin skin, the allochthon is thickened by duplexing, requiring shortening of 90-120 km (Mazzotti et al., 2000; Scrocca et al., 2005). This requires a significant radial component of shortening during the rollback of the CA. The extra crust must either be subducted or deformed farther west. For the thick skin, steeper thrust faults rooted in basement require shortening of only 10-30 km (Menardi-Noguera and Rea, 2000; Butler et al., 2004; Scrocca et al., 2005). The thick-skin model requires a change from the earlier thin-skin thrusting when the CA encounters Apulia. Thus, the ApP collided with the CA and underwent thin-skin shortening of ~200 km, while the larger AP underwent thick-skin shortening of tens of kilometers.

Seismic Data Analysis

CAT/SCAN is a land (39 stations) and marine (12 stations) seismic experiment to image crust and mantle structure beneath Calabria and its transition to the SA (Fig. 1). The deployment from Dec. 2003-Oct. 2005 included linear arrays across the CA and SA and a regional grid spanning the transition between the two areas.

We applied common conversion point (CCP) stacking of receiver functions (RF) (Dueker and Sheehan, 1998; Wilson et al., 2004) using 95 events with Mw>6.0 with epicentral distances of 30° to 110° (Fig. DR1). RFs were produced by deconvolving P-phase vertical seismograms from radial and transverse seismograms (Ligorria and Ammon, 1999). This procedure extracts Ps, S waves converted from the P at refracting interfaces. The amplitude of the conversions depends upon the impedence contrast across the interface and the incidence angle. A Ps phase from the top of a low-velocity body will be reversed in polarity from the incident wave.

RFs from a single station span a range of azimuths and incidence angles illuminating subsurface refractors at different points. To optimize this data, we depth migrated the radial conversions along their raypaths and stacked them into CCP bins. The bins are 15x15 km across and 0.5 km thick forming a volume 210x315x60 km (Fig. 3, DR2). To fill empty bins we used a smoothing algorithm averaging over distances inversely with data density. A regularized inversion enforces smoothness in the absence of data. In the image, red are positive and blue are negative conversions. A generic velocity model was used for the depth migrations, thus depth errors up to several km are possible.

To get robust constraints on features of our CCP image along the linear SA array, we applied a complementary single station RF inversion technique. We computed RFs using teleseismic events with Mw>5.5 to obtain maximum back-azimuth (baz) coverage (~60 RF per station). We analyzed baz dependence of the RF datasets using harmonic expansion coefficients (HEC) (Gilardin and Farra, 1998). Surface geology and the HEC were used as *a priori* information on the velocity profile at each station. We inverted the RF data using the 2-stage NA approach (Sambridge, 1999a,b), a Monte-Carlo inversion technique. In the first part, the dataset is iteratively compared with synthetics computed from models sampling the parameter space. In the second part, we use a Bayesian approach to obtain *a posteriori* probability distributions (PPD) for each parameter, from which we compute statistical estimators. To compute synthetics from 3D structures, we coupled the NA with the RAYSUM code (Frederiksen and Bostock, 2000). Details are in DR3.

Results and interpretation

The CCP volume images large-scale crustal structures below the SA. A number of high-amplitude coherent features persist over large regions where station control is good. There are also features of limited extent, some of them multiples. The CCP volume (Fig. 3, DR2) shows 3

strong Ps converters, which gently dip SW and are continuous throughout the illuminated parts of the SA. We focus on the shallowest converter located at 8-11 km depth; it is located at the bottom of the well-constrained structure of SA (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 2 distinct surfaces elsewhere.

Calabria, in the lower left of Figure 3, exhibits a very different character without the strong conversions seen in the SA. This fits the contrasting structure of Calabria, which is still subducting oceanic crust and has not (yet) collided with Apulia. The transition between the SA 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 CRBB in the AP (Fig. 4, DR3). The Puglia-1 well provides geology and velocity constraints (≤7 km). The CRBB RF shows little azimuthal dependence, consistent with the flat-lying AP, and can be modeled using a 1D S-velocity profile. The inversion yields velocity layering similar to the well. We find that a low velocity corresponding to the clastic layer in the AP is required, and that AP layering is composed of two main units with the deeper (dolomites) faster than the shallower (carbonates). With this structure the RF (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. Moho is clear at 30 km, consistent with earlier estimates.

This correlation is reinforced by the inversion of VENO, which exhibits almost the same structure beneath low-velocity foreland strata. The 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.

The red CCP converter is lost where the AP plunges beneath the mountain belt. The RF for the seismic stations (SX17, TRIC) at this position are complex due to 3D structure and cannot be easily inverted.

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

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

The stations farther west are off section. The base of the ApP in the thick-skin model fits the LVZ in SGIO because the profile and station are close and does not indicate this model is preferred. Rather, it is evidence of the good fit of the RFs to the local geology. The most

significant result in SGIO and CAVE 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 SA (Piana Agostinetti et al., 2002). The Apulian layers are not seen in the inversion, but would comprise almost the entire crust if present intact.

Consistency between the geology, RF inversions and CCP image on the AP foreland is strong (Fig. 4; 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 foldbelt where the Apulia begins to plunge downward.

The shallow parts of the SA 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 ApP. LVZs at their base are seen in SGIO and POLA.

At greater depth, the interpretations beneath the SA differ. For the thick skin model (Fig. 4c), the LVZ corresponds to the base of AP 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 skin model (Fig. 4b), the LVZ and red converter lie in the midst of imbricated AP strata. It is possible that there is a preserved low-velocity clastic horizon, but would have to be thick and coherent enough to generate the conversions seen in the RF and CCP. Alternatively, the thrusts could be thin skin, 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 those in either model. In the thin-skin model, the Apulian carbonates would extend down to the Moho. In the thick-skin model, the Tyrrhenian stations are beyond the western edge of the AP. An initially thin or tectonically thinned basement would underlie the Apennine nappes. Scrocca et al. (2005) propose the formation of a shallower "New" Tyrrhenian Moho related to the Tyrrhenian extension.

Conclusions

Both thin- and thick-skin models contain elements that fit and misfit CAT/SCAN seismic data. We find that the thick-skin 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 AP across the orogen is compelling. For the thin-skin model to fit, the extent of imbrication of the AP must be drastically reduced, greatly lowering the shortening estimates for the orogen. The low amount of shortening implied by the thick-skin model suggests the CA primarily migrated to the E-SE and implies some obliquity to the orogen (e.g., Rosenbaum and Lister, 2004). However, left-lateral deformation is known primarily from late extension that and postdates thrusting (Catalano et al., 2004). The greater shortening of the thin-skin model implies a more radial expansion of the CA, 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 shallow Moho near the Tyrrhenian. Thus both models need to be fully integrated with the 3D geometry of the subduction system.

Acknowledgements

This work was funded by US National Science Foundation grant EAR99-10554 and by INGV. We thank all the participants in the CAT/SCAN fieldwork and L. Margheriti for a constructive review. Data collection and archival were facilitated by IRIS. LDEO publication No. 7086.

[1]GSA Data Repository item 2005##, [brief description], is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

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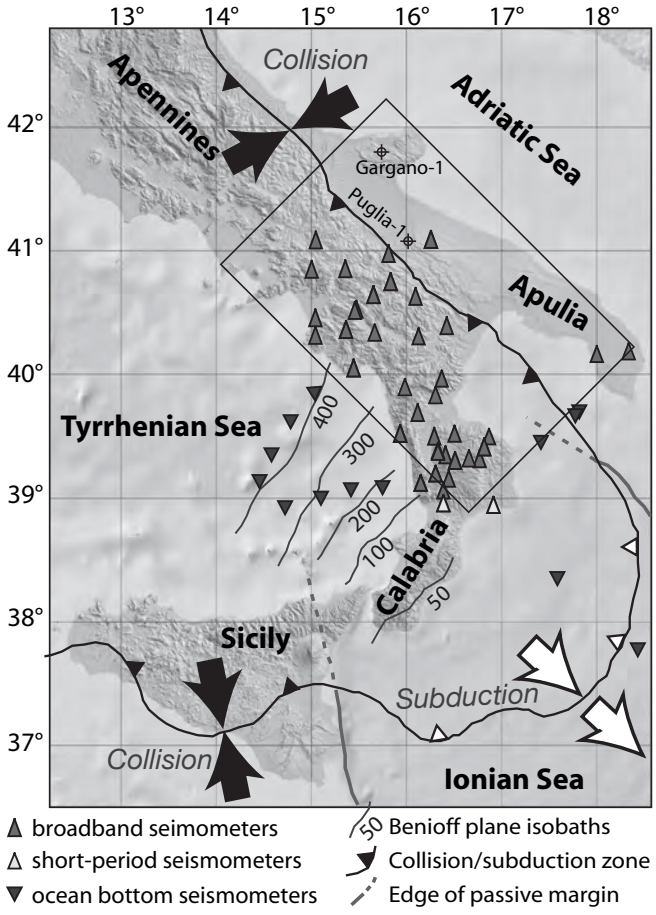
Figure 1. Map of the CAT/SCAN seismic array. An active Wadati-Benioff zone to 500 km depth is present only beneath the CA where oceanic crust is subducted. In the SA, the arc has collided with the AP. We use events recorded by the array to examine the crustal structure of the region in the box.

Figure 2. Contrasting interpretations of the SA. A) Thin-skinned model with rootless nappes of AP detached from the basement (Mazzotti et al., 2000). B) Thick-skinned model with basement involved thrusting (Menardi Noguera and Rea, 2000). C) Geology of southern Apennines with the lines of the two sections (modified from Ciarapica and Passeri, 2005). Overall figure modified from Scrocca et al. (2005).

Figure 3. Perspective image of CCP volume. Cutaway shows strong continuous features across the SA and change in character at the SA-CA transition. Dots are CAT/SCAN stations and dashed line is Apennine thrust front. Stations used for 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 RF inversions along profile (Fig. 3). Red lines show correlations (top and base Apulia–solid; base Apennine–dashed). Thin **(B)** and Thick **(C)** skin geological models 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.


13°
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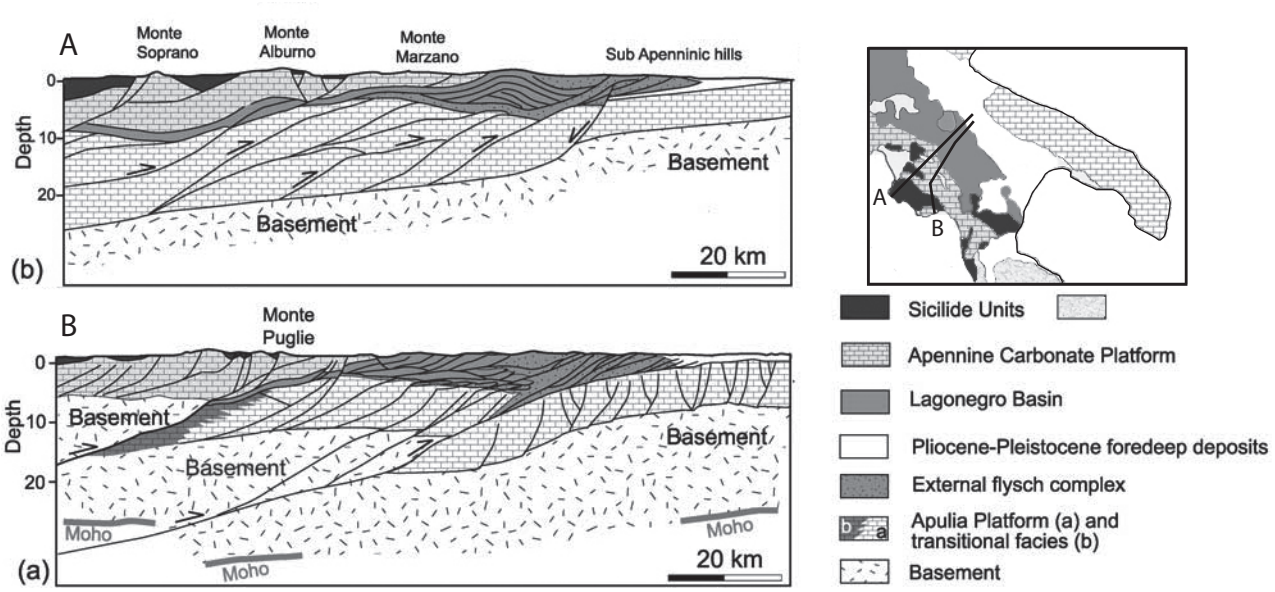
38°
37°
Collision
Apennines
Adriatic Sea
Gargano-1
Puglia-1
Apulia
Tyrrhenian Sea
400
300
200
100
50
Calabria
Sicily
Subduction
Collision
Ionian Sea
broadband seimometers
short-period seismometers
ocean bottom seismometers
50 Benioff plane isobaths
Collision/subduction zone
Edge of passive margin

Figure 1


A
Monte Soprano
Monte Alburno
Monte Marzano
Sub Apenninic hills
Depth
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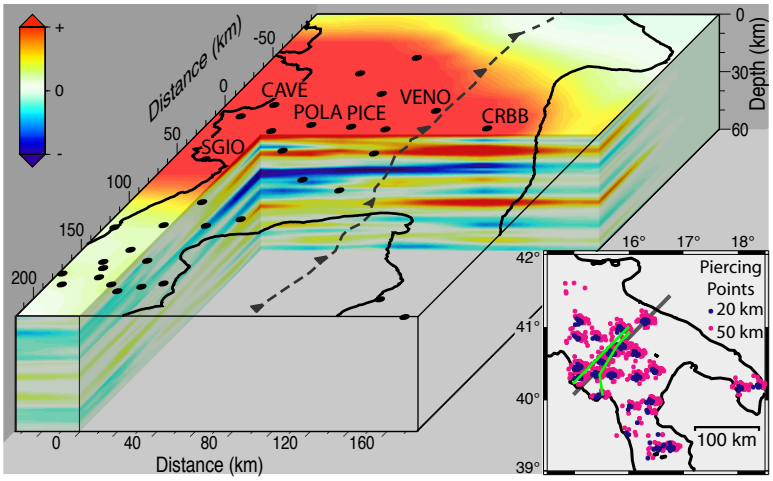
(b)
B
Monte Puglie
Basement
Basement
Basement
Moho
Moho
Moho
20 km
(a)
A
B
Sicilide Units
Apennine Carbonate Platform
Lagonegro Basin
Pliocene-Pleistocene foredeep deposits
External flysch complex
b
a
Apulia Platform (a) and transitional facies (b)
Basement

Figure 2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CAVE
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PICE
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Depth (km)
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80
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Piercing
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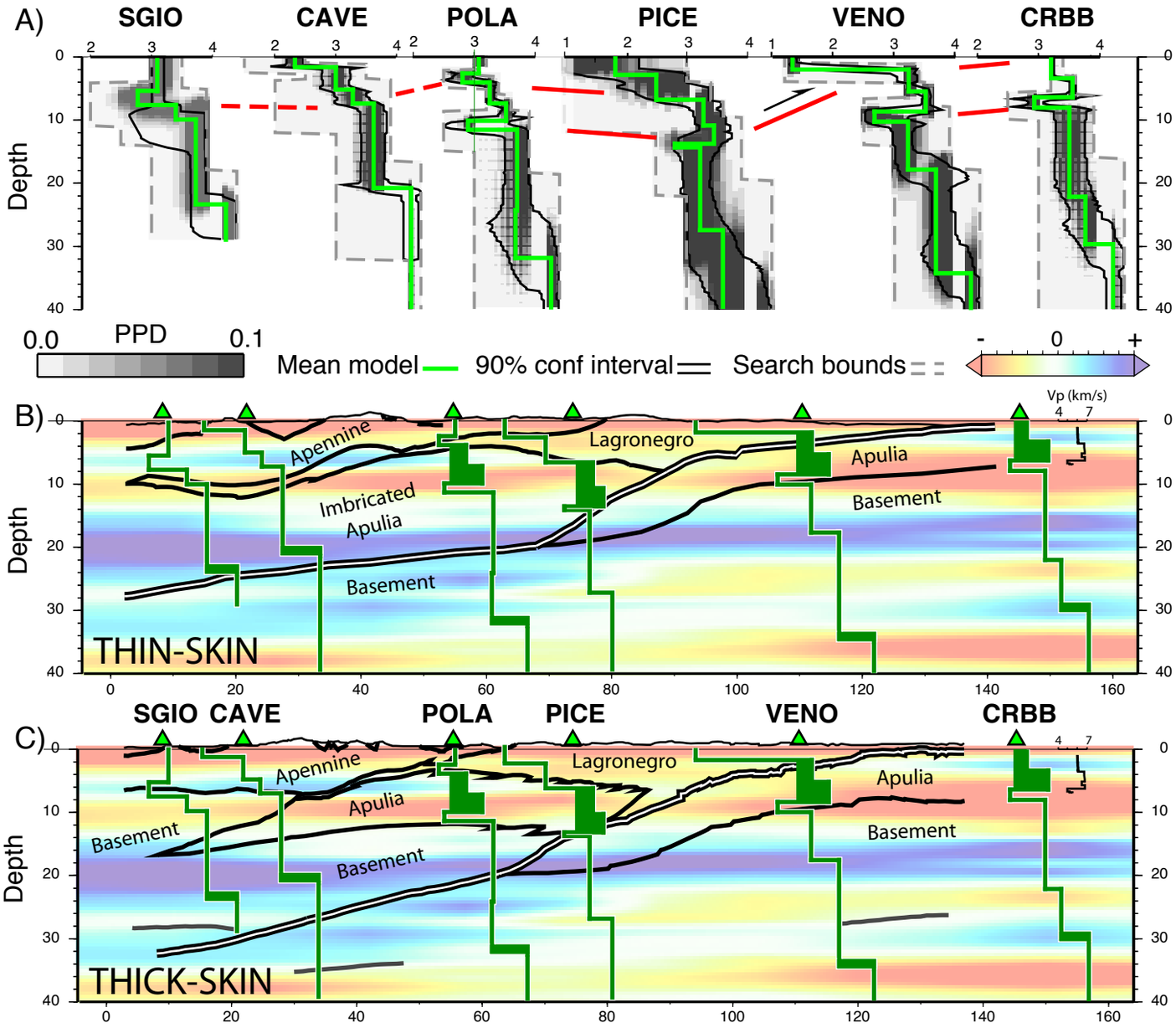
Figure 3


A)
SGIO
CAVE
POLA
PICE
VENO
CRBB
Depth
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Mean model
90% conf interval
Search bounds
B)
Vp (km/s)
Apennine
Lagronegro
Apulia
Imbricated Apulia
Basement
THIN-SKIN
C)
SGIO CAVE
POLA
PICE
VENO
CRBB
Apennine
Lagronegro
Apulia
Basement
Basement
Basement
THICK-SKIN

Figure 4